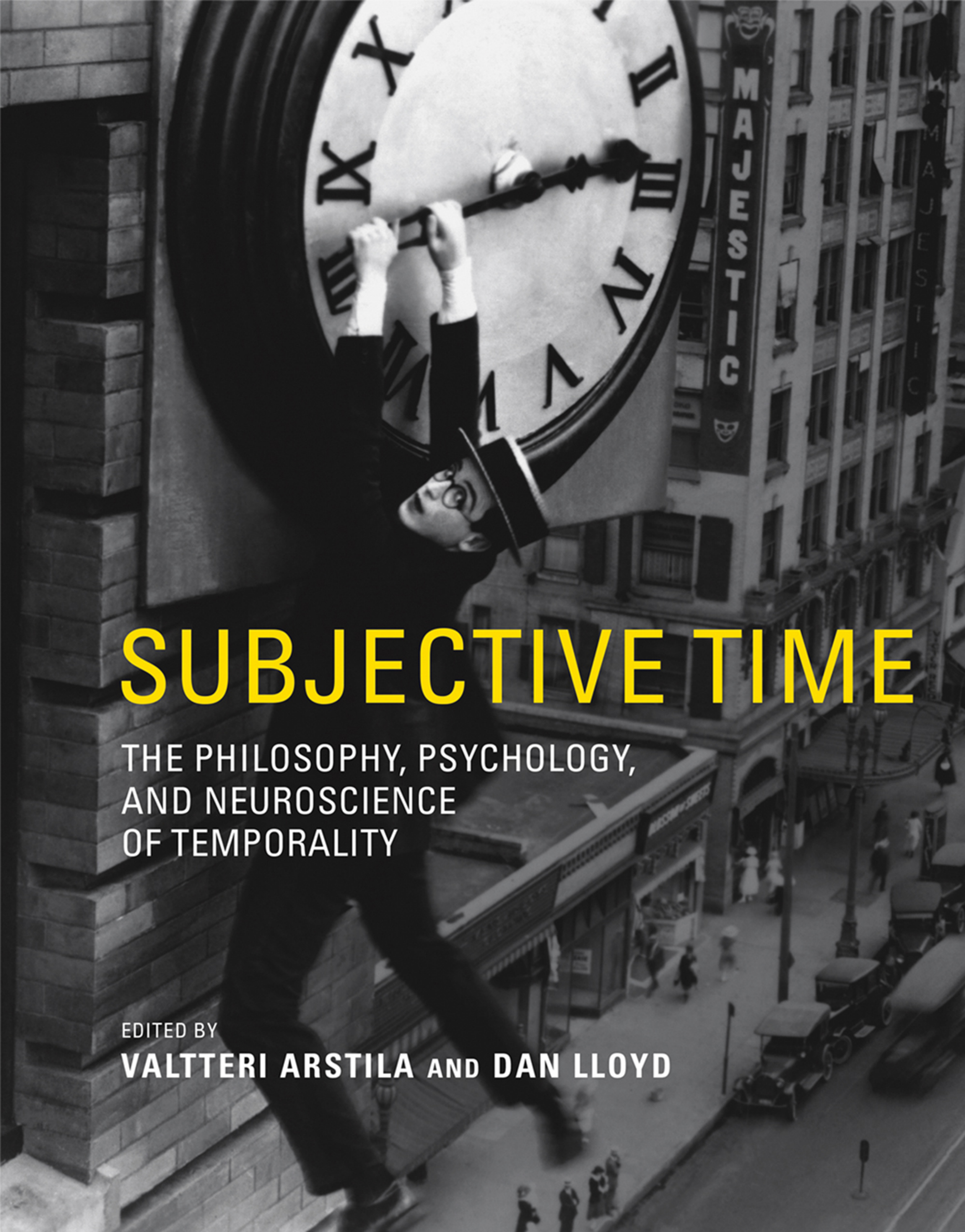

SUBJECTIVE TIME

THE PHILOSOPHY, PSYCHOLOGY, AND NEUROSCIENCE OF TEMPORALITY

EDITED BY
VALTTERI ARSTILA AND DAN LLOYD

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The Philosophy, Psychology, and Neuroscience of Temporality

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Preface

A

Something happens—you see “*A*.” Or, “*A* appears to you.” Now,

B,

something else. *A* and *B* differ in shape and location, two spatial properties you can easily and immediately distinguish. But they also differ in their time of occurrence, equally easy to discern. You were aware that *A* was first, that a short interval separated *A* and *B*, an interval much shorter than the gap between *B* and the present moment. Perhaps you looked at *A* longer than you looked at *B*, a difference you notice either at the time, or after a little reflection. The first letter may have been attended with brief questions: What is this? Is this *A* a section heading? The start of a sentence? A symbol to denote an example of an event? But *B* is not so ambiguous.

Looking back, you can clearly locate these fleeting thoughts in their time line of occurrence. In addition, you were aware, at least peripherally, of a temporal context, a background against which *A* and *B* appeared. Before *A*, you opened a book. During *A*, you held the book open; perhaps you noticed a background noise or the smell of coffee. Meanwhile, the interval between *B* and the present moment is growing—“now” is moving forward, while *A* and *B* are “sinking” into the past. You can observe this lengthening gap or not, but when you attend to it again in a few seconds you will notice that it has grown without your attention to it.

As the seconds pass, the initially discrete *A* and *B* seem to draw closer together. Reflecting on *A* and *B* now, it is as if it were a single brief episode, *A*-*B*, followed by a stream of reading, a flow of further events in a river of passing time. Other features of *A*-*B* come to mind as you read, which you fit without confusion into the growing story line, distinguishing aspects you noticed at the time and others you are noticing now that are nonetheless connected to the initial experience. As you turn the page, you’ll still remember the book’s opening lines. You can rehearse them with novelistic elaborations, picture them in detail, really focus on them, but even so you’ll never confuse them with something you perceive at the present moment. Meanwhile, you are anticipating the next word in every . . .

statement
(was that what you expected? Or did you anticipate "sentence"?), and the flow of the discussion going forward. . . .

These are all aspects of *subjective time*, the experience of the temporal properties of events and processes: their order, duration, time of occurrence, context among simultaneous events and events before and after, and more. Our temporal awareness is a ubiquitous feature of conscious life. The lightning flash and the thunder's rumble engage different senses, but can be effortlessly compared in order and duration. One coffee cup has been on the table since yesterday, while a very similar cup you just set down has been there for a shorter time. They may look just alike, but their recent histories distinguish them emphatically. If you look away from one cup and then back at it, the cup is the same, but there are two perceptual episodes, two lookings, and like *A* and *B* their temporal properties are clear to you. Perhaps in the midst of reading a stray thought occurs to you—a forgotten errand, perhaps—and you make a mental note to come back to the topic later. This purely internal rumination also has its temporal properties, just as do the external events, and weaves among those events without confusion. Finally, these comments may inspire you to think about time itself in its psychological manifestations, to reflect on the pure flow of time, carrying all along. But this thought about time occurs in time, flowing among exactly the flow it ponders.

How does subjective time work? In his *Confessions,* Augustine expressed a famous frustration with time:

> What then *is* time? If no one asks me, I know. If I want to explain it to a questioner, I do not know. (Sheed & Foley, 2006, 242)

When we talk of the perception of an object, we can begin with the thing and its causal influences on sense organs, and a further cascade of effects culminating in a conceptually rich awareness of the object. This account will raise many further questions, but it seems to be a concrete starting point. But time is strange. The *A-B* example had its effects at the time, but it is not currently provoking our retinas. Yet we can get back to it; it is "still there" for us to consider. Indeed, the initial glimpses of *A* and *B* were never co-present, so how could "and then" be constructed? There is, of course, some sort of causal story to link the original *A-B* sequence with our current state of awareness, but why doesn't this path deliver a *perception* of *A-B*, to be confused with here-and-now perception? *A-B* keeps its "pastness" regardless of further reflective contortions. Conversely, *A-B* remains the same initial sequence, even as its temporal properties evolve (as it becomes more remote). The objects arrayed before you each have temporal properties, some prominent in your awareness and others less so. Two indistinguishable coffee cups may have similar histories as cups, but their contents do not: yesterday's neglected coffee and the cup brewed ten minutes ago are importantly different, and these temporal differences can be quite reliably distinguished. As we think about it, we notice that the sensory field and the effervescent states of awareness (sensations and reflections both) comprise an intricate and nuanced *temporal field*, and subtle distinctions within the field might be traced to many origins involving memory, perception, inference, and more. How could something like this come to be? Subjective time is a puzzle that cuts across the mysteries of memory, perception, and consciousness itself.

Our awareness of subjective time thus seems to be the ground bass of conscious life. To understand subjective time is to understand something central to being human. But of course our temporal discernment is not merely a mysterious enrichment of experience. The physical world is dynamic at every scale, and our survival depends on our ability to track complex processes and anticipate change. Accordingly, the mystery of subjective time is not merely the challenge of providing an adequate philosophical description of the many turning gears that constitute our human awareness of time. Our time must mesh with world time. Somehow the internal temporal field guides us in our intricate interactions with the temporal dynamics of everything else (including the temporal field itself). Understanding how this is possible is obviously both challenging and important to psychology and neuroscience.

Usually, the connection of subjective time to objective timing is good enough to get by. We can't always return a tennis serve, but we can usually pour a cup of coffee. With our many temporal competencies, we would expect that laboratory measurements of our human temporal abilities would reveal generally accurate capacities to judge duration, order, simultaneity, and the like. However, this turns out to be shockingly far from the truth. Instead, time estimations in many experiments differ from objective time, and are readily manipulated to produce a variety of temporal illusions. Considering numerous forms of inaccuracy, our temporal competence acquires an additional layer of mystery—how do we even do as well as we do? The psychology of subjective time, even in optimal conditions, does not reveal a clockwork timepiece in the brain. How then does the brain keep time?

Subjective time bends in other ways as well, most notably as a side effect of various mental disorders, including schizophrenia, ADHD, and Parkinson's disease. Likewise, under the influence of drugs or hypnosis, under conditions of stress and all the other natural shocks that flesh is heir to, time warps. How could something so transparent in daily life be so fragile?

In sum, we are beings who live in time with such ease that we hardly notice that the time in which we live is deeply mysterious. Fundamental and pervasive brain processes embody the experience of subjective time, and although their exact nature is a subject of speculation, there are many informed guesses. Psychologically, many probes reveal a multiform and inconsistent capacity for time judgments of many sorts. Finally, the very nature of temporal experience, lived from the inside, is open to philosophical question. Ultimately, all of these strands must weave together to provide a coherent understanding of this foundation of human experience.

This book is a grand tour of the issues above: the philosophy, psychology, and neuroscience of *subjective time*.

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Contributors

Melissa J. Allman
Department of Psychology, Michigan State University, East Lansing, US

Holly Andersen
Department of Philosophy, Simon Fraser University, Burnaby, Canada

Valtteri Arstila
Department of Philosophy & Centre for Cognitive Neuroscience, Department of Psychology, University of Turku, Turku, Finland

Yan Bao
Department of Psychology and Key Laboratory of Machine Perception (MoE), Peking University, Beijing, China; Institute of Medical Psychology and Human Science Center, Ludwig Maximilian University Munich, Munich, Germany

Dean V. Buonomano
Departments of Neurobiology and Psychology & Brain Research Institute, University of California, Los Angeles, Los Angeles, US

Niko A. Busch
Institute of Medical Psychology, Charité–Universitätsmedizin Berlin, and Berlin School of Mind and Brain, Humboldt-Universität zu Berlin, Germany, Berlin, Germany

Barry Dainton
Department of Philosophy, University of Liverpool, Liverpool, UK

Sylvie Droit-Volet
Laboratoire de Psychologie Sociale et de Psychologie Cognitive, LAPSCO, Université Blaise Pascal, Clermont-Ferrand, France

Christine M. Falter
Faculty of Behavioural and Social Sciences, University of Groningen, Netherlands

Thomas Fraps
Independent magician, Munich, Germany

Shaun Gallagher
Department of Philosophy, University of Memphis, Memphis, US; School of Humanities, University of Hertfordshire, Hatfield, UK; School of Humanities and Social Inquiry, University of Wollongong, New South Wales, Australia

Alex O. Holcombe
School of Psychology, University of Sydney, Sydney, Australia

Edmund Husserl (1859–1938)

William James (1842–1910)

Piotr Jaśkowski (1957–2011)

Jeremie Jozefowiez
Laboratoire URÊCA, Université Lille Nord de France, Domaine Universitaire du Pont de Bois, Villeneuve d'Ascq Cedex, France; Escola de Psicologia, Universidade do Minho, Braga, Portugal

Ryota Kanai
Institute of Cognitive Neuroscience, Department of Psychology, University College London, London, UK; Sackler Centre for Consciousness Science, School of Psychology, University of Sussex, Brighton, UK

Allison N. Kurti
The Department of Psychology, University of Florida, Gainesville, US

Dan Lloyd
Department of Philosophy and Program in Neuroscience, Trinity College, Hartford, US

Armando Machado
Escola de Psicologia, Universidade do Minho, Braga, Portugal

Matthew S. Matell
Department of Psychology, Villanova University, Villanova, US

Warren H. Meck
Department of Psychology and Neuroscience, Duke University, Durham, US

James Mensch
The Faculty of Humanities, Charles University, Prague, Czech Republic

Bruno Mölder
Department of Philosophy, University of Tartu, Tartu, Estonia

Catharine Montgomery
School of Natural Sciences and Psychology, Liverpool John Moores University, Liverpool, UK

Konstantinos Moutoussis
Department of Philosophy and History of Science, National and Kapodistrian University of Athens, Athens, Greece

Peter Naish
Department of Psychology, Open University, Milton Keynes, UK

Valdas Noreika
Centre for Cognitive Neuroscience, Department of Psychology, University of Turku, Turku, Finland; Oxford Centre for Human Brain Activity, Department of Psychiatry, University of Oxford, Oxford, UK

Sukhvinder S. Obhi
Centre for Cognitive Neuroscience & Department of Psychology, Wilfrid Laurier University, Waterloo, Canada

Alan O'Donoghue
School of Psychology, Keele University, Keele, UK

Ruth Ogden
School of Natural Sciences and Psychology, Liverpool John Moores University, Liverpool, UK

Georgios Papadelis
Department of Music Studies, School of Fine Arts, Aristotle University of Thessaloniki, Thessaloniki, Greece

Ian B. Phillips
St. Anne's College, Oxford University, Oxford, UK

Ernst Pöppel
Institute of Medical Psychology and Human Science Center, Ludwig Maximilian University Munich, Munich, Germany; Parmenides Center for the Study of Thinking, and of Art and Science, Pullach, Germany; Department of Psychology, Peking University, and Institute of Psychology, Chinese Academy of Sciences, Beijing, China

John E. R. Staddon
Biology Department, Duke University, Durham, US; Department of Psychology, University of York, York, UK

Dale N. Swanton
Center for Molecular and Behavioral Neuroscience, Rutgers University, Newark, US

Rufin VanRullen
Université de Toulouse, France; CNRS-CerCo, UMR 5549, Toulouse, France

Argiro Vatakis
Cognitive Systems Research Institute (CSRI), Athens, Greece

Till M. Wagner
Department of Physics, University of Oxford, Oxford, UK

John Wearden
School of Psychology, Keele University, Keele, UK

Marc Wittmann
Department of Empirical and Analytical Psychophysics, Institute for Frontier Areas in Psychology and Mental Health, Freiburg, Germany

Agnieszka Wykowska
Allgemeine und Experimentelle Psychologie, Department Psychologie, Ludwig-Maximilians-Universität, Munich, Germany

Kielan Yarrow
Department of Psychology, City University London, London, UK

Bin Yin
Department of Psychology and Neuroscience, Duke University, Durham, US

Dan Zahavi
Center for Subjectivity Research, University of Copenhagen, Copenhagen, Denmark

I Historical Sources

Time has been a perennial issue for philosophy. It held center stage before Socrates, as the first Western "natural philosophers" grappled with the origin of all things—already a question of transformation, from chaotic beginnings to the present world they observed. Thus change, and the interchange of one and many, perplexed them, leading to debates among opposing philosophers and their schools over the meaning and possibility of motion and change, generating puzzles like Zeno's paradoxes of motion. Plato and Aristotle both considered time explicitly, but as with the pre-Socratics, their concern was metaphysical. Philosophy takes a turn toward subjective time with the *Confessions* of Augustine (354–430 C.E). Augustine favored the metaphysical view sometimes called "presentism," the idea that only the present instant exists. But—in order to have something to confess—Augustine needed some sort of psychological access to the past. He therefore proposed that our concept of time is based in memory, through which the past is brought to bear on the present. In this way, our experience of the Now expands to form a temporal landscape through which we pass.

The modern interest in subjective time traces primarily to two authors, William James (1842–1910) and Edmund Husserl (1859–1938). In this section, we provide excerpts from both. In *The Principles of Psychology*, William James endorses a view reminiscent of Augustine. The instantaneous Now is only a slice of the experienced Now; the experience of the present includes fringes of the just-past and the soon-to-be. We live in a "specious present" of some seconds in length, bracketing the instantaneous Now. The specious present is not an isolated idea, but rather fits within James's lively discussions of the nature of consciousness generally. Here, we've included James's introduction of the "stream of consciousness" and its dynamism of "flights and perches" within the "nucleus and fringes" of awareness. The selections reveal James's rich descriptions of a phenomenology in which change is the only constant. James interwove his phenomenology with the varied empirical results of his time. James reports on systematic measures of time judgments and their routine distortions, findings updated and reinterpreted in the subsequent chapters of this collection.

The Principles of Psychology is laden with citations and long quotations, helping to locate James among his contemporaries and immediate precursors. The specious present, in particular, is introduced through a quotation from one "E. R. Clay," a reference echoed in myriad commentaries on James. However, there was no such person, as Holly Andersen determines in chapter 2. The real author of the quotation, E. R. Kelly, links the idea of the specious present to James's actual predecessors with respect to his influential doctrine. This philosophical lineage, and the logical evolution of the specious present, is Andersen's topic.

William James is a vivid and concrete writer whose positions are often ambiguous. Edmund Husserl is the converse, a philosopher whose writings can be abstract and obscure, but ultimately define intricate philosophical positions in great detail. Husserl's views evolved over decades, beginning with his *Logical Investigations* (published in 1900), and reflect his appreciation and awareness of James. In 1905, Husserl devoted a lecture course to the phenomenology of internal time consciousness. His notes for the course, together with Husserl's many emendations on the original notes and new sketches from 1907 to 1911, were edited by Edith Stein in 1917 and published (with many emendations by Husserl) under the nominal editorship of Martin Heidegger in 1928.

Husserl, meanwhile, reflected on temporality time and time again. Two collections of his explorations of time have been published in the last decade, the "Bernau Manuscripts," written after revising lecture notes with Stein in 1917–18, and the posthumously collected "C Manuscripts." Chapter 4 presents new translations by James Mensch of key sections of the *Phenomenology of Internal Time Consciousness*, along with translations (the first in English) of sections of the Bernau and C manuscripts. In these selections, Husserl outlines the method of phenomenology, focusing on things as they appear to consciousness, without any explanatory reference to physical reality and with explicitly expressed indifference to psychological methods of investigating the empirical basis of phenomenology. Then he analyzes the action of consciousness as the interpretation of sensory information, reconstrued to constitute the objects of awareness (perception and reflection). This schema can be applied to time consciousness. Like James (and Augustine), Husserl extends the immediate moment to intimate past and future. Unique operations of consciousness open the window to subjective time. Looking back, "retention" or "primary memory" holds a trace of all experiences, holding them as "just-past" for a brief fading moment. Looking ahead, "protention" describes the immediate anticipation of the just-next. All the contents of consciousness, including the awareness of time's passage, are subject to this temporal structure, and with each passing moment the entire structure undergoes a sliding transformation toward the past.

Husserl's evolving thought is sometimes tentative and obscure, and often interconnected with other Husserlian themes. It can be difficult on initial reading. Thus, in chapter 3 James Mensch offers a commentary and introduction to Husserl's philosophy of subjective time, leading up to his translations of selections from Husserl's three forays into lived time.

1 Excerpts from *The Principles of Psychology*

William James

1.1 Preface

[p. v] … Every natural science assumes certain [p. vi] data uncritically, and declines to challenge the elements between which its own 'laws' obtain, and from which its own deductions are carried on. Psychology, the science of finite individual minds, assumes as its data (1) *thoughts and feelings*, and (2) a *physical world* in time and space with which they coexist and which (3) *they know*. Of course these data themselves are discussable; but the discussion of them (as of other elements) is called metaphysics and falls outside the province of this book. This book, assuming that thoughts and feelings exist and are vehicles of knowledge, thereupon contends that psychology when she has ascertained the empirical correlation of the various sorts of thought or feeling with definite conditions of the brain, can go no farther—can go no farther, that is, as a, natural science. If she goes farther she becomes metaphysical. All attempts to *explain* our phenomenally given thoughts as products of deeper-lying entities (whether the latter be named 'Soul,' 'Transcendental Ego,' 'Ideas,' or 'Elementary Units of Consciousness') are metaphysical. This book consequently rejects both the associationist and the spiritualist theories; and in this strictly positivistic point of view consists the only feature of it for which I feel tempted to claim originality. ...

I have therefore treated our passing thoughts as integers, [p. vii] and regarded the mere laws of their coexistence with brain-states as the ultimate laws for our science. The reader will in vain seek for any closed system in the book. It is mainly a mess of descriptive details, running out into queries which only a metaphysics alive to the weight of her task can hope successfully to deal with. That will perhaps be centuries hence; and meanwhile the best mark of health that a science can show is this unfinished-seeming front. ...

1.2 The Stream of Thought. (Chapter IX)

[p. 224] We now begin our study of the mind from within. Most books start with sensations, as the simplest mental facts, and proceed synthetically, constructing each higher stage from those below it. But this is abandoning the empirical method of investigation. No one ever had a simple sensation by itself. Consciousness, from our natal day, is of a teeming multiplicity of objects and relations, and what we call simple sensations are results of discriminative attention, pushed often to a very high degree. ... The only thing which psychology has a right to postulate at the outset is the fact of thinking itself, and that must first be taken up and analyzed. If sensations then prove to be amongst the elements of the thinking, we shall be no worse off as respects them than if we had taken them for granted at the start.

The first fact for us, then, as psychologists, is that thinking of some sort goes on. I use the word thinking, ... for every form of consciousness indiscriminately. If we could say in English 'it thinks,' as we say 'it rains' or 'it blows,' we should be [p. 225] stating the fact most simply and with the minimum of assumption. As we cannot, we must simply say that *thought goes on*.

1.2.1 FIVE CHARACTERS IN THOUGHT

How does it go on? We notice immediately five important characters in the process...:

1) Every thought tends to be part of a personal consciousness.
2) Within each personal consciousness thought is always changing.
3) Within each personal consciousness thought is sensibly continuous.
4) It always appears to deal with objects independent of itself.
5) It is interested in some parts of these objects to the exclusion of others, and welcomes or rejects—*chooses* from among them, in a word—all the while.

...
[We omit the discussion of the first characteristic.—Eds.]
[p. 229]

2) *Thought is in Constant Change.*

…
[p. 231] Are not the sensations we get from the same object, for example, always the same? Does not the same piano-key, struck with the same force, make us hear in the same way? Does not the same grass give us the same feeling of green, the same sky the same feeling of blue, and do we not get the same olfactory sensation no matter how many times we put our nose to the same flask of cologne? It seems a piece of metaphysical sophistry to suggest that we do not; and yet a close attention to the matter shows that *there is no proof that the same bodily sensation is ever got by us twice.*

What is got twice is the same OBJECT. We hear the same *note* over and over again; we see the same *quality* of green, or smell the same objective perfume, or experience the same *species* of pain. The realities, concrete and abstract, physical and ideal, whose permanent existence we believe in, seem to be constantly coming up again before our thought, and lead us, in our carelessness, to suppose that our 'ideas' of them are the same ideas. ... We take no heed, as a rule, of the different way in which the same things look and sound and smell at different distances and under different circumstances. The sameness of the *things* is what we are concerned to ascertain; and any sensations that assure us of that will probably be considered in a rough way to be the same with each other. ...

[p. 233] [H]owever we might in ordinary conversation speak of getting the same sensation again, we never in strict theoretic accuracy could do so; and that whatever was true of the river of life, of the river of elementary feeling, it would certainly be true to say, like Heraclitus, that we never descend twice into the same stream. ...

For ... it is obvious and palpable that our state of mind is never precisely the same. Every thought we have of a given fact is, strictly speaking, unique, and only bears a resemblance of kind with our other thoughts of the same fact. When the identical fact recurs, we *must* think of it in a fresh manner, see it under a somewhat different angle, apprehend it in different relations from those in which it last appeared. ...

[p. 234] Experience is remoulding us every moment, and our mental reaction on every given thing is really a resultant of our experience of the whole world up to that date. The analogies of brain-physiology must again be appealed to corroborate our view. ...

[p. 236] ... No doubt it is often *convenient* to formulate the mental facts in an atomistic sort of way, and to treat the higher states of consciousness as if they were all built out of unchanging simple ideas. It is convenient often to treat curves as if they were composed of small straight lines, and electricity and nerve-force as if they were fluids. But in the one case as in the other we must never forget that we are talking symbolically, and that there is nothing in nature to answer to our words. *A permanently existing 'idea' or 'Vorstellung' which makes its appearance before the footlights of consciousness at periodical intervals, is as mythological an entity as the Jack of Spades.*

3) *Within each personal consciousness, thought is sensibly continuous.* [p. 237]

I can only define 'continuous' as that which is without breach, crack, or division. … The proposition that within each personal consciousness thought feels continuous, means two things:

1. That even where there is a time-gap the consciousness after it feels as if it belonged together with the consciousness before it, as another part of the same self;
2. That the changes from one moment to another in the quality of the consciousness are never absolutely abrupt.

...

[p. 239] Consciousness, then, does not appear to itself chopped up in bits. Such words as 'chain' or 'train' do not describe it fitly as it presents itself in the first instance. It is nothing jointed; it flows. A 'river' or a 'stream' are the metaphors by which it is most naturally described. *In talking of it hereafter, let us call it the stream of thought, of consciousness, or of subjective life.*

But now there appears, even within the limits of the same self, and between thoughts all of which alike have this same sense of belonging together, a kind of jointing and separateness among the parts, of which this statement seems to take no account. I refer to the breaks that are produced by sudden *contrasts in the quality* of the successive segments of the stream of thought. If the words 'chain' and 'train' had no natural fitness in them, how came such words to be used at all? Does not a loud explosion rend the consciousness upon which it abruptly breaks, in twain? Does not every sudden shock, appearance of a new object, [p. 240] or change in a sensation, create a real interruption, sensibly felt as such, which cuts the conscious stream across at the moment at which it appears? Do not such interruptions smite us every hour of our lives, and have we the right, in their presence, still to call our consciousness a continuous stream?

...

[p. 241] Here, again, language works against our perception of the truth. We name our thoughts simply, each after its thing, as if each knew its own thing and nothing else. What each really knows is clearly the thing it is named for, with dimly perhaps a thousand other things. It ought to be named after all of them, but it never is. Some of them are always things known a moment ago more clearly; others are things to be known more clearly a moment hence. Our own bodily position, attitude, condition, is one of the things of which *some* awareness, however inattentive, invariably accompanies the knowledge of whatever else we know. We [p. 242] think; and as we think we feel our bodily selves as the seat of the thinking. If the thinking be *our* thinking, it must be suffused through all its parts with that peculiar warmth and intimacy that make it come as ours. ...

[p. 243]

[Transitive and Substantive Parts of the Stream] As we take, in fact, a general view of the wonderful stream of our consciousness, what strikes us first is this different pace of its parts. Like a bird's life, it seems to be made of an alternation of flights and perchings. The rhythm of language expresses this, where every thought is expressed in a sentence, and every sentence closed by a period. The resting-places are usually occupied by sensorial imaginations of some sort, whose peculiarity is that they can be held before the mind for an indefinite time, and contemplated without changing; the places of flight are filled with thoughts of relations, static or dynamic, that for the most part obtain between the matters contemplated in the periods of comparative rest.

Let us call the resting-places the 'substantive parts,' and the places of flight the 'transitive parts,' of the stream of thought. It then appears that the main end of our thinking is at all times the attainment of some other substantive part than the one from which we have just been dislodged. And we may say that the main use of the transitive parts is to lead us from one substantive conclusion to another.

...

[p. 245] If there be such things as feelings at all, *then so surely as relations between objects exist in rerum naturâ, so surely, and more surely, do feelings exist to which these relations are known*. There is not a conjunction or a preposition, and hardly an adverbial phrase, syntactic form, or inflection of voice, in human speech, that does not express some shading or other of relation which we at some moment actually feel to exist between the larger objects of our thought. If we speak objectively, it is the real relations that appear revealed; if we speak subjectively, it is the stream of consciousness that matches each of them by an inward coloring of its own. In either case the relations are numberless, and no existing language is capable of doing justice to all their shades. ... We ought to say a feeling of *and*, a feeling of *if*, a feeling of *but*, and a feeling of *by*, quite as readily as we say a feeling [p. 246] of *blue* or a feeling of *cold*. ...

The lingering consciousnesses, [p. 247] if of simple objects, we call 'sensations' or 'images,' according as they are vivid or faint; if of complex objects, we call them 'percepts' when vivid, 'concepts' or 'thoughts' when faint. For the swift consciousnesses we have only those names of 'transitive states,' or 'feelings of relation,' which we have used. As the brain-changes [p. 248] are continuous, so do all these consciousnesses melt into each other like dissolving views. Properly they are but one protracted consciousness, one unbroken stream. [p. 249]

Feelings of Tendency. So much for the transitive states. But there are other unnamed states or qualities of states that are just as important [p. 250] and just as cognitive as they, and just as much unrecognized by the traditional sensationalist and intellectualist philosophies of mind. ... [p. 251] [O]ur psychological vocabulary is wholly inadequate to name [them]. But namelessness is compatible with existence. There are innumerable consciousnesses of [p. 252] emptiness, no one of which taken in itself has a name, but all different from each other. The ordinary way is to assume that they are all emptinesses of consciousness, and so the same state. But the feeling of an absence is *toto cœlo* other than the absence of a feeling. It is an intense feeling. The rhythm of a lost word may be there without a sound to clothe it; or the evanescent sense of something which is the initial vowel or consonant may mock us fitfully, without growing more distinct. Every one must know the tantalizing effect of the blank rhythm of some forgotten verse, restlessly dancing in one's mind, striving to be filled out with words.

...

[p. 254] Now what I contend for, and accumulate examples to show, is that 'tendencies' are not only descriptions from without, but that they are among the *objects* of the stream, which is thus aware of them from within, and must be described as in very large measure constituted of *feelings* of *tendency*, often so vague that we are unable to name them at all. It is, in short, the re-instatement of the vague to its proper place in our mental life which I am so anxious to press on the attention. ... [p. 255] What must be admitted is that the definite images of traditional psychology form but the very smallest part of our minds as they actually live. The traditional psychology talks like one who should say a river consists of nothing but pailsful, spoonsful, quartpotsful, barrelsful, and other moulded forms of water. Even were the pails and the pots all actually standing in the stream, still between them the free water would continue to flow. It is just this free water of consciousness that psychologists resolutely overlook. Every definite image in the mind is steeped and dyed in the free water that flows round it. With it goes the sense of its relations, near and remote, the dying echo of whence it came to us, the dawning sense of whither it is to lead. The significance, the value, of the image is all in this halo or penumbra that surrounds and escorts it,—or rather that is fused into one with it and has become bone of its bone and flesh of its flesh; leaving it, it is true, an image of the same *thing* it was before, but making it an image of that thing newly taken and freshly understood.

…

[p. 258] It is just like the 'overtones' in music. Different instruments give the 'same note,' but each in a different voice, because each gives more than that note, namely, various upper harmonics of it which differ from one instrument to another. They are not separately heard by the ear; they blend with the fundamental note, and suffuse it, and alter it; and even so do the waxing and waning brain-processes at every moment blend with and suffuse and alter the psychic effect of the processes which are at their culminating point.

Let us use the words *psychic overtone, suffusion*, or *fringe*, to designate the influence of a faint brain-process upon our thought, as it makes it aware of relations and objects but dimly perceived.[1]

…

[p. 259] Relation, then, to our topic or interest is constantly felt in the fringe, and particularly the relation of harmony and discord, of furtherance or hindrance of the topic. …

[p. 261] The most important element of these fringes is, I repeat, the mere feeling of harmony or discord, of a right or wrong direction in the thought. …

[p. 269] The only images *intrinsically* important are the halting-places, the substantive conclusions, provisional or final, of the thought. Throughout all the rest of the stream, the feelings of relation are everything, and the terms related almost naught. These feelings of relation, these psychic overtones, halos, suffusions, or fringes about the terms, may be the same in very different systems of imagery. …

[p. 271] This is all I have to say about the sensible continuity and unity of our thought as contrasted with the apparent discreteness of the words, images, and other means by which it seems to be carried on. Between all their substantive elements there is 'transitive' consciousness, and the words and images are 'fringed,' and not as discrete as to a careless view they seem. Let us advance now to the next head in our description of Thought's stream.

4. *Human thought appears to deal with objects independent of itself; that is, it is cognitive, or possesses the function of knowing.*

…

[p. 276] The object of every thought, then, is neither more nor less than all that the thought thinks, exactly as thought thinks it, however complicated the matter, and however symbolic the manner of the thinking may be. It is needless to say that memory can seldom accurately reproduce such an object, when once it has passed from before the mind. It either makes too little or too much of it. ... The mass of our thinking vanishes for ever, beyond hope of recovery, and psychology only gathers up a few of the crumbs that fall from the feast. The next point to make clear is that, *however complex the object may be, the thought of it is one undivided state of consciousness*.

...

[p. 278] The reason why this fact is so strangely garbled in the books seems to be what ... I [have] called the psychologist's fallacy. We have the inveterate habit, whenever we try introspectively to describe one of our thoughts, of dropping the thought as it is in itself and talking of something else. We describe the things that appear to the thought, and we describe other thoughts *about* those things—as if these and the original thought were the same. If, for example, the thought be 'the pack of cards is on the table,' we say, "Well, isn't it a thought of the pack of cards? Isn't it of the cards as included in the pack? Isn't it of the table? And of the legs of the table as well? The table has legs—how can you think the table without virtually thinking its legs? Hasn't our thought then, all these parts—one part for the pack and another for the table? And within the pack-part a part for each card, as within the table-part a part for each leg? And isn't each of these parts an idea? And can our thought, then, be anything but an assemblage or pack of ideas, each answering to some element of what it knows?"

Now not one of these assumptions is true. The thought taken as an example is, in the first place, not of 'a pack of cards.' It is of 'the-pack-of-cards-is-on-the-table,' an entirely different subjective phenomenon, whose Object implies the pack, and every one of the cards in it, but whose conscious constitution bears very little resemblance to that of the [p. 279] thought of the pack *per se*. What a thought *is*, and what it may be developed into, or explained to stand for, and be equivalent to, are two things, not one.

5) *It is always interested more in one part of its object than in another, and welcomes and rejects, or chooses, all the while it thinks*. [p. 284]

The phenomena of selective attention and of deliberative will are of course patent examples of this choosing activity. But few of us are aware how incessantly it is at work in operations not ordinarily called by these names. Accentuation and Emphasis are present in every perception we have. We find it quite impossible to disperse our attention impartially over a number of impressions.

[p. 285] Helmholtz says that we notice only those sensations which are signs to us of *things*. But what are things? Nothing, as we shall abundantly see, but special groups of sensible qualities, which happen practically or aesthetically to interest us, to which we therefore give substantive names, and which we exalt to this exclusive status of independence and dignity. But in itself, apart from my interest, a particular dust-wreath on a windy day is just as much of an individual thing, and just as much or as little deserves an individual name, as my own body does.

[p. 288] Looking back, then, over this review, we see that the mind is at every stage a theatre of simultaneous possibilities. Consciousness consists in the comparison of these with each other, the selection of some, and the suppression of the rest by the reinforcing and inhibiting agency of attention. The highest and most elaborated mental products are filtered from the data chosen by the faculty next beneath, out of the mass offered by the faculty below that, which mass in turn was sifted from a still larger amount of yet simpler material, and so on.

1.3 Attention. (Chapter XI)

…

[p. 402] *My experience is what I agree to attend to*. Only those items which I *notice* shape my mind—without selective interest, experience is an utter chaos. Interest alone gives accent and emphasis, light and shade, background and foreground—intelligible perspective, in a word. It varies in every [p. 403] creature, but without it the consciousness of every creature would be a gray chaotic indiscriminateness, impossible for us even to conceive. ...

Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains [p. 404] of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state which in French is called *distraction*, and *Zerstreutheit* in German.

1.4 Discrimination and Comparison. (Chapter XIII)

…

[p. 488] [T]he fatal ‘psychologists’ fallacy’ (p. 196) [is that] of treating an inferior state of mind as if it must somehow know implicitly all that is explicitly known [p. 489] *about the same topic* by superior states of mind. The thing thought of is unquestionably the same, but it is thought twice over in two absolutely different psychoses,—once as an unbroken unit, and again as a sum of discriminated parts. It is not one thought in two editions, but two entirely distinct thoughts of one thing. And each thought is within itself a *continuum*, a *plenum*, needing no contributions from the other to fill up its gaps. As I sit here, I think objects, and I make inferences, which the future is sure to analyze and articulate and riddle with discriminations, showing me many things wherever I now notice one. Nevertheless, my thought feels quite sufficient unto itself for the time being; and ranges from pole to pole, as free, and as unconscious of having overlooked anything, as if it possessed the greatest discriminative enlightenment. We all cease analyzing the world at some point, and notice no more differences. The last units with which we stop are our objective elements of being. ...

[p. 495] Another condition which then favors [discrimination] is that the sensations excited by *the differing objects should not come to us simultaneously but fall in immediate* SUCCESSION upon the same organ. ... The reason why successive impression so much favors the result seems to be that there is a real *sensation of difference*, aroused by the shock of transition from one perception to another which is unlike the first. This sensation of difference has its own peculiar quality, as difference, which remains sensible, no matter of what sort the terms may be, between which it obtains. It is, in short, one of those transitive feelings, or feelings of relation, of which I treated in a former place (pp. 245 ff.); and, when once aroused, its object lingers in the memory along with the substantive terms which precede and follow, and enables *our judgments of comparison* to be made. We shall soon see reason to believe that no two terms can possibly be *simultaneously* perceived to differ, unless, in a preliminary operation, we have successively attended to each, and, in so doing, had the transitional sensation of difference between them aroused. A field of consciousness, however complex, is never analyzed unless some of its ingredients have changed. We *now* discern, 'tis true, a multitude of coexisting things about us at every moment: but this is because we have had a long education, and each thing we now see distinct has been already differentiated from its neighbors by repeated [p. 496] appearances in successive order. To the infant, sounds, sights, touches, and pains, form probably one unanalyzed bloom of confusion. ...

1.5 The Perception of Time. (Chapter XV)

[p. 605] In the next two chapters I shall deal with what is sometimes called internal perception, or the perception of *time*, and of events as occupying a date therein, especially when the date is a past one, in which case the perception in question goes by the name of *memory*. To remember a thing as past, it is necessary that the notion of 'past' should be one of our 'ideas.' We shall see in the chapter on Memory that many things come to be thought by us as past, not because of any intrinsic quality of their own, but rather because they are associated with other things which for us signify pastness. But how do these things get *their* pastness? What is the *original* of our experience of pastness, from whence we get the meaning of the term? It is this question which the reader is invited to consider in the present chapter. We shall see that we have a constant feeling *sui generis* of pastness, to which every one of our experiences in turn falls a prey. To think a thing as past is to think it amongst the objects or in the direction of the objects which at the present moment appear affected by this quality. This is the original of our notion of past time, upon which memory and history build their systems. And in this chapter we shall consider this immediate sense of time alone.

If the constitution of consciousness were that of a string of bead-like sensations and images, all separate,

> "we never could have any knowledge except that of the present instant. ... [p. 606] Each of our successive states of consciousness, the moment it ceased, would be gone forever. Each of those momentary states would be our whole being." (Mill 1869, 319)

... Our consciousness would be like a glow-worm spark, illuminating the point it immediately covered, but leaving all beyond in total darkness. Whether a very highly developed practical life be possible under such conditions as these is more than doubtful; it is, however, conceivable.

I make the fanciful hypothesis merely to set off our real nature by the contrast. Our feelings are not thus contracted, and our consciousness never shrinks to the dimensions of a glow-worm spark. *The knowledge of some other part of the stream, past or future, near or remote, is always mixed in with our knowledge of the present thing.*

A simple sensation ... is an abstraction, and all our concrete states of mind are representations of objects with some amount of complexity. Part of the complexity is the echo of the objects just past, and, in a less degree, perhaps, the foretaste of those just to arrive. Objects fade out of consciousness slowly. If the present thought is of A B C D E F G, the next one will be of B C D E F G H, and the one after that of C D E F G H I—the lingerings of the past dropping successively away, and the incomings of the future making up the loss. These lingerings of old objects, these incomings of new, are the germs of memory and expectation, the retrospective and the prospective sense of time. They give that continuity to [p. 607] consciousness without which it could not be called a stream.

[p. 608]

1.5.1 THE SENSIBLE PRESENT HAS DURATION

Let any one try, I will not say to arrest, but to notice or attend to, the *present* moment of time. One of the most baffling experiences occurs. Where is it, this present? It has melted in our grasp, fled ere we could touch it, gone in the instant of becoming. ... It is, in fact, an altogether ideal abstraction. ... Reflection leads us to the conclusion [p. 609] that it *must* exist, but that it *does* exist can never be a fact of our immediate experience. The only fact of our immediate experience is what Mr. E. R. Clay [1882, 167ff.] has well called ‘the *specious* present’:

> “The relation of experience to time has not been profoundly studied. Its objects are given as being of the present, but the part of time referred to ... is a very different thing from the conterminous of the past and future which philosophy denotes by the name Present. The present [of experience—Eds] … is really a part of the past—a recent past—delusively given as being a time that intervenes between the past and the future. Let it be named the specious present, and let the past, that is given as being the past, be known as the obvious past. All the notes of a bar of a song seem to the listener to be contained in the present. All the changes of place of a meteor seem to the beholder to be contained in the present. At the instant of the termination of such series, no part of the time measured by them seems to be a past. Time, then, considered relatively to human apprehension, consists of four parts, viz., the obvious past, the specious present, the real present, and the future. Omitting the specious present, it consists of three … nonentities—the past, which does not exist, the future, which does not exist, and their conterminous, the present. ... ”

In short, the practically cognized present is no knife-edge, but a saddle-back, with a certain breadth of its own on which we sit perched, and from which we look in two directions into time. The unit of composition of our perception of time is a *duration*, with a bow and a stern, as it were—a rearward—and a forward-looking end.[2] It is only [p. 610] as parts of this *duration-block* that the relation of *succession* of one end to the other is perceived. We do not first feel one end and then feel the other after it, and from the perception of the succession infer an interval of time between, but we seem to feel the interval of time as a whole, with its two ends embedded in it. The experience is from the outset a synthetic datum, not a simple one; and to sensible perception its elements are inseparable, although attention looking back may easily decompose the experience, and distinguish its beginning from its end. ...

And just as in certain experiences we may be conscious of an extensive space full of objects, without locating each of them distinctly therein; so, when many impressions follow in excessively rapid succession in time, although we may be distinctly aware that they occupy some duration, and are not simultaneous, we may be quite at a loss to tell which comes first and which last; or we may even invert their real order in our judgment. ...

[p. 611]

1.5.2 ACCURACY OF OUR ESTIMATE OF SHORT DURATIONS

We must now proceed to an account of the *facts* of time-perception in detail as preliminary to our speculative conclusion. Many of the facts are matters of patient experimentation, others of common experience.

First of all, we note a marked *difference between the elementary sensations of duration and those of space*. The former have a much narrower range; the time-sense may be called a myopic organ, in comparison with the eye, for example. The eye sees rods, acres, even miles, at a single glance, and these totals it can afterward subdivide into an almost infinite number of distinctly identified parts. The units of duration, on the other hand, which the time-sense is able to take in at a single stroke, are groups of a few seconds, and within these units very few subdivisions—perhaps forty at most, as we shall presently see—can be clearly discerned. The durations we have practically most to deal with—minutes, hours, and days—have to be symbolically conceived, and constructed by mental addition. ... To 'realize' a quarter of a mile we need only look out of the window and *feel* its length by an act which, though it may in part result from organized associations, yet seems immediately performed. To realize an hour, we must count 'now!—now!—now!—now!—' indefinitely. Each 'now' is the feeling of a separate *bit* of time, and the exact sum of the bits never makes a very clear impression on our mind.

[Duration of the Specious Present] How many bits can we clearly apprehend at once? Very few if they are long bits, more if they are extremely short, most if they come to us in compound groups, each including smaller bits of its own. ...

[P. 612] Wundt and his pupil Dietze have both tried to determine experimentally the *maximal extent of our immediate distinct consciousness for successive impressions*. Wundt found that twelve impressions could be distinguished clearly as a united cluster, provided they were caught in a certain rhythm by the mind, and succeeded each other at intervals not smaller than 0.3 and not larger than 0.5 of a second. This makes the total time distinctly apprehended to be equal to from 3.6 to 6 seconds. Dietze gives larger figures. The most favorable intervals for clearly catching the strokes were when they came at from 0.3 second to 0.18 second apart. *Forty* strokes might then be remembered as a whole, and identified without error when repeated, provided the mind grasped them in five sub-groups of eight, or in eight sub-groups of five strokes each. ... [p. 613] This would make 40 times 0.3 second, or 12 seconds, to be the *maximum filled duration* of which we can be both *distinctly and immediately* aware.

The maximum unfilled, or *vacant duration*, seems to lie within the same objective range. ...

These figures may be roughly taken to stand for the most important part of ... the *specious present*. The specious present has, in addition, a vaguely vanishing backward and forward fringe; but its nucleus is probably the dozen seconds or less that have just elapsed.

If these are the maximum, what, then, is the *minimum* amount of duration which we can distinctly feel?

The smallest figure experimentally ascertained was by Exner, who distinctly heard the doubleness of two successive clicks of a Savart's wheel, and of two successive snaps [p. 614] of an electric spark, when their interval was made as small as about 1/500 of a second.

With the eye, perception is less delicate. Two sparks ... ceased to be recognized as successive by Exner when their interval fell below 0.044" ...

[p. 615]

[Comparing Durations] *To be conscious of a time interval at all is one thing; to tell whether it be shorter or longer than another interval is a different thing*. A number of experimental data are on hand which give us a measure of the delicacy of this latter perception. The problem is that of the *smallest difference between two times* which we can perceive.

The difference is at its minimum when the times themselves are very short. ...

[p. 616] This minimum absolute difference, of course, increases as the times compared grow long. Attempts have been made to ascertain what *ratio* it bears to the times themselves. According to Fechner's 'Psychophysic Law' it ought always to bear the same ratio. Various observers, however, have found this not to be the case. On the contrary, very interesting *oscillations* in the accuracy of judgment and in the direction of the error—oscillations dependent upon the absolute amount of the times compared—have been noticed by all who have experimented with the question. Of these a brief account may be given.

In the first place, *in every list of intervals experimented with there will be found what Vierordt calls an* 'INDIFFERENCE-POINT;' that is to say, an interval which we judge with maximum accuracy, a time which we tend to estimate as neither longer or shorter than it really is, and away from which, [p. 617] in both directions, errors increase their size.[3] This time varies from one observer to another, but its average is remarkably constant ... , about three fourths of a second, [p. 618] as the interval of time most easy to catch and reproduce. ... [B]oth Estel and Mehner found that multiples of this time were more accurately reproduced than the time-intervals of intermediary length;[4] and Glass found a certain periodicity, with the constant increment of 1.25 sec., in his observations. There would seem thus to exist something like a periodic or rhythmic sharpening of our time-sense, of which the period differs somewhat from one observer to the next.

[Other Empirical Observations of the Sense of Time] *Our sense of time*, like other senses, *seems subject to the law of contrast*. ... [A]n interval sounded shorter if a long one had immediately preceded it, and longer when the opposite was the case.

Like other senses, too, *our sense of time is sharpened by practice*. ...

Tracks of time filled (with clicks of sound) *seem longer than vacant ones* of the same duration, when the latter does not exceed a second or two.[5] This ... becomes reversed when longer times are taken. It is, perhaps, in accordance with this law that a *loud* sound, limiting a short interval of time, makes it appear longer, a *slight* sound shorter. ...

There is a certain emotional *feeling* accompanying the intervals of time, as is well known in music. *The sense of haste goes with one measure of rapidity, that of delay with another*; and these two feelings harmonize with different mental moods. ...

[p. 619]

WE HAVE NO SENSE FOR EMPTY TIME. ...

Let one sit with closed eyes and, abstracting entirely from the outer world, attend exclusively to the passage of time. ... There seems under such circumstances as these no variety in the material content of our thought, and what we notice appears, if anything, to be the pure series of durations budding, as it were, and growing beneath our indrawn gaze. Is this really so or not? ...

It takes but a small exertion of introspection to show [p. 620] ... that *we can no more intuit a duration than we can intuit an extension, devoid of all sensible content*. ... Our heart-beats, our breathing, the pulses of our attention, fragments of words or sentences that pass through our imagination ... are apprehended by us, as they occur, in their totality. ... In short, empty our minds as we may, some form of *changing process* remains for us to feel, and cannot be expelled. And along with the sense of the process and its rhythm goes the sense of the length of time it lasts. Awareness of *change* is thus the condition on which our perception of time's flow depends; but there exists no reason to suppose that empty time's own changes are sufficient for the awareness of change to be aroused. The change must be of some concrete sort—an outward or inward sensible series, or a process of attention or volition.

[p. 622] [W]e see that in the time-world and the space-world alike the first known things are not elements, but combinations, not separate units, but wholes already formed. The condition of *being* of the wholes may be the elements; but the condition of our *knowing* the elements is our having already felt the wholes as wholes.

... No one has anything like a *perception* of the greater length of the time between now and the first century than of that between now and the tenth. To an historian, [p. 623] it is true, the longer interval will suggest a host of additional dates and events, and so appear a more *multitudinous* thing. And for the same reason most people will think they directly perceive the length of the past fortnight to exceed that of the past week. But there is properly no comparative time *intuition* in these cases at all. It is but dates and events, *representing* time; their abundance *symbolizing* its length. ...

[p. 624] From this we pass naturally to speak of certain familiar variations in our estimation of lengths of time. *In general, a time filled with varied and interesting experiences seems short in passing, but long as we look back. On the other hand, a tract of time empty of experiences seems long in passing, but in retrospect short.* A week of travel and sight-seeing may subtend an angle more like three weeks in the memory; and a month of sickness hardly yields more memories than a day. The length in retrospect depends obviously on the multitudinousness of the memories which the time affords. Many objects, events, changes, many subdivisions, immediately widen the view as we look back. Emptiness, monotony, familiarity, make it shrivel up. ...

[p. 625] *The same space of time seems shorter as we grow older*—that is, the days, the months, and the years do so; whether the hours do so is doubtful, and the minutes and seconds to all appearance remain about the same. ...

[p. 626] So much for the apparent shortening of tracts of time in *retrospect*. They shorten *in passing* whenever we are so fully occupied with their content as not to note the actual time itself. A day full of excitement, with no pause, is said to pass 'ere we know it.' On the contrary, a day full of waiting, of unsatisfied desire for change, will seem a small eternity.

[p. 627] I do not say that *everything* in these fluctuations of estimate can be accounted for by the time's content being crowded and interesting, or simple and tame. Both in the shortening of time by old age and in its lengthening by *ennui* some deeper cause *may* be at work. This cause can only be ascertained, if it exist, by finding out *why we perceive time at all*. To this inquiry let us, though without much hope, proceed.

THE FEELING OF PAST TIME IS A PRESENT FEELING. ...

[p. 628] Even though we *were* to conceive the outer successions as forces stamping their image on the brain, and the brain's successions as forces stamping their image on the mind, still, between the mind's own changes *being* successive, and *knowing their own succession*, lies as broad a chasm as between the object and subject of any case of cognition in the world. *A succession of feelings, in and of itself, is not a feeling of succession. And since, to our successive* *feelings, a feeling of their own succession is added, that must be treated as an* [p. 629] *additional fact requiring its own special elucidation*, which this talk about outer time-relations stamping copies of themselves within, leaves all untouched.

I have shown, at the outset of the article, that what is past, to be known as past, must be known *with* what is present, and *during* the 'present' spot of time. …

If we represent the actual time-stream of our thinking by an horizontal line, the thought *of* the stream or of any segment of its length, past, present, or to come, might be figured in a perpendicular raised upon the horizontal at a certain point. The length of this perpendicular stands for a certain object or content, which in this case is the time thought of, and all of which is thought of together at the actual moment of the stream upon which the perpendicular is raised. …

[p. 630] And since we saw a while ago that our maximum distinct *intuition* of duration hardly covers more than a dozen seconds (while our maximum vague intuition is probably not more than that of a minute or so), we must suppose that *this amount of duration is pictured fairly steadily in each passing instant of consciousness* by virtue of some fairly constant feature in the brain-process to which the consciousness is tied. *This feature of the brain-process, whatever it be, must be the cause of our perceiving the fact of time at all*. The duration thus steadily perceived is hardly more than the 'specious present,' as it was called a few pages back. Its *content* is in a constant flux, events dawning into its forward end as fast as they fade out of its rearward one, and each of them changing its time-coefficient from 'not yet,' or 'not quite yet,' to 'just gone' or 'gone,' as it passes by. Meanwhile, the specious present, the intuited duration, stands permanent, like the rainbow on the waterfall, with its own quality unchanged by the events that stream through it. Each of these, as it slips out, retains the power of being reproduced; and when reproduced, is reproduced with the duration and neighbors which it originally had. Please observe, however, that the reproduction of an event, *after* it has once completely dropped out of the rearward end of the specious present, is an entirely different psychic fact from its direct perception in the specious present as a thing immediately past. A creature might be entirely devoid of *reproductive* memory, and yet have the time-sense; but the [p. 631] latter would be limited, in his case, to the few seconds immediately passing by. …

[T]*he original paragon and prototype of all conceived times is the specious present, the short duration of which we are immediately and incessantly sensible.*

[p. 632]

TO WHAT CEREBRAL PROCESS IS THE SENSE OF TIME DUE? *Now, to what element in the brain-process may this sensibility be due?* It cannot, as we have seen, be due to the mere duration itself of the process; it must be due to an element present at every moment of the process, and this element must bear the same inscrutable *sort* of relation to its correlative feeling which all other elements of neural activity bear to their psychic products, be the latter what they may. Several suggestions have been made as to what the element is in the case of time. Treating of them in a note,[6] I will try to express briefly the only conclusion which [p. 633] seems to emerge from a study of them and of the facts—unripe though that conclusion be.

[p. 634] The phenomena of 'summation of stimuli' in the nervous system prove that each stimulus leaves some latent activity [p. 635] behind it which only gradually passes away. ... [T]o state it in neural terms, *there is at every moment a cumulation of brain-processes overlapping each other, of which the fainter ones are the dying phases of processes which but shortly previous were active in a maximal degree. The* AMOUNT OF THE OVERLAPPING *determines the feeling of the* DURATION OCCUPIED. WHAT EVENTS *shall appear to occupy the duration depends on just* WHAT PROCESSES *the overlapping processes are*. We know so little of the intimate nature of the brain's activity that even where a sensation monotonously endures, we cannot say that the earlier moments of it do [p. 636] not leave fading processes behind which coexist with those of the present moment. *Duration and events together form our intuition of the specious present with its content.*[7] *Why* such an intuition should result from such a combination of brain-processes I do not pretend to say. All I aim at is to state the most *elemental* form of the psycho-physical conjunction.

I have assumed that the brain-processes are sensational ones. Processes of active attention ... will leave similar fading brain-processes behind. If the mental processes are conceptual, a complication is introduced. ...

[p. 638] To pass, now, to conceptual processes: Suppose I think of the Creation, then of the Christian era, then of the battle of Waterloo, all within a few seconds. These matters have their dates far outside the specious present. The processes by which I think them, however, all overlap. What events, then, does the specious present seem to contain? Simply my successive *acts of thinking* these long-past things, not the long-past things themselves. ...

[p. 641] *But whether our feeling of the time which immediately-past events have filled be of something long or of something short, it is not what it is because those events are past, but because they have left behind them processes which are present. To those processes, however caused, the mind would still respond by feeling a specious present, with one part of it just vanishing or vanished into the past. ...*

[p. 642] Let me sum up, now, by saying that we are constantly conscious of a certain duration—the specious present—varying in length from a few seconds to probably not more than a minute, and that this duration (with its content perceived as having one part earlier and the other part later) is the original intuition of time. Longer times are conceived by adding, shorter ones by dividing, portions of this vaguely bounded unit, and are habitually thought by us symbolically. Kant's notion of an *intuition* of objective time as an infinite necessary continuum has nothing to support it. The *cause* of the intuition which we really have cannot be the *duration* of our brain-processes or our mental changes. That duration is rather the *object* of the intuition which, being realized at every moment of such duration, must be due to a permanently present cause. This cause—probably the simultaneous presence of brain-processes of different phase-fluctuates; and hence a certain range of variation in the amount of the intuition, and in its subdivisibility, accrues.

1.6 Memory. (Chapter XVI)

[p. 643] In the last chapter what concerned us was the direct *intuition* of time. We found it limited to intervals of considerably less than a minute. Beyond its borders extends the immense region of *conceived* time, past and future, into one direction or another of which we mentally project all the events which we think of as real, and form a systematic order of them by giving to each a date. The relation of conceived to intuited time is just like that of the fictitious space pictured on the flat back-scene of a theatre to the actual space of the stage. The objects painted on the latter (trees, columns, houses in a receding street, etc.) carry back the series of similar objects solidly placed upon the latter, and we think we see things in a continuous perspective, when we really see thus only a few of them and imagine that we see the rest. ...

The stream of thought flows on; but most of its segments fall into the bottomless abyss of oblivion. Of some, no memory survives the instant of their passage. Of others, it is confined to a few moments, hours, or days. Others, again, leave vestiges which are indestructible, and by means of which they may be recalled as long as life endures. Can we explain these differences?

1.6.1 PRIMARY MEMORY

The first point to be noticed is that *for a state of mind to survive in memory it must have endured for a certain length of time*. In other words, it must be what I call a substantive state. Prepositional and conjunctival states of mind are not remembered as independent facts—we cannot recall [p. 644] just how we felt when we said ‘how’ or ‘notwithstanding.’ Our consciousness of these transitive states is shut up to their own moment—hence one difficulty in introspective psychologizing.

Any state of mind which is shut up to its own moment and fails to become an object for succeeding states of mind, is as if it belonged to another stream of thought. Or rather, it belongs only physically, not intellectually, to its own stream, forming a bridge from one segment of it to another, but not being appropriated inwardly by later segments or appearing as part of the empirical self. ... All the intellectual value for us of a state of mind depends on our after-memory of it. Only then is it combined in a system and knowingly made to contribute to a result. Only then does it *count* for us. So that *the* EFFECTIVE *consciousness we have of our states is the after-consciousness*; and the more of this there is, the more influence does the original state have, and the more permanent a factor is it of our world.

[p. 645] As a rule sensations outlast for some little time the objective stimulus which occasioned them. This phenomenon is the ground of those ‘after-images’ which are familiar in the physiology of the sense-organs. ...

In every sphere of sense, an intermittent stimulus, often enough repeated, produces a continuous sensation. This is because the after-image of the impression just gone by blends with the new impression coming in. The effects of stimuli may thus be superposed upon each other many stages deep, the total result in consciousness being an increase in the feeling's intensity, and in all probability, as we saw in the last chapter, an elementary sense of the lapse of time. …

[p. 646] The physical condition in the nerve-tissue of this primary memory is called by Richet 'elementary memory.' … But what elementary memory makes us aware of is the *just* past. The objects we feel in this directly intuited past differ from properly recollected objects. An object which is recollected, in the proper sense of that term, is one which has been absent from consciousness altogether, and now revives anew. It is brought back, recalled, fished up, so to speak, from a reservoir in which, with countless other objects, it lay buried and lost from view. But an object of primary memory is not thus [p. 647] brought back; it never was lost; its date was never cut off in consciousness from that of the immediately present moment. In fact it comes to us as belonging to the rearward portion of the present space of time, and not to the genuine past. In the last chapter we saw that the portion of time which we directly intuit has a breadth of several seconds, a rearward and a forward end, and may be called the specious present. All stimuli whose first nerve-vibrations have not yet ceased seem to be conditions of our getting this feeling of the specious present. They give rise to objects which appear to the mind as events just past. …

The [p. 648] first condition which makes a thing susceptible of recall after it has been forgotten is that the original impression of it should have been prolonged enough to give rise to a *recurrent* image of it, as distinguished from one of those primary after-images which very fleeting impressions may leave behind, and which contain in themselves no guarantee that they will ever come back after having once faded away. A certain length of stimulation seems demanded by the inertia of the nerve-substance. Exposed to a shorter influence, its modification fails to 'set,' and it retains no effective tendency to fall again into the same form of vibration at which the original feeling was due. This, as I said at the outset, may be the reason why only 'substantive' and not 'transitive' states of mind are as a rule recollected, at least as independent things. The transitive states pass by too quickly.

1.6.2 ANALYSIS OF THE PHENOMENON OF MEMORY

Memory proper, or secondary memory as it might be styled, is the knowledge of a former state of mind after it has already once dropped from consciousness; or rather *it is the knowledge of an event, or fact*, of which meantime we have not been thinking, *with the additional consciousness that we have thought or experienced it before.*

[p. 649] The first element which such a knowledge involves would seem to be the revival in the mind of an image or copy of the original event. And it is an assumption made by many writers that the revival of an image is all that is needed to constitute the memory of the original occurrence. But such a revival is obviously not a *memory*, whatever else it may be; it is simply a duplicate, a second event, having absolutely no connection with the first event except that it happens to resemble it. ...

[p. 650] That condition is that the fact imaged be *expressly referred to the past*, thought as *in the past*. But how can we think a thing as in the past, except by thinking of the past together with the thing, and of the relation of the two? And how can we think of the past? In the chapter on Time-perception we have seen that our intuitive or immediate consciousness of pastness hardly carries us more than a few seconds backward of the present instant of time. Remoter dates are conceived, not perceived; known symbolically by names, such as 'last week,' '1850;' or thought of by events which happened in them, as the year in which we attended such a school, or met with such a loss.—So that if we wish to think of a particular past epoch, we must think of a name or other symbol, or else of certain concrete events, associated therewithal. Both must be thought of, to think the past epoch adequately. And to 'refer' any special fact to the past epoch is to think that fact *with* the names and events which characterize its date, to think it, in short, with a lot of contiguous associates.

But even this would not be memory. Memory requires more than mere dating of a fact in the past. It must be dated in my past. In other words, I must think that I directly experienced its occurrence. It must have that 'warmth and intimacy' which were so often spoken of in the chapter on the Self, as characterizing all experiences 'appropriated' by the thinker as his own.

A general feeling of the past direction in time, then, a particular date conceived as lying along that direction, and defined by its name or phenomenal contents, an event imagined as located therein, and owned as part of my experience,—such are the elements of every act of memory.

[p. 652] Memory is then the feeling of belief in a peculiar complex object; but all the elements of this object may be known to other states of belief; nor is there in the particular combination of them as they appear in memory anything so peculiar as to lead us to oppose the latter to other sorts of thought as something altogether *sui generis*, needing a special faculty to account for it. When later we come to our chapter on Belief we shall see that any represented object which is connected either mediately or immediately with our present sensations or emotional activities tends to be believed in as a reality. The sense of a peculiar active relation in it to ourselves is what gives to an object the characteristic quality of reality, and a merely imagined past event differs from a recollected one only in the absence of this peculiar feeling relation. The electric current, so to speak, between it and our present self does not close. But in their other determinations the re-recollected past and the imaginary past may be much the same. In other words, there is nothing unique in the *object* of memory, and no special faculty is needed to account for its formation. It is a synthesis of parts thought of as related together, perception, imagination, comparison and reasoning being analogous syntheses of parts into complex objects. The objects of any of these faculties may awaken belief or fail to awaken it; *the object of memory is only an object imagined in the past* (usually very completely imagined there) *to which the emotion of belief adheres*.

1.6.3 MEMORY'S CAUSES

[p. 653] Such being the *phenomenon* of memory, or the analysis of its object, can we see how it comes to pass? can we lay bare its causes?

Its complete exercise presupposes two things:

1) The *retention* of the remembered fact;
2) Its *reminiscence, recollection, reproduction*, or *recall*.

Now *the cause both of retention and of recollection is the law of habit in the nervous system, working as it does in the 'association of ideas.'*

[p. 657] The only hypothesis, in short, to which the facts of inward experience give countenance is that *the brain-tracts excited by the event proper, and those excited in its recall, are in part different from each other*. If we could revive the past event without any associates we should exclude the possibility of memory, and simply dream that we were undergoing the experience as if for the first time. Wherever, [p. 658] in fact, the recalled event does appear without a definite setting, it is hard to distinguish it from a mere creation of fancy. ...

Notes

1. … [T]he fringe, as I use the word, means nothing like this; it is part of the object cognized,—substantive qualities and things appearing to the mind in a fringe of relations. Some parts—the transitive parts—of our stream of thought cognize the relations rather than the things; but both the transitive and the substantive parts form one continuous stream, with no discrete 'sensations' in it. …

2. Locke, in his dim way, derived the sense of duration from reflection on the succession of our ideas [1975 (org. 1690), book II, chapter XIV (section 3) and chapter XV (section12)]. Reid justly remarks that if ten successive elements are to make duration, "then one must make duration, otherwise duration must be made up of parts that have no duration, which is impossible. … I conclude, therefore, that there must be duration in every single interval or element of which the whole duration is made up. Nothing, indeed, is more certain than that every elementary part of duration must have duration, as every elementary part of extension must have extension. Now, it must be observed that in these elements of duration, or single intervals of successive ideas, there is no succession of ideas, yet we must conceive them to have duration; whence we may conclude with certainty that there is a conception of duration where there is no succession of ideas in the mind." (1850, essay III, chapter V) …

3. Curious discrepancies exist between the German and the American observers with respect to the direction of the error below and above the point of indifference—differences perhaps due to the fatigue involved in the American method. The Germans lengthened intervals below it and shortened those above. With seven Americans experimented on by Stevens this was exactly reversed. The German method was to passively listen to the intervals, then judge; the American was to reproduce them actively by movements of the hand. In Mehner's experiments there was found a second indifference-point at about 5 seconds, beyond which times were judged again too long. …

4. Estel's figures led him to think that *all* the multiples enjoyed this privilege; with Mehner, on the other hand, only the *odd* multiples showed diminution of the average error; thus, 0.71, 2.15, 3.55, 5,

6.4, 7.8, 9.3, and 10.65 second were respectively registered with the least error. (Cf. Estel 1885, 57; Mehner 1885, 562–565).

5. (Wundt 1874, 287; Hall & Jastrow 1886, 62).

6. Most of these explanations simply give the signs which, adhering to impressions, lead us to date them within a duration, or, in other words, to assign to them their order. Why it should be a time-order, however, is not explained. ... "Thus, if this supposition be true, there is an element in our concrete time-perceptions which has no place in our abstract conception of Time. In Time physically conceived there is no trace of intensity; in time psychically experienced, duration is primarily an intensive magnitude, and so far literally a perception." Its 'original' is, then, if I understand Mr. Ward, something like a *feeling* which accompanies, as pleasure and pain may accompany, the movements of attention. Its brain-process must, it would seem, be assimilated in general type to the brain-processes of pleasure and pain. ...

7. It would be rash to say definitely just how many seconds long this specious present must needs be, for processes fade 'asymptotically,' and the distinctly intuited present merges into a penumbra of mere dim *recency* before it turns into the past which is simply reproduced and conceived. Many a thing which we do not distinctly date by intercalating it in a place between two other things will, nevertheless, come to us with this feeling of belonging to a *near* past. This sense of recency is a feeling *sui generis*, and may affect things that happened hours ago. It would seem to show that their brain-processes are still in a state modified by the foregoing excitement, still in a 'fading' phase, in a spite of the long interval.

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2 The Development of the “Specious Present” and James’s Views on Temporal Experience

Holly Andersen

2.1 Introduction

The term “specious present” was introduced to philosophy and psychology by William James in his influential *Principles of Psychology* (1890). The specious present doctrine, as it is often referred to, is the view that we experience the present moment as nonpunctate, as having some short but nonzero duration. It can be illustrated by comparing our experience of the now or present moment with the way the present is represented on a timeline. Mathematically or physically, the present can be represented by a single point on a timeline separating past from future, moving along the line from the past toward the future. Such a present moment has no duration. In contrast, the temporal character of our experience at least *prima facie* seems to span some duration, one that might range from as short as several hundred milliseconds to, as James thought, as long as twelve seconds or more.

Perception of motion is frequently offered as a justification for the specious present doctrine. Motion requires some nonzero amount of time in which to take place. We perceive many kinds of motion *as motion*, rather than perceiving static successive locations of objects and inferring motion from them. Perceptual differences with different rates of motion highlight the temporal span of experience. Motion that is extremely fast, for instance, may not appear as motion at all. We see movies as continuous, even though they are comprised of changing static images; we see overly fast motion as simply a blur or a line. At the other end of the range, motion that is extremely slow doesn’t perceptually appear to be motion either. The movement of the hour hand of a clock is not perceptible by simply looking at it. In order to notice that it has moved, we have to compare its current position to a previous position that we remember rather than perceive. Within a certain range of rate of change, though, we perceive motion *as* motion, rather than inferring that motion has taken place. This must mean, the reasoning goes, that our experience of time was sufficiently extended as to include a portion of that movement.

The way in which the specious present is described can sound self-contradictory. It involves attributing to the experience at a given moment of consciousness contents that must span some nonzero interval of physical time. It can be understood to take experience to be punctate and simply include nonpunctate contents; more realistically, though, it takes experience to both include nonpunctate content and to do so in a way that is both spread over some range of time and yet still "present" in some sense of the word. And even though the idea is that we perceive these contents at the same time, punctate or not, we do not perceive them as simultaneous. Wilfrid Sellars called this "an incoherent combination of literal simultaneity and literal successiveness" (1982, 232).

Whether or not the specious present doctrine ultimately turns out to be self-contradictory, it raises a variety of intriguing challenges and questions for our understanding of time itself, of temporal awareness specifically, for consciousness in general, and for the connection between experience and the physical processes that give rise to it. Do we really experience the present as temporally extended, or are first-person reports to this effect somehow misguided or false? Is the discrepancy between experienced and represented time merely apparent, or are they genuinely in conflict? What implications does this discrepancy have for our epistemic positions with respect to time itself, or for finding the physical processes underpinning temporal experience? Many of these questions come down to what may be the primary overarching questions on which the specious present doctrine bears: the temporal extent of the *content* of consciousness, the temporal extent of *acts* of consciousness, and how these two temporal extents compare with one another.

James's introduction of the specious present doctrine spawned a wide range of philosophical and scientific discussions, some of which endorse the nonpunctate nature of temporal experience, some of which problematize it, and some of which take it for granted and apply it (see, inter alia, Broad, 1923; Le Poivedin, 1999; Dainton, 2001; Grush, 2003; Kelly, 2005; Oaklander, 2002). There is an already strong and growing trend to attempt to ground Husserlian phenomenology of time consciousness in various aspects of cognitive science (see, inter alia, Gallagher, 1997; Varela, 1999; Lutz & Thompson, 2003; Grush, 2006). Even Husserl's phenomenological analysis was stimulated by his reading of James on this point. It is hard to overestimate the relevance of the specious present doctrine in the philosophy of time and temporal consciousness.

This doctrine has roots stretching far back into British empiricism. The historical development of the specious-present doctrine is rich ground to mine in order to answer, or reframe, questions about the nature of our temporal experience and the constraints it places on the kind of physical processes that could ground it. The problems with which philosophers struggled, and that gave rise to different views on what the experienced present moment might be, are reflected in the contemporary debate. There are multiple distinct ways in which one could flesh out what precisely a thick present looks like in this history, with different implications for both our experience of the present specifically, and for conscious experience more broadly. This means that the history of thinking on temporal experience is not only (as it turns out) interesting in its own right, it can also enrich contemporary investigations on these points.

2.2 Four Themes regarding Temporal Experience

There are several recurring themes as we trace distinct lines of influence on James's development of the specious present doctrine (which are also, not coincidentally, important influences on the development of Husserl's phenomenology of inner time consciousness). In what follows, I will trace out these lines of influence, highlighting the evolution of four themes through a number of different thinkers. These themes are closely interconnected, but each highlights a distinct facet or element of a philosophical position such that the position bears on the question of the temporal extent of the experienced present.

The first theme is a distinction between a strict or philosophical versus a "vulgar" or popular conception of the present. In the strict or philosophical sense, the present moment is punctate, even though it may not appear to be so. If one were to advocate a strict notion of the present in experience, one would need to then explain why our experience of it is illusory, since it phenomenologically seems to encompass at least some short duration (see the third theme below for an example of such an explanation). The vulgar conception of the present, so named because it is utilized by those not immersed in philosophical thinking, applies the term "present" to an extended period of time. Sometimes this is a very extended period of time, such as the present year or present era, and sometimes it refers to a shorter period that is specifically understood to be perceptual in character.

The second theme concerns the division of labor between perception and memory. For philosophers such as Reid, the present moment, in experience and out of it, must be punctate, and anything else that might mistakenly be ascribed to the present moment in experience must actually be the work of memory. This is because Reid, and others like Stewart who follow him in this regard, are committed to views about consciousness that are incompatible with experience genuinely encompassing a nonzero duration. Where precisely a given philosopher draws the line between perception and memory is a function of the theory of consciousness being advocated; allowing for a nonzero duration to the present moment in experience places restrictions on the kinds of theories of consciousness one can endorse. Claiming that we only perceive the strict present forced Stewart, for instance, to rely on attention as a supplement to perception. As such, we can learn a great deal about theories of consciousness from claims about where perception ends and memory begins.

The third theme is the question of whether temporal experience should be treated as some kind of faculty for sensing a peculiar sort of object. Consciousness includes, for many authors to be discussed here, a faculty for perceiving objects in the world, where those faculties deliver their objects imperfectly. In vision, for instance, we have limited spatial resolution with the naked eye, and must rely on enhancing devices such as microscopes to make spatial discriminations beyond a certain range. Analogously, the present moment in experience is understood by some to really be punctate, and only appear somewhat extended because our time sense has a limited resolution capacity. If we had a time sense aid, like a temporal microscope, we could discriminate indefinitely smaller units of time.

The fourth and final theme is closely connected to each of the previous three. Those pre-James authors who most clearly espouse something akin to the specious present doctrine do so as a consequence of endorsing a particular idea about consciousness: namely, that to be conscious at all requires some kind of change or contrast. One could take such contrast to be sufficiently provided by simultaneous awareness of two different objects; in that case, there are no temporal requirements on consciousness. However, the common view on this is that the contrast or change should be between states of consciousness: a change between one note and another note in a song, for instance. Anytime we are aware of a change, it is *from* one perception *to* another. If such a successive contrast or change is required to be conscious of anything at all, then there is a temporal requirement on consciousness—it must span at least two such moments in order for a change to be noticeable.

2.3 James and His Red Herring

James dedicates an entire chapter in *Principles of Psychology* (1890) to "The Perception of Time." In this chapter, he presents an array of phenomena that are part of the character of temporal experience to be investigated by and accounted for in psychology. He offers several arguments to the effect that consciousness must span a period of time, each of which continues at least one of the four themes presented earlier. The first such argument is that consciousness would shrink to a tiny point, and leave too much "in total darkness" (ibid., 606), if it did not have some temporal depth. James describes the strict present, a point with no extension, as only an ideal, in the way that a perfectly round circle would be an ideal. We conclude it exists only because we think it must, not because we ever actually experience it.

Instead of being conscious of or in a single instant of time, James says, we experience a wider expanse of time as the present.

> In short, the practically cognized present is no knife-edge, but a saddle-back, with a certain breadth of its own on which we sit perched, and from which we look in two directions into time. The unit of composition of our perception of time is a duration, with a bow and a stern, as it were—a rearward- and a forward-looking end. (1890, 609)

The specious present is introduced as a description of the actually experienced (as opposed to idealized and abstract) present. James quotes a long passage from an author he enigmatically and misleadingly refers to as E. R. Clay. The passage, in its entirety, is:

> The relation of experience to time has not been profoundly studied. Its objects are given as being of the present, but the part of time referred to by the datum is a very different thing from the conterminous of the past and future which philosophy denotes by the name Present. The present to which the datum refers is really a part of the past—a recent past—delusively given as being a time that intervenes between the past and the future. Let it be named the specious present, and let the past, that is given as being the past, be known as the obvious past. All the notes of a bar of a song seem to the listener to be contained in the present. All the changes of place of a meteor seem to the beholder to be contained in the present. At the instant of the termination of such series, no part of the time measured

> by them seems to be a past. Time, then, considered relatively to human apprehension, consists of four parts, viz., the obvious past, the specious present, the real present, and the future. Omitting the specious present, it consists of three … nonentities—the past, which does not exist, the future, which does not exist, and their conterminous, the present; the faculty from which it proceeds lies to us in the fiction of the specious present. (James, 1890, 609; taken from [anonymous] 1882, 167–8)

This passage is the definitive presentation of the specious present doctrine, along with the earlier passage from James about the saddle of the present.

A point to note here, which will be followed up in a later section, is that James's presentation of the experienced present in this chapter is not accompanied by a description of what he takes experience in general to be like. In order to find how James conceives of experience, of which the experience of the present is one element (albeit a very important one), one has to look earlier in *Principles*. This is relevant because the description James provides of the specious doctrine in the chapter "Perception of Time" could potentially be understood in a number of incompatible ways if one were to only read that chapter. One might take James to be saying that experience itself comes in instantaneous elements, each including content that spans a longer period of time than the act of consciousness itself. Or, one could understand him to say that both the content of experience, and the vehicle of experience itself, come in longer units than mere instants. In order to see how James advocates the latter rather than the former view, one needs to consider the other things James says about experience in *Principles*, especially concerning the stream of thought and consciousness of self.

Until quite recently, scholars writing about the specious present were forced to simply repeat James's citation for the author of the passage quoted in *Principles* (Meyers, 1971; Plumer, 1985; Pockett, 2003; Dainton, 2006). There were no records of an author matching the name "E. R. Clay." This effectively precluded research into the origin of this idea, or into the other things its original author might have said on the matter.

It turns out that there is no such person as "E. R. Clay," and the book from which James took this passage was published anonymously. E. Robert Kelly was a cigar manufacturer in Boston who apparently retired early and had a strong amateur interest in philosophy. *The Alternative: A Study in Psychology* (1882) was his sole contribution to the field, and it bears the hallmarks of someone who was enthusiastic about philosophy but not widely read in it. Robert Kelly's son, Edmund Kelly, was a prominent Socialist around the turn of the century in the New England area. Edmund Kelly was friends with James, which is most likely the way James ended up with a copy of the book (Gilbert, 1972).

Kelly's book was motivated, as he claims in his introductory chapters, by a concern that positivism had somehow forced Common Sense philosophy to give up tenable positions only because these positions had not yet been sufficiently well-articulated. His aim was to provide a series of philosophical definitions of terms that would restore Common Sense to its rightful philosophical ground. Kelly's understanding of Common Sense philosophy, based on his own references, came primarily from Sir William Hamilton, of whom Kelly writes in awed tones.

While many of the definitions provided by Kelly are awkward, he does make several interesting points regarding temporal experience beyond the passage quoted by James. For instance, Kelly thinks that the specious present allows for our experience of motion, and as a result, that we must draw a distinction between "paradoxic" and "anti-paradoxic" experience. Paradoxic experience occurs when the object of experience does not, or could not, exist as experienced. Any experience of temporally extended things as temporally extended—a trill of notes in a song, the flight of a bird, the trail of a meteor—is paradoxic, because such objects do not exist at any given moment of experience and, by definition, movement requires time during which to occur. Yet we experience them both as occurring now, and as taking time. Therefore, Kelly concluded, the experience itself is paradoxic. Interestingly, once such paradoxic experience is completely past, it reverts to being anti-paradoxic, veridical experience of existent objects. We genuinely *experienced* the movement of genuinely moving things, but only once both movement and experience are no longer present; we cannot experience such things veridically as they occur.

James's mis-citation of Kelly's book, whether intended to preserve Kelly's anonymity or simply done by mistake, had the unfortunate consequence of obscuring the real sources from which James drew for his chapter "The Perception of Time." In the same section of the chapter in which the Kelly quote appears, James also cited Shadworth Hodgson, although the Hodgson passage is relegated to the footnotes. Hodgson, as we'll see shortly, made almost exactly the same point as Kelly regarding our experience of the present, and gave it a similar name—the "empiric present." The passage James cited in the body of the chapter contained an arguably more concise presentation of the doctrine, and motivated it with the contrast between the experienced and the mathematized present. It also had a somewhat catchier name. This placement does not, however, indicate much of interest regarding the development of the novel doctrine of the specious present. For that, we must look to Hodgson, and to the brand of empiricism known as Scottish Common Sense, where psychologically oriented philosophers had already recognized the significance of temporal duration for consciousness.

2.4 Scottish Common Sense

The work of Kant and Hume on time and experience has been widely examined. It turns out, however, that there was a lively and ongoing discussion concerning experience and its temporal characteristics in the Scottish Common Sense tradition, from Thomas Reid, through Dugald Stewart and Thomas Brown, and up through Sir William Hamilton. James drew liberally from these psychologist-philosophers in writing *Principles*, as did both Kelly and Hodgson (see below), the two independent inventors of the doctrine of the specious present.

Locke (1690) argues that knowledge comes only from perception or reflection. He applied this formula in order to explain, among other things, how we arrive at our ideas of duration and succession. We come to our idea of duration by reflecting on our ideas which themselves have some duration; likewise, we come to our idea of succession by reflecting on the succession of ideas in our minds. In the context of a chapter on memory, Thomas Reid takes aim at Locke's account. He does not challenge the background view of knowledge as derived solely from perception and reflection, but rather challenges the path Locke charts from reflection to knowledge of duration and succession. Reid (1786) makes two points of interest to us here. The first concerns the feasibility of using the succession of ideas as a means of coming to understand duration. Reid poses a dilemma for Locke: either (1) the ideas that constitute the succession have duration themselves, or (2) they do not have duration. If they lack duration (2), then they can't constitute a succession—they would simply be simultaneous, lacking distance between them. If, on the other hand, they had duration (1) so as to constitute a succession, then a single idea would still have duration, even though it is not a succession. Either way, we could not reach the idea of duration from the succession of ideas.[1]

The second point Reid raises is that Locke's account presupposes memory as a prerequisite for being capable of reflecting on ideas and their succession in our minds. We could not notice that our ideas succeeded one another in time unless we were able to remember a previous idea and compare it to a current, distinct, idea. This point is not a criticism of Locke per se, other than perhaps as a criticism for neglecting to mention that memory is also required in order to reach our ideas of succession and duration. But Reid's emphasis on this point touches on several of the themes explicated in section 2. In order to reach knowledge of succession and duration via the succession and duration of ideas, consciousness itself must have certain characteristics that enable us to hold fast to multiple ideas separated in time from one another, and to compare these ideas to one another.

Reid's positing of memory as playing the role of holding onto an immediately prior idea in order to compare it to its successor is a consequence of how Reid divides up the roles that perception and memory can fill, another theme from section 2. Reid draws a distinction between the vulgar or crude, and strict or philosophical, ways of speaking about the present. This is one of the very first occasions on which the issue of the temporal span of experience is explicitly raised, although Reid's view is that the actual span of experience is zero.

> … Philosophers and the vulgar differ in the meaning they put on upon what is called the *present* time, and are thereby led to make a different limit between sense and memory.
>
> Philosophers give the name of the *present* to that indivisible point of time, which divides the future from the past: but the vulgar find it more convenient in the affairs of life, to give the name of present to a portion of time, which extends more or less, according to circumstances, into the past or the future. (1785, 348)

Thus, on Reid's account we cannot perceive succession at all—we can *perceive* a single instantaneous slice of a succession and *remember* the rest. This distinction between the crude or vulgar conception of the present and the strict or philosophical conception of the present starts with Reid but will change rather dramatically by the time it reaches James. In Reid's version of it, the vulgar usage of the present is not confined to anything that is necessarily *perceptual* in character—Reid mentions the vulgar referring to the present week or the present year. This distinction will subsequently become perceptual in character: the vulgar conception of the present will be the duration during which objects of perception appear to be present.

Reid acknowledges that it certainly seems to us as if we perceive successions directly. He accounts for this by analogy to vision and the *minimum visibile*. There is a smallest spatial size that we are capable of perceptually discerning as a result of limited sensory abilities, even though there are in fact smaller spatial areas. Similarly, there is a smallest temporal duration we are capable of discerning, even though temporal durations themselves come in indefinitely smaller units. Our experience of the present moment is actually punctate, but we are unable to recognize this because we cannot discern sufficiently short temporal intervals.

This idea of the limited temporal resolution of perception, the third theme discussed in section 2, is taken up again by Dugald Stewart (1792). Stewart followed Reid in the Scottish Common Sense tradition and elaborated many of Reid's positions, responding to criticisms and potential problems that had arisen with respect to Reid's work. Stewart took the analogy with the *minimum visibile* even further than Reid had. Stewart described how we are capable of discerning spatial objects only down to a certain size. However, with the aid of a microscope, we can see that spatial discriminations can be made much more finely. If we had, he surmised, something like a temporal microscope, we would be able to discern indefinitely smaller temporal intervals (1792, 61). As such, the implication goes, there is nothing special or privileged about the features of experience that suggest a given temporal duration to the present moment—it is simply a function of how short-sighted we are, so to speak, with respect to time.

One of Stewart's most important contributions to the discussion regarding the temporal characteristics of experience is the way in which he reconciled certain aspects of experience with Reid's strict division between perception and memory. The problem is that both Reid and Stewart thought perception was capable of discerning only one object at a given instant. And yet, it seems that we are capable of immediately perceiving a great deal more than this. Stewart's example is that of perceiving a geometric figure. He thought we could only perceive a single point of the figure in any given instant. We seem, however, able to perceive the entire figure at a glance. On Reid's account, memory ought to be playing a key role in this phenomenon, but it appears that perception is doing the work.

Stewart added to Reid's account in two ways in order to address this problem. He introduced attention as a key faculty needed to bridge perception and memory, and he got some mileage out of the limited temporal resolution of consciousness. Perception, he claims, can only take in a single object with each act. But, these acts of perception are quite short, much shorter than the smallest temporal duration we can discern. Furthermore, we do not remember everything we perceive. We only remember the content of perceptual acts to which we pay attention for a sufficient amount of time. The amount of time required to attend to "a perception" in order to remember it is longer than the time it takes to perceive the object, but shorter than the shortest temporal duration we can notice. Thus, in what seems to us like a single instant, there are actually multiple distinct acts of perception, which are attended to in multiple distinct acts, such that we remember the perceptual contents of the attention-acts apparently simultaneously (1792, 53–54). It is an awkward theory, but it preserves the major features of Reid's account of perception and memory while accommodating apparently conflicting features of experience.

Thomas Brown (1851) took issue with the way philosophers like Stewart doubled consciousness, by separating acts of perception, memory, or attention from consciousness by making them *objects* of consciousness, while, Brown argued, they should be thought of as *constituting* consciousness. He also made two key steps along the road from Reid to James: the notion of "rapid retrospect," a precursor to the specious present doctrine, and the idea that consciousness requires a contrast between two distinct sensations, theme 4 from section 2.

Brown failed to move past some of the views developed by Reid, as a result of which he came up just short of giving the first full version of a specious present doctrine. He accepted Reid's division of labor where perception could only be instantaneous while memory supplied the remainder. Brown responded to the apparent conflict between this view and experience in a subtler and arguably more satisfactory manner than Stewart did. He distinguished between the kind of memory that is clearly memory—with objects that are in the obvious past—and the kind of memory that does not seem like memory, whose objects are only just past. He calls this second kind of memory rapid retrospect.

> When we think of feelings long past, it is impossible for us not to be aware that our mind is then truly retrospective … But when the retrospect is of very recent feelings—of feelings, perhaps, that existed as distinct states of the mind, the very moment before our retrospect began, the short interval is forgotten, and we think that that primary feeling, and our consideration of the feeling, are strictly simultaneous. … When it is any thing more than the sensation, thought, or emotion, of which we are said to be conscious, it is a brief and rapid retrospect. (1851, 303)

This skirts very close to the specious present doctrine as presented by James, but it maintains the view that perception must be punctate. Brown argued that in order for a self to be conscious as a self, it must encompass at least two distinct sensations. He provides the example of an imaginary consciousness that was abruptly created fully formed, listening to a single tone on a flute. Such a creature would have no consciousness that it was a self—it would only know the tone. If this is succeeded by the fragrance of a rose, however, one could compare the previous and new sensations together, from which one would be conscious of oneself as spanning both of those sensations—conscious of the earlier one, and now conscious of the new one. This means that a condition necessary for the possibility of consciousness is content that spans more than a single instant, although Brown does not go so far as to say that consciousness itself spans more than a single instant. He places the implicitly temporal constraint on consciousness that it involve nonpunctate content even if perception itself occurs in a punctate instant.

The final philosopher to consider here is Sir William Hamilton. Hamilton expands on Brown's constraint that consciousness must involve contrast between distinct states, a view that had become widely accepted by then. Hamilton offered five "special conditions on consciousness," conditions that must be met in order to be conscious, two of which are relevant to this discussion. Hamilton's third condition simply is the point we just saw Brown make: consciousness requires some kind of change or contrast. If we were only to experience a single thing unchangingly, we would "be absolutely unconscious" (1861, 203). From this third condition Hamilton drew a corollary, which he made the fifth condition—memory.

When these two conditions are put together, Hamilton goes further than Brown by making explicit how the conditions for consciousness have a temporal dimension:

> In the internal perception of a series of mental operations, a certain time, a certain duration, is necessary for the smallest section of continuous energy to which consciousness is competent. Some minimum of time must be admitted as the minimum of consciousness. (1861, 257)

Hamilton goes so far as to say that duration is "a necessary condition of thought" (1856, 571). Here we have the culmination of an ongoing development in Scottish Common Sense philosophy, which clearly prefigures the specious present doctrine as James presents it.

James credited Reid, Stewart, Brown, Hamilton, and others with shaping psychology as a field in the pre-technical, pre-specialized "youth of our science," and took *Principles* to be a step from their work toward an empirical, fully scientific, "English" psychology (1890, 192). There is a discernible movement, from Reid through Stewart, Brown and Hamilton and culminating in James, where the issue of the temporality of experience—including the experience of temporal objects as well as the temporal properties experience must have in order to function as it does—raises problems within the psychologies offered by each philosopher, which the next then solves by complicating the picture with the addition of new faculties.

These issues persist in James's writings even outside of his chapter on the perception of time. Consider Reid's criticism of Locke for failing to recognize the role that memory must play in reflection in order for us to reach certain ideas like succession. James answers Comte's criticism of the use of introspection as a method in psychology by citing memory as a necessary supplement to occurrent consciousness. Comte claimed (see James, 1890, 188 for reference) that introspection must necessarily lag at least slightly behind everything in consciousness, because it is by definition impossible to both have an experience and to reflect on that experience in the same moment. James responds, in part, that the contents for which we introspect linger just long enough that we can, with the use of memory, reliably introspect in just the way Comte denied (*Principles*, 189).

James's answer is strongly connected to the Scottish Common Sense views on the matter, because James is not in this case talking about memory in general. He specifically means the kind of memory that Brown termed "rapid retrospect," the kind of memory that Reid claimed was necessary in order to discern that a succession of ideas is, in fact, a succession. It is just this aspect of memory that James will go on to say, just a few chapters later in *Principles*, is in fact the backward-looking part of the saddle that is the specious present. Presumably he did not rely on the specious present in refuting Comte because he had not yet introduced it; it is interesting that he took recourse to the same answer that the Common Sense tradition would have given.

2.5 Hodgson

The philosopher who had the most impact on establishing the characteristics of temporal experience as an important issue is, ironically, someone least associated with the topic, and whose name has been largely erased from intellectual history. Shadworth Hollway Hodgson was a monumental figure in the philosophical circles of late-nineteenth century Britain. He wrote three major books (*Time and Space*, 1865; *Philosophy of Reflection*, 2 vols., 1878; *Metaphysic of Experience*, 4 vols., 1898) published widely in venues such as *Mind*, and was a co-founder and then president of the Aristotelian Society for fourteen years. And yet, scarcely twenty years after the publication of his four-volume lifework, Hodgson's name was all but absent from philosophical discussion, a situation that then turned into almost complete ignorance of his existence and influence during his lifetime. Given his extensive involvement in psychology and philosophy in Britain during this period, it is a historical puzzle as to why he receives so little attention in comparison with his peers.

Hodgson published two books prior to James's publication of the *Principles*. James certainly read one in particular, *Philosophy of Reflection* (1878), which he referenced a number of times. While Kelly did state the specious present doctrine, and provided the name that stuck, Hodgson had actually already developed and named the doctrine four years earlier in calling it the "empiric present." Furthermore, based on evidence such as correspondence between the two, it is clear that Hodgson had a deep and ongoing impact on James's thought, as part of a friendship that included but was not limited to philosophical discussion and lasted for decades.

In *Philosophy of Reflection*, Hodgson takes up the line of thought we have just traced through the Scottish Common Sense philosophers. Hamilton established that some minimum duration is necessary for consciousness, as a consequence of consciousness depending on a contrast between two different states or objects (classed together as "feelings").

> The minimum of consciousness contains two different feelings. One alone would not be felt. … But of this *apparent* simultaneity there are two cases: the first is that of a real simultaneity, the two sub-feelings are really parts in coexistence, not in succession; the second is that in which one of them is felt as growing fainter (called going when referred to its place in succession), the other as growing stronger (called coming when referred to the succession). The simultaneous perception of both sub-feelings, whether as parts of a coexistence or of a sequence, is the total feeling, the minimum of consciousness, and this minimum has duration. (1878, 249–50)

This passage illustrates how Hodgson started from, but then went on to clarify and expand, Hamilton's temporal requirement that consciousness include at least two feelings and thus span some duration. Two feelings that are felt simultaneously are sufficient for consciousness, but not the *only* way we can be conscious. We can compare two feelings without those feelings fully co-existing: one is "coming" and the other is "going," and, as such, they overlap without being simultaneous. This means that Hodgson allows for temporally extended feelings that, within the temporally extended range of consciousness, wax and wane in the way James describes in his chapter on the perception of time.

Hodgson even presents a paragraph that is almost identical with the one Kelly provided, with just a slight difference in terminology for the name of the doctrine. Compare to the passage in section 2.3 that James quoted from Kelly:

> Crudely and popularly we divide the course of time into Past, Present, and Future; but, strictly speaking, there is no Present; it is composed of Past and Future divided by an indivisible point or instant. That instant, or time-point, is the strict *present*. What we loosely call the Present is an empirical portion of the course of time, containing at least the minimum of consciousness, in which the instant of change is the present time-point. (1878, 253)

Hodgson continues with the distinction, introduced by Reid, between a crude or vulgar conception of the present and the strict conception of the present. But now Hodgson adds the idea that on the strict conception, the present is not an entity, and that what we call the present is simply that minimum duration required to encompass at least two distinct feelings in order to be conscious. This is really the first statement of the specious present doctrine as such.

It is well-known that James's *Principles* served as an important source of ideas and inspiration for Husserl as he wrote the lectures that became the *Phenomenology of Inner Time Consciousness*. As such, Hodgson had an indirect influence on Husserl's project of understanding the structure of temporal experience, as did Reid, Hamilton, and others. However, it turns out that Hodgson also had a direct influence on Husserl (1966), via the massive tome he published after James had published the *Principles*. In *Metaphysic of Experience*, volume I, Hodgson lays a groundwork for his project with a number of remarkable features. The first is the manner in which Hodgson takes his empiricist examination of experience so far that he ends up with something that is, more or less, Husserlian phenomenology. Given the break between empiricist, analytically oriented philosophy and phenomenologically oriented philosophy that is generally taken to occur somewhere in the early twentieth century, Hodgson occupies a unique historical position in both of these traditions just prior to such a split. It is likely that the way in which Hodgson's work was so quickly dropped from British philosophical discussion concerned the radically analytic turn it took soon after his publication of the *Metaphysic*, a turn in which his style of philosophizing simply had no place. This makes Hodgson a culminating figure of eighteenth- and nineteenth-century empiricism.

The second remarkable feature of Hodgson's volume I, obviously connected to the first, is how strikingly Hodgson's first four chapters or so parallel the points made by Husserl in *Phenomenology of Inner Time Consciousness*, even to the extent of using the same examples as illustration. Reading Hodgson's first volume, and then reading Husserl, the connections between the two are so strong as to make it highly unlikely that they are merely coincidental. And in fact, it turns out that Husserl had read Hodgson's *Metaphysic of Experience* right around the time that he was compiling the notes that were subsequently edited into the posthumous *Phenomenology* (Andersen & Grush, 2009). It is not an accident that Husserl's *Phenomenology* has such striking similarities to Hodgson's *Metaphysic*.

The upshot of this is that Hodgson deserves a great deal more credit for his views on time and experience, as well as his influence on James's views on these matters and on Husserl's. Furthermore, there is a wealth of historically and philosophically rich material in Hodgson's writings that sheds light on empiricist thought at the time and on contemporary discussions of temporal experience.

2.6 Later James

We've now seen that many of the ideas articulated by James in *Principles* regarding temporal experience had been actively discussed for more than a century before he wrote, and that Hodgson played a key role in James's development of the specious present doctrine. In this section I will present a schematic argument to the effect that there is an important shift in James's thinking about temporal experience from the time he wrote *Principles* to his later writings on pragmatism. Further, in order to understand James's view on temporal experience specifically, we must understand the picture of experience in general that is the foundation of his pragmatism. James moves from simply *contrasting* the experienced versus "real" present, noting that they differ, to *privileging* the experienced present over the purportedly real one. This shift was part of his larger critique of intellectualism, and at least in part a response to what James saw as misuse of the specious present doctrine. He takes an unusually broad and rich view of experience, which is why he can rest the notion of truth squarely on it. Without keeping in mind this enriched notion of experience as described in his pragmatic writings, our understanding of James's views on the experience of time will be impoverished. The shift in James's thinking and the notion of experience on which he relies fundamentally alter the way we should think about his views on what the specious present is and what it indicates about experience and time.

As we've already seen, James originally presented the specious present doctrine in contrast with the "obvious present." The specious present is temporally extended, encompassing some part of the immediate past and having both a forward-looking and a rearward-looking element. The obvious present is punctate; it is the point on a timeline where the past and future meet. James presents the specious present as a feature of our *experience* of time, and the obvious present as a feature of a (mathematical) representation of time. Importantly, he does not take a stance on what the real nature of time is, or on which of the two conflicting representations of time should take precedence (which would, indeed, be rather odd in a book establishing the principles of psychology). In labeling the experiential phenomenon "specious," meaning apparent or illusory, there is a slight implication that the experience is mistaken or nonveridical. James is primarily concerned with describing this feature of experience and discussing the measurements of its range, rather than adjudicating our time sense as a reliable indicator of time itself.

When we look forward about twenty years, though, a different picture emerges. Between 1902 and 1910, James developed his pragmatism as a full-fledged radicalization of empiricism (James, 1904). Even more than Peirce, from whom he took the term, James relied on experience as the ultimate arbiter of truth. His version of pragmatism is surprisingly misunderstood, a situation partially explained by James's use of evocative and metaphorical language to present it (his talk of the usefulness of beliefs and our need to inquire as to their "cash value" evoked unfortunate stereotypes of crass Americans to his British audience).

James was struck by Bergson's writings on time and memory, and heartily endorsed Bergson's rejection of the overintellectualization taking place within philosophy.[2] Concepts, thought James, and the logic that governs them, were being given too much weight when apparent conceptual contradictions arose. A variety of philosophers in the Hegelian tradition, for instance, thought that there were contradictions within the content of immediate experience. James thought this a ridiculous impossibility. Any contradiction that might arise in immediate experience would only be due to the concepts chosen to imperfectly describe or represent that experience. Prior to description, experience can be rich and complex, but not self-contradictory. Use of concepts to describe experience constituted taking something dynamic and changing and cutting out a static piece. In any potential contradiction, then, the blame should rest on the static concepts rather than experience itself.

This can be illustrated by looking at the use to which McTaggart, as an example, put the specious present. McTaggart (1908) famously argued for the unreality of time. As part of that argument, he addressed the criticism that our experience certainly is of a genuinely moving present moment. We experience time, and we experience the present as moving: how then, the criticism goes, can it be unreal? McTaggart rather cleverly avoids answering the charge that his view contradicts experience by reference to the specious present. Because the extent of the specious present may be slightly different for different people, there may be some event that is still present to one while past to another. Thus, claims McTaggart, experience contradicts itself already. He certainly need not reconcile his view to our experience of the present; there is nothing wrong with contradicting the self-contradictory. As to the unreality of time itself, a large part of McTaggart's argument comes down to the fact that past and future are exclusive—they cannot be predicated of the same thing. And yet the reality of time implies that we must call an event future and past, he claims. Therefore, McTaggart concludes, time itself is contradictory and cannot exist. It is this kind of use of concepts and the logic governing concepts against which James reacted so strongly. If our concept-logic allows us to conclude that, because of a contradiction, time itself does not exist, this should be taken as indicating a shortcoming in the concepts and logic used to reach that conclusion.

James's crusade against intellectualism constituted his taking a stand on a generic version of the contrast on which we just saw that he remained agnostic in *Principles*, namely, on how to think about a phenomenon when there is a conflict between the way our concepts represent it and the way we experience it. Pre-pragmatism, James can be understood as agnostic with respect to this conflict. Post-pragmatism, James comes down emphatically on the side of experience over concepts. James makes points that apply to a wide range of experiences that are potentially contradictory when described in certain ways, as well as to the experience of the present. "Time itself comes to us in drops" of experience, rather than indefinitely subdividable increments (1909, 734). Representations of temporal experience that involve the assumption that time itself, especially the present moment, "really" are punctate make time artificial and static, and with it, experience. In an especially Jamesian turn of phrase, he says, "But all these abstract concepts are but as flowers gathered, they are only moments dipped out from the stream of time, snap-shots taken, as by a kinetoscopic camera, at a life that in its original coming is continuous" (1909, 735–6).

His lectures on pragmatism contain an extremely elaborate and inclusive view of what experience itself is. James's pragmatism, recall, recast the notion of truth as simply being that which best organizes our experiences; beliefs are useful if they are true, and they are true if they are useful (1907, 575). This might look trivially false, if one were to evaluate such statements using something like a representational view of experience, where experience simply represents how things are in the world. In that sort of view, experience gives us access to the world that is the way it is, regardless of our experience. James thought this was insufficiently empiricist (ibid., 508). To genuinely rely on experience for knowledge, we need to accept that there really is nothing but experiences on which to rely. Ideas or beliefs about the world should provide schemes by which we can reliably act in the world and achieve desired consequences, and allow us to reliably predict what will happen. Most importantly, beliefs are true when they allow us to make the most sense out of our experiences.

> 'Truth' in our ideas and beliefs means the same thing that it means in science. It means, [the pragmatists] say, nothing but this, *that ideas (which themselves are but parts of our experience) become true just in so far as they help us to get into satisfactory relation with other parts of our experience*, to summarize them and get about among them by conceptual short-cuts instead of following the interminable succession of particular phenomena. (1907, 512; italics in original)

James makes the notion of experience so broad that it encompasses as a subset any other category, such as representations, ideas, conceptions, and so on, that one might use as a means of defining truth. This understanding of experience was sufficiently novel that James's pragmatism had a rather bad initial reception, at least in Britain, and continues to be frequently misunderstood. If one were to start with what he says about truth and its relationship to experience, and combine it with an ordinary understanding of experience, then the resulting notion of truth may seem weak or untenable. If, on the other hand, we start by assuming that there is something interesting to the notion of truth James offers in his pragmatist writings, and then work toward the notion of experience needed to serve that role for truth, it becomes clear that James intends "experience" to be much richer and more fundamental than it is ordinarily taken to be.

In order to fully understand James's views on the specious present, then, we need to consider the chapter "The Perception of Time," and we also need to take a broader view of James's later writings that bear on temporal experience specifically. But in order to understand James's views on the experience of time, we need to get clear on James's extremely unique and rich views on experience more broadly, and the relationship between experience and the concepts we use to render that experience coherent, to relate different experiences together, and to predict and control experiences in the future.

2.7 Conclusion

Contemporary discussions of temporal experience rely on the characterization of the specious present doctrine as James presented it in chapter 15 of *The Principles of Psychology*. Because of James's peculiar citation of Kelly in that chapter, the historical development of this doctrine has been obscured. As I have shown here, there was a substantive and ongoing discussion of the temporal character of experience from which James drew for his own work. The philosophers contributing to this discussion, including but certainly not limited to Reid, Stewart, Brown, Hamilton, and Kelly, had a great deal more to say on the subject than made it into James's brief presentation. The four themes presented earlier illustrate how this history of the specious present draws connections between perception, memory, attention, consciousness, representations of time, and the nature of experience in general.

James himself also had a great deal more to say about experience and its temporal characteristics than is found in *Principles*. His pragmatism included at least two key issues that need to be accommodated in any adequate presentation of his views on the experience of time. The first is his critique of intellectualism, and of the way in which our conceptualization of experience can lead us astray. The second is the incredibly rich view of experience that James takes. His pragmatism, depending so radically on experience, and on truth as what best organizes that experience, will sound trite if accompanied by an insufficient understanding of what James takes experience to include. Likewise, our understanding of the specious present doctrine should be informed by James's views on experience in general, including the writings subsequent to *Principles*.

In conclusion, then, there is a fascinating set of mysteries associated with the history of the specious present doctrine. A few, such as the identity of "Clay," have been uncovered. Some, like Hodgson's abrupt disappearance from philosophical discussion, remain. And this history provides a wealth of ideas to mine for refinement of contemporary accounts of temporal experience.

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Notes

1. James references Reid’s criticism of Locke’s “dim” account in the same chapter where the specious present is introduced (1890, 609).

2. See especially “Bergson’s Critique of Intellectualism” (James, 1909).

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3 A Brief Account of Husserl's Conception of Our Consciousness of Time

James Mensch

Husserl's texts on time consciousness are among the most difficult he penned. He devoted only a single published monograph, *The Phenomenology of Internal Time Consciousness*, to the subject.[1] The editing of this text is largely the work of Edith Stein, who compiled it in 1917 from earlier lectures and notes, her task being complicated by the fact that Husserl revised this material even as she worked on it.[2] For the rest, Husserl's manuscripts on time-consciousness remained unpublished until the beginning of this century. The two chief sources of this material are *Die Bernauer Manuskripte über das Zeitbewusstsein (1917/18)*, which Rudolf Bernet and Dieter Lohmar edited,[3] and *Späte Texte über Zeitkonstitution (1929–1934): Die C-Manuskripte*, edited by Dieter Lohmar.[4] As even a cursory reading of the lectures and these manuscripts reveals, Husserl's method is exploratory and tentative. Descriptive passages are interwoven with thought-experiments. These often consist of speculative endeavors to bring some systematic clarity to the descriptions. Husserl's depiction of his method in the *Bernau Manuscripts* is quite telling. He writes: "As in this treatise, so generally: we bore and we blast mineshafts in all possible directions. We consider all the logical possibilities to catch sight of which of these present essential possibilities and which yield essential impossibilities, and thus we ultimately sort out a consistent system of essential necessities" (*BM*, 189).

Given these facts, a selection of representative texts cannot hope to present the subtlety and richness of his analyses. It will also necessarily exhibit lacunae in presenting the essentials of his thought. To ameliorate these difficulties, I shall begin by giving the broader background of his thought. Then, I will link his texts to present his basic position on how we become conscious of time.

3.1 The Phenomenological Epoché

In the first of these texts, "The Exclusion of Objective Time," translated in chapter 4, Husserl begins with an early version of his phenomenological epoché. This epoché is described as an exclusion: in his words, "the complete exclusion of every assumption, stipulation, and conviction with regard to objective time." (section 4.1). This exclusion is demanded by the nature of phenomenological analysis. Broadly speaking, the subject of this analysis consists of our convictions regarding some matter. Husserl's question is: what is the evidence that we have for such convictions? Adopting James's (and Hume's) radical empiricism, Husserl seeks such evidence in our experience.[5] As a phenomenologist, he takes this experience as the phenomena (i.e., the appearances and connections of appearances) that found our convictions. The exclusion of these convictions along with "every assumption" and "stipulation" concerning what we are trying to verify is, then, simply a matter of investigative procedure. As Husserl's student, Roman Ingarden, expressed it, the suspension of our convictions allows us to avoid the error of the *petitio principii*.[6] Logically, this is the fallacy of assuming, as part of one's demonstration, the conclusion that one wants to establish.

Phenomenologically, we commit this error when we confuse the evidence for some thesis with the thesis itself. Suppose our thesis is that we are seeing a spatiotemporal object—in Husserl's example, the copper ashtray on our desk (see section 4.2). We reach over and pick it up and turn it in our hand, viewing it first from one side and then another. As we do so, we experience a flow of perspectivally arranged visual appearances. We sense its weight and texture as we handle it. We also smell the remains of the ashes on it. All these experiences convince us that it is, indeed, an ashtray. They are the evidence for our conviction. To state the obvious, the ashtray itself is none of its appearances. Visually, it appears perspectivally. But these appearances do not themselves appear perspectivally. We cannot turn a perspectival view of an object about the way we turn an object.[7] Regarded phenomenologically, the object is simply the referent of the series of appearances through which we grasp it. Now, the point of the epoché when we apply it to the conviction that we are seeing the ashtray is to suspend our positing of this referent so as to regard the appearances through which it appears. It is, for Husserl, to examine the validity of our interpreting these appearances as appearances *of* the ashtray. If we are serious in our examination, we cannot, of course, assume the existence of their referent—the actual ashtray—in our assessment of this interpretation.

3.2 Learning to See

As Husserl observes, "in infancy we had to learn to see things." For the infant, "the field of perception" does not yet contain such objects (*CM*, 112).[8] To see a spatial-temporal object, we have to pick out a coherent pattern of perspectivally arranged perceptions and assign it a referent. Seeing it signifies that we can assert that all the perceptions of the pattern are "of" it. We then "see" that it is one thing showing itself in different perspectives. That we had to learn how to do this is shown by the cases where sight is restored to those who lost their sight at an early age or were born blind. They show that something beyond the mere registering of visual data is required to "see," for example, the same cat as it presents first one side and then another to the viewer. The neurologist, Oliver Sacks, writes with regard to Virgil, an individual who had his sight restored: "He would pick up details incessantly—

an angle, an edge, a color, a movement—but would not be able to synthesize them, to form a complex perception at a glance. This was one reason the cat, visually, was so puzzling: he would see a paw, the nose, the tail, and ear, but could not see all of them together, see the cat as a whole."[9]

For Husserl, our learning how to see shows that perception is interpretation. He writes in this regard,

> It belongs to perception that something appears within it, but *interpretation* [*die Interpretation*] makes up what we term appearance—be it correct or not, anticipatory or overdrawn. The *house* appears to me through no other way but that I interpret in a certain fashion actually experienced contents of sensation. I hear a *barrel organ*—the sensed tones I take as *barrel organ tones*. Even so, I perceive via interpretation what mentally appears in me, the *penetrating joy, the heartfelt sorrow,* etc. They are termed "appearances" or, better, appearing contents precisely for the reason that they are contents of perceptive interpretation " (*LU*, 4, 762).

Put in these terms, what Virgil had to learn was how to interpret the visual features he saw. To synthesize them into a complex perception of the cat, he had to interpret them as features of one and the same object. In childhood, we learn such interpretations automatically. Like our appropriation of language, the process seems effortless. This, however, is not the case if, like Virgil, we have to begin much later.

3.3 The Schema

According to Husserl, sensory contents enter into the perceptual process by our interpreting them as appearances of some object. To take them as such is to place them in a framework of identity in multiplicity. We do so when we continually take them in the same sense. As he writes in describing how "we suppose ourselves to perceptually grasp one and the same object through the change of experiential contents," "different perceptual contents are given, but they are taken (interpreted, apperceived) 'in the same sense' ... the interpretation according to this 'sense' is a character of experience which first constitutes 'the being of the object for me'" (*LU*, 3, 397). What we have, then, is a schema involving a threefold structure. On the objective side, we have the appearing object. As a one-in-many, it is the intentional object understood as an appearing sense.[10] On the subjective side, the side of what is "truly immanent" in consciousness, we have the "perceptual contents." On the same side, we also have the "perceptual acts in the sense of interpretative intentions" (ibid.). The acts make the contents intentional by transforming them from senseless sense data into "representing contents"—contents that point unambiguously to the corresponding features of the object (*LU*, 4, 609). They do this through assuming that the contents have a single referent—that is, fit together to form the recurring pattern of perceptions through which a given object exhibits its specific sense.

Husserl uses this relation between interpretation, the contents there to be interpreted, and the appearing object throughout his career.[11] "Constitution," for him, is the constitution of an appearing object through an interpretation of data. This schema holds, not just for the complex objects, called “states of affairs,” where the underlying data are our perceptions of individual objects. It also holds for the straightforward perception of an individual object and, in fact, for the constitution of the appearances that we take as referring to this object. Such appearances achieve their presence through an interpretation of underlying data. The data, on this lowest level, are what Husserl calls “time-constituting phenomena.”

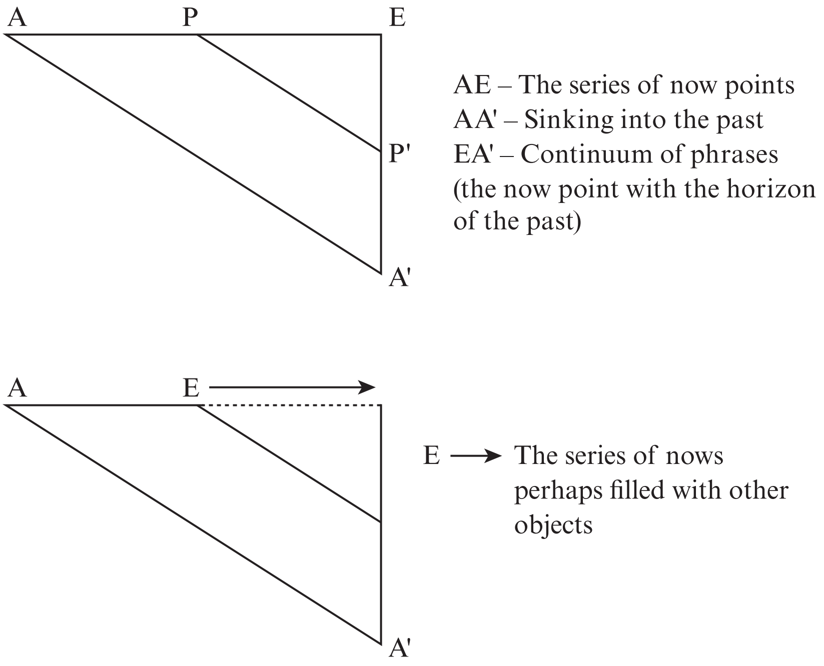
3.4 Impressions and Retentions

In common with Kant, Husserl believes that without a “transcendent affection” of externally provided impressions, consciousness has no material for its syntheses. As he puts it: “The ‘source-point’ with which the ‘production’ of the enduring object begins is a primal impression” (*PdiZ*, 29). This means, he adds in an appendix, “Consciousness is nothing without impression” (ibid., 100). Impressions, then, are the origin of our consciousness of time. They are the first of the time-constituting phenomena. By themselves, however, they are insufficient. Limited to them, we would experience change—that is, the constant alteration of contents in the now—but not their departure into the past. For this, another type of phenomena is required, that of retention. To introduce it, Husserl describes the experience of listening to a melody. As the new tones sound, within a certain margin of diminishing clarity, the previous tones continue to be present. This makes it possible for us to hear the melody, enjoying the relation of the tones. The already sounded tones are not present the way the sounding ones are; rather, they undergo continuous modification. They “die away,” they get fainter and fainter. There is here, as Husserl observes, a certain analogy with a physical object receding and contracting as it gets further away from us: “In receding into the past, the temporal object also contracts and in the process becomes obscure” (*PdiZ*, 26). Ultimately, it disappears altogether. As Husserl insists, the dying away of the fresh experience that fills the temporal field is not a physical phenomenon. The tone that has sounded and yet is still present is not a “weak tone.” It is not an “echo” or a “reverberation” (ibid., 31). Yet, even though no sensuous contents are there to sustain its presence, we still have the experience of holding it fast for a while, our grasp of it getting weaker and weaker. For Husserl, a “retention” is this experience. A retention is a consciousness of the dying away, of the sinking down of what we impressionally experience (ibid.). This experience is one of the continuous modification of what we retain, the modification being that of its dying or fading away.

Husserl understands this modification as a serial process. In this, he agrees with Kant, who asserts that “if I were to lose from my thought the preceding [impressions] ... and not reproduce them when I advance to those which follow, a complete presentation [of an extended event] would never arise.”[12] The necessity here is that of preventing the impression from vanishing as I advance to the now of the next impression. The same necessity applies to the reproduction that preserves the past impression. It, too, must be reproduced if it is not to vanish, and so on serially. Husserl accepts this necessity in his account of the continuous modification of the dying away that marks our experience of retention. Thus, first we have the impression, which we experience as a consciousness—say, of a tone-now. Then, "when the consciousness of the tone-now, the primal impression, passes over into retention, this retention itself is a now in turn, something actually existing" (*PdiZ*, 29). With the expiry of *its* now, this retention is itself retained, and so on serially. Thus, the retention "changes into retention of retention and does so continuously." The result is that "a fixed continuum of retentions arises in such a way that each later point is a retention for every earlier point" (ibid.). What we have, then, is a chain of retentions of retentions of retentions … of some original impression. Each retention retains the impression by retaining the earlier retentions. Each, however, also modifies it insofar as the reproduction is never exact but rather more faded. The same holds for a temporal phase consisting of a number of impressions. Each of these impressions has its own continuity of attached retentions and the whole phase is retained in a continuity of such continuities "belonging to the different time-points of the duration of the object" (ibid., 29). How long is this phrase retained? Husserl never gives an exact answer. It would seem, however, that in the short-term memory he is describing, the retained fades away within a minute. Afterwards, its recollection is a matter of long-term memory.

3.5 Interpretations and the Time Diagram

In the second of our translated texts, "The Constitution of Things and Their Appearances. Constituted and Primal Interpretations," Husserl describes this retentional process as one of the "shading off" (*Abschattung*) of the primary impressional contents (section 4.2). When we proceed along a retentional chain—that is, "lengthwise along the flow of consciousness"—then "we find the manifold modified primary contents that are characterized as retentional modifications of the primary content's character as now" (ibid.). By themselves, these retentions (or shadings-off) of the primary content simply present the content as fading or dying away. As such, they are insufficient to give us a sense of a content's sinking down into pastness. For this, we have to turn to yet another type of time-constituting phenomenon—that of the interpretations of these shadings-off. The interpretations take each shading-off as a degree of temporal departure. Thus, the primary contents are not just subject to the retentional modifications that appear in the fading of the content. They also "carry primary interpretations that, in their flowing connectedness, constitute the temporal unity of the immanent content in its receding into the past" (ibid.). Thus, just as we interpret a spatial object's getting smaller and contracting together as its spatial departure, so we interpret a primary content's fading as its temporal departure from the now that we occupy. Attached to each retention is, then, "a primal interpretation that is no longer constituted." (ibid.). The series of such interpretations gives us the ongoing interpretation of the fading, but still retained content as sinking into the past—that is, as departing further and further from our now. Through this process, the content is constituted as temporally departing. In the words



AE – The series of now points
AA' – Sinking into the past
EA' – Continuum of phrases
(the now point with the horizon
of the past)

E ⟶ The series of nows
perhaps filled with other
objects

Figure 3.1

of the text we have translated, it becomes constituted "in the flow of the temporal multiplicities of the shadings-off" of the original impression (ibid.).

Husserl provides a pair of diagrams to illustrate this process, shown in figure 3.1 (*PdiZ*, 28). The horizontal lines represent the advance of time. The sinking into pastness of the retained as time advances is depicted by the diagonal lines. Thus, in the advance from A to E, the impressional content, A, sinks down to point A′, while the subsequent content, P, sinks down to point P′. As is readily evident, the same holds for all the impressional contents between A and P. If we take AP to designate a stretch of time filled by a temporally extended event, then at the time, E, the event is retained as A′P′. Thus, the vertical lines give the result of this sinking down. A′P′, for example, can be seen as designating our retentional consciousness of the melodic phrase we heard at time AP. A crucial assumption here is that the sinking down is constant. If the impressional content, P, for example, sank down at a faster rate than A so that the diagonal lines connecting A to A′ and P to P′ crossed, then their temporal order would be scrambled. It would seem to us that P was further past than A. To avoid this, all the contents have to be subject to the same constant modification, the same rate, so to speak, of fading. The interpretation of this fading as temporal departure must itself be fixed. The diagram indicates these necessities by the diagonal lines that run parallel to each other.

3.6 Protentions

Our sense of time does not just involve a retention of the past. It also includes our anticipation of the future. When a person hears what she interprets as a familiar melody, she anticipates its notes. Her expectation of what is coming is fulfilled as the melody unfolds. A similar process occurs when you reach for a glass. As your arm moves toward it, the fingers of your hand open to its anticipated shape. Your arm extends to its anticipated distance. Grasping the glass, you apply just enough strength to lift its anticipated weight. Knowing how to do this involves having the correct anticipations. In the performance of this action, each anticipation is matched by a corresponding perception. When the match is perfect, the action proceeds effortlessly, the flow of perceptions being just what you anticipate. If, however, you miscalculate, if you interpret the glass as being heavier than it is, your hand will fly upward, spilling its contents. Here, as in the case of the melody, the interpretation brings with it an anticipation of what will be experienced.

This link between anticipation and interpretation points to the schema. In our grasp of the future, we find an interpretation, contents there to be interpreted, and the resulting appearing objectivity. Husserl terms the contents that are thus interpreted "protentions." In his descriptions, they appear as the mirror image of retentions. Thus, just as the retentional process is a "steady continuum of retentions such that each later point is a retention of the earlier," the whole forming a chain of retentions of retentions of the originally given impression (*Pdiz*, 29), so protention also has a mediated intentionality. Its serial process, however, goes in the reverse direction. As he describes this in the text translated from the Bernau Manuscripts in chapter 4 of this volume: "Every preceding protention relates to every succeeding one in the protentional continuum just as every succeeding retention relates to the preceding one in the same [retentional] series. The preceding protention intentionally includes all the later. It implies them. The successive retention intentionally implies all the earlier" (section 4.3). Thus, while the retentional chain can be described as an already-having of an already-having … of an original impression, the protentional chain, as the inverse of this, is a having-in-advance of a having-in-advance … of a future impression.

The sense of futurity implied in this having-in-advance results from our interpretation of our protentions. The retentions of a content, as they succeed one another, fade until they decrease to nothingness. The protentions of a content, in their succession, increase in vividness, the succession terminating in the actually present content. We take such an increase as this content's approach to the now that we occupy. Both primary memory (retention) and protention play their part in our grasp of the tones of a melody. In Husserl's words, "Primary memory of the tones that, as it were, I have just heard and expectation (protention) of the tones that are yet to come fuse with the interpretation of the tone that is now appearing and that, as it were, I am now hearing" (*PdiZ*, 35). The interpretation locates it in time. It has its horizon of pastness and futurity. This is absolutely necessary if it is to exist in time. As Husserl writes: "the *immanent* temporal object—this immanent tone-content, for example—is what it is only insofar as during its actually present duration it points ahead to a future and points back to a past" (ibid., 297). Husserl, we should note, is silent on the subjective origin of these protentions (as he is on the origin of the corresponding retentions). He only remarks that while impressions are externally provided, their retentions are "produced through consciousness's own spontaneity" (ibid., 100). The same, it would seem, holds for the protentions.

3.7 Intention and Fulfillment

What does it mean to say that a duration "points ahead to a future and points back to a past"? Husserl speaks about this in terms of "intentions." He writes, "A duration cannot even be represented, or in other words, posited, without its being posited in a temporal context, that is, without the presence of *intentions aimed at the context*" (*PdiZ*, 303). The word "intention" indicates an aiming; however, in Husserl's phenomenology, this aiming has to be understood in terms of his notion of constitution. Constitution, as indicated above, is a matter of taking contents in terms of a referent. If the contents support this interpretation, then the interpretative intention is said to be fulfilled. What we intended to see in interpreting the contents according to a given sense becomes actually present. In normal life, this process is ongoing. Suppose, for example, I notice what seems to be a cat crouching under a bush on a bright, sunny day. As I move to get a better look, its features seem to become more clearly defined. One part of what I see appears to be its head, another its body, still another its tail. Based upon what I see, I anticipate that further features will be revealed as I approach: this shadow will be seen as part of the cat's ear; another will be its eye, and so forth. If my interpretations are correct, then my experiences should form a part of an emerging pattern that exhibits these features and perceptually manifests the object I assume I am seeing. If, however, I am mistaken, at some point my experiences will fail to fulfill my expectations. What I took to be a cat will dissolve into a flickering collection of shadows. As this example indicates, to interpret is to anticipate. It is to expect a sequence of contents that will present the object. This expectation, even if we are not directly conscious of it, makes us attend to some contents rather than others. It serves, in other words, as a guide for our connecting our perceptions according to an anticipated pattern. It also allows us to see the perceptions we have as either fulfillments or disappointments of our interpretative intention.

This relation of intention to fulfillment is embedded in our consciousness of time. In retention, our intention directs itself to the expiring content. The data supporting this intention are the fadings that form the shadings-off of the original content. Each one modifies and yet preserves it. Each forms a member of the retentional chain linking our consciousness to it. Our interpretative intention, which takes such fadings as departure into pastness, proceeds through them to constitute our consciousness of the expiring content. The presence of this content fulfills our intention.

Here, we should note a crucial limitation of the schema that informs this account of constitution. Not all consciousness is constituted. The consciousness that exists through an interpretation of retained data is constituted, but the retained data themselves—i.e., the retentions that present such fadings—are not constituted. They are primal, nonconstituted consciousness. With them, the notion of a content of consciousness is one with that of consciousness of this content—namely, that of the fading. If we did not assert this, we would end in a regress. If our awareness of the contents that serve as the material for our constitution required a prior constitution with its own distinct contents and interpretation, we would have to posit one prior consciousness after another to explain the presence of the interpreted contents required by each such consciousness. The same argument applies to the impressions and protentions that also form part of the time-constituting phenomena. It also applies to the momentary interpretation that is attached to each of these. As noted above, for Husserl, this is "a primal interpretation that is no longer constituted" (section 4.2).

Husserl terms our being conscious of something "intentionality." Like the retentional chain itself, this intentionality is serial in nature. Just as each retention is a retention *of* a previous retention, so the consciousness identified with each retention is a consciousness *of* the consciousness identified with the previous retention. As such, it is a mediated consciousness of the original content. The retentional chain, in other words, is understood as a consciousness of a consciousness of … the original content. Each of these consciousnesses is not, itself, constituted. Each, however, contributes to the constitution of the expiring content. The same description applies in a reverse direction with regard to the protentional chain. As Husserl writes in the text translated in chapter 4, "the intentionality [of the anticipation] is continually mediated in its aiming at everything in what is coming … it proceeds from one phase to the next .. and, through this, to what follows this and so on to all the phases," proceeding through them to the anticipated content (section 4.3).

In both cases, we can speak of fulfillments. The intentionality present in a retention is partially fulfilled by the retention it retains—the retention it is "of." Its ultimate fulfillment is through all the retentions that link it to the original content—the very content (i.e., consciousness) that is present through these retentions. Similarly, the intentionality of a protention is fulfilled in and through the protentions that link it to the approaching content. As Husserl expresses this in the translated text:

> the intention goes to the fulfillments or rather goes from anticipation to anticipation in the continuum of anticipations, thereby proceeding toward constantly newly fulfilled anticipations (fulfilled according to the phrase). What we confront here are two sides of one and the same process. Thus, we observe the same thing with the retentions [where we have] the intention directed to the past primal data and the retention directed to the past retentions. (Section 4.3)

In both cases, the intention ends in and is fulfilled by the content that anchors the continua—be this the continuum of anticipations or that of retentions.

3.8 The Constitution of the Perceptual Interpretation

According to Husserl, to perceive is to interpret. The perceptual interpretation is not external to the perceptual process, but rather develops within it, its basis being what we retain. This development is, in fact, one with the growth of our protentional intentionality. As Husserl describes this, when an experience first begins, there is no retention of it and, hence, no definitely formed protention (*BM*, 37). The latter begins with the formation of retentions. In his words, "The further the event advances, the more it offers for differentiated protentions; 'the style of the past is projected onto the future'" (ibid., 38). What arises is the motivation for anticipating something *as* something. In a concrete perceptual experience, this is the motivation for seeing something as something in particular. As Husserl expresses it: "The running off of the retentional branches … works on the protention, determining its content, tracing out its sense." The result is an "indicating in advance, a motivation that can be seen" (ibid.). Concretely, the result is a determination of what we intend to see as based on our retained experience. When we do see what our retained experience motivates us to see, our intention is fulfilled. This intention is formed through our protentions. As such, it shares their serial character. Thus, as Husserl writes, "every intention, in its passing over, passes through every new intention and, in this process, it is not just the final intention that 'fulfills' itself … rather every intention fulfills itself. The null point [the intended event] is the fulfillment for every previous intention—this, through the fact that every later intention includes the earlier in itself" (ibid., 42). Thus, to take our example of intending to see a cat crouching under a bush on a bright sunny day, the approach to the animal involves a whole series of anticipated perceptions. Each, when fulfilled, determines the cat more closely and motivates the anticipation of the next perception. We anticipate that the perception will further determine the cat, that is, fill in some detail that had previously been missing. The end intention, that of picking up the cat and holding it, contains all the previous intentions insofar as they are all involved in the approach to the animal. Here, as Husserl writes, "'intention' signifies the mediation of consciousness, which is always intentional, always functioning in the context of intentions, and which, in the limiting case—that of the final intention —is unmediated original consciousness" (ibid., 40). Thus, the limiting case, the final intention of holding the cat, is mediated by all the intentions that form the elements of the protentional chain leading up to it. Only when we are actually holding the cat can we speak of the unmediated consciousness that comes with having the final intention fulfilled.

For Husserl, then, our protentions, in expressing what we expect to see, shape the interpretative intentions that direct the perceptual process. Statically, we can regard the intentional relation of consciousness to its object as a many-to-one relation, the many perceptual experiences being taken as experiences *of* one object. Genetically, however, we have to think of the perceptual process as ongoing. Here, intentionality does not just involve the intention to interpret a succession of experiences as experiences *of* some particular object, it also includes the expectation that, as one continues this interpretation, the object will unfold itself until it fulfills the final intention. This developing expectation or protention is an intentional selection. Protending, we attend to some contents rather than others. We focus on those that match our protentions (*BM*, 3–4). Doing so, we seek out the pattern of perceptions that will present us with our intended reference. We also interpret these perceptions as fulfillments. As Husserl writes, in describing our hearing a tone: "As long as the tone sounds ... protention continually directs itself to what comes and receives it in the mode of fulfillment, intentionally shaping it. Every primal presence is, therefore, not just content, but 'interpreted' content. Primal presentation is, thus, fulfilled expectation" (*BM*, 7).

What we have here is the "specific mode of intentionality" that characterizes perception. This intentionality refers the actually experienced contents "back to what preceded," i.e., to the retentions that formed the basis for our protentions (*BM*, 226). Husserl's conception of the appearing of the perceptual object is, thus, a dynamic one. The appearing is a continual fulfillment of the protentional reference of a preceding consciousness by a new consciousness with its new impressional data. Each preceding consciousness embodies our interpretative intention to see a given object by virtue of the protentional reference that is present in its retained contents. Each thus looks to its successor for fulfillment (ibid., 8–9).

3.9 Self-Awareness and Duration

According to Husserl, the genetic view of consciousness as a flowing, ongoing perceptual process makes our background self-awareness understandable. Such self-awareness signifies that we are not just conscious of objects. We also possess a background awareness of the consciousness that is directed to them. As Husserl expresses this: "Consciousness exists as flowing and is a stream of consciousness that appears to itself as a flowing. We can also say that the being of the flowing is a 'perceiving' of ourselves" (*BM*, 44). To see this, we must observe with Husserl that consciousness flows because of the retentional and protentional transformations of the impressions we receive. By virtue of these transformations, time with its contents appears to advance from the future, pass through the present, and depart into pastness. Every momentary consciousness is marked by these transformations. As such, "every momentary consciousness … is … inherently a protention of what is to come and a retention of what has already occurred" (ibid., 46). The "of" indicates *the self-awareness* of this flowing since the retentions are a present awareness of what is flowing away, while the protentions are a present awareness of what is flowing toward one. Thus, as we regard an object we are always self-aware—that is, conscious of our just-past, our present and our just-about-to-come states. Such awareness is built into our consciousness of the object given that we are conscious of it through these states. For Husserl, then, it is "completely understandable" that a consciousness, so structured as to have "a backward reference to the old and a forward reference to the new … is necessarily a consciousness of itself as streaming" (ibid., 47–48).

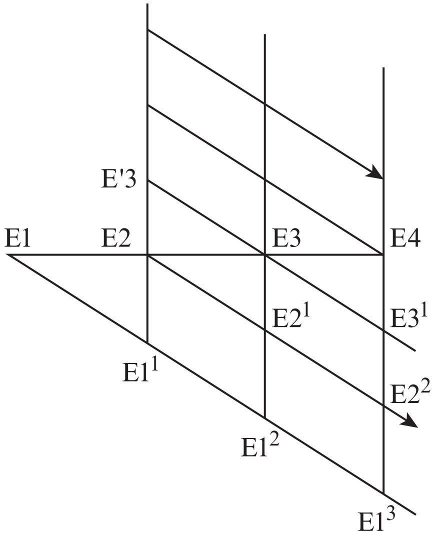


Figure 3.2

The fact that we constitute the object through our retained and protended states means that it is presented as enduring through them. Husserl calls the intentionality that is directed to it a "crosswise intentionality" (*Querintentionalität*). The reason for this is that it cuts across the retentional and protentional chains.[13] In terms of Husserl's time diagram, it can be represented as proceeding up the vertical. In the Bernau manuscripts, Husserl extends the vertical lines of his original diagram above the horizontal (*BM*, 23). Below their intersections with the horizontal lie our present retentions of past contents. Above are represented our present protentions of what is to come. A vertical line thus represents *both* our retained and protended experiences. These form the material that our perceptual interpretation links together by uncovering their pattern. Doing so, the interpretation assigns these experiences a referent—this being the object that we take as appearing through them.

To adequately represent this process, we must imagine the protentions and retentions moving downward on the line. In figure 3.2, the diagonal lines above the horizontal line represent downward movement of the protentions, while the diagonals below the horizontal represent the corresponding downward motion of the retentions as time advances from E1 to E2 to E3 to E4. As the protentions approach the intersection of the vertical with the horizontal, they approach the now, only to pass through it, becoming transformed into retentions of the contents that they once protended. Now, according to Husserl, the crosswise intentionality that passes through the retained aims at the object that appears (and will appear) through this shifting pattern of appearances. As one and the same, this object endures through what we retain. As Husserl expresses this, in directing my attention to a sounding tone, "I immerse myself attentively in the 'crosswise intentionality'" of the flow (PdiZ., 82). When I do so, "the enduring tone stands before me, constantly expanding in its duration" (ibid.). It does so because the "intentional phases" presenting its expiring movements "are displaced … they pass over into one another precisely as phenomena of one thing, which is shaded-off in the flowing phenomena" (ibid., 117). The "one thing" that presents itself through such shadings-off is grasped as enduring through them—that is, as enduring through the departure of the moments that present it.

3.10 Constitution of the Ego

Our final translated text, "The Primal Phenomenon of the Living Present,"which comes from the 1930s, extends the above analysis to the constitution of the ego. Its context is a radicalization of the epoché that Husserl introduced in our first text. This is now understood as "*radical 'limitation' to the living present and the will to speak only about this*" (Ms. C 3, 3b, summer 1930).[14] This epoché, Husserl writes, "leads to the originary lasting streaming—in a certain sense to the *nunc stans*, the lasting 'present,' whereby the word 'present' is actually not suitable since it indicates a modality of time" (Ms. C 7, 14a, July 1, 1932).[15] As the text we translated expresses this, the present that we reach "is not something like a present in its normal, if expanded, sense of a streaming, persistent piece [of time] lying between the streaming past and future" (section 4.4). What we confront here is a streaming outside of the context of the past and future. One way to think of it is in terms of the time diagram. Husserl's "radical limitation" is a limitation to the vertical line of this diagram, here considered as extended above the horizontal so as to include our protentions. In this limitation, we bracket the positing that occurs through the retentional and protentional chains that link this extended vertical to the past and the future. Only the endpoints of these chains remain. They continually move downward, their movement signifying the passage from protentions to impressions and from thence to retentions. Thus, experientially, we continue to have all these elements in our perceptual life. Our living present includes our protentions, impressions, and retentions in their continuous transformation. Only the interpretations that position this life's contents in extended time have been suspended.

Husserl's claim is that with this reduction to our living present, we are at the core of our subjectivity. The living present that we have reached is the "primal form of its being" (section 4.4). As noted earlier, the epoché is a device for uncovering the evidence we have for a particular conviction. The conviction now in question is that of ourselves as the subject of our consciousness, the subject that can say "I" or, in Latin, "ego." Thus, when we ask what the relation of this core is to our ego, our question concerns the evidence for this conviction. For Husserl, it is answered by a description of the processes through which this primal core, this streaming atemporal present, constitutes itself as a subject.

To see what these processes are, we must first note with Husserl that the ego remains "absolutely identical in all actual and possible changes of experiences." It does not change when the contents of our consciousness change. As such, "it cannot *in any sense be taken as a genuine component or moment* of the experiences" that change as we turn our attention from one thing to another (*Ideen I*, 123). As he elsewhere writes, "It is simply an ego of the cogito which [in the change of experiences] gives up all content." This means, he adds, that it is "an empty form that is 'individualized' through the stream: this, in the sense of its uniqueness" (Ms. E III 2, 18).[16] In other words, what makes the ego unique is this content. Apart from such content, it is only a form that "informs," so to speak, the streaming content of our conscious life. To see what this form is, we have to turn to the C manuscripts, where Husserl defines it as the centering of consciousness. In his words: "The ego is the 'subject' of consciousness; subject, here, is only another word for the centering which all life possesses as an egological life, i.e., as a living in order to experience something, to be conscious of it" (Ms. C 3, 26a, March 1931; *CMs*, 35). As he elsewhere puts this: "I am I, the center of the egological [*Ichlichkeiten*]" (Ms. C 7, 9b, June–July 1932; *CMs*, 122).

The question, then, becomes that of the constitution of this centering. Such centering, for Husserl, involves both space and time. When I regard myself in terms of my experience, I always find that I am "here." This means that I cannot depart from myself, but always find myself at the spatial center or zero-point of my environment. This is the point from which the "near" and the "far" are measured. Phenomenologically regarded, this "here" is defined by the perspectival unfolding of the objects that surround me as I move through the world. The sides that the objects show all point to me as a center. I interpret the different rates of their perspectival unfolding as exhibiting their different distances from me. As the familiar experience of gazing from a moving car window shows, objects I take as close by have a higher angular rate of turning than those that I apprehend as further away. This sense of space with its correlative zero-point depends, of course, on my apprehending time. The unfolding perspectives of the objects surrounding me cannot vanish the moment after their apprehension. Retention is required to grasp the rate of their unfolding, and protention is needed if I am to make use of what I retain to make my way in the world. Retaining and anticipating their relative rates of unfolding, I thus locate myself in my world. This locating is not just spatial, but temporal. Situated between my retained past and anticipated future, I find myself at a temporal zero-point. Given that the content that I retain and protend positions me spatially, the "now" of this zero-point is always accompanied by a "here." I, thus, constantly take myself as a spatial-temporal center.

In our final text, Husserl describes the constitution of this temporal zero-point as follows:

> A lasting and remaining primal now is constituted in this streaming. It is constituted as a fixed form for a content that streams through it and as a source point for all constituted modifications. In union with this constitution of the fixed form of the primally welling primal now, there is also constituted a two-sided continuity of forms that are just as fixed. Thus, in *toto*, there is constituted a fixed continuum of form in which the primal now is a primal welling middle point for two continua taken as branches of the modes of [temporal] modifications: the continuum of what is just-past and that of futurities. (Section 4.4)

Despite its somewhat labored prose, this passage has a clear doctrine. It is that the egological now is constituted as a "fixed form," *through which* time appears to flow and *in which* its moments appear to well up as present and actual. A focus on the now, in other words, exhibits the passing through the now as a welling-up, the result being that the now appears as a "primal welling middle point." The constitution of this point occurs "in union with" a second constitution—that of the continua of the past and the future. With the latter, we have the constitution of the temporal environment that allows the source of time to *appear* as a "welling middle point"—i.e., as a source of time—within this environment. I stress the word "appear" since the source of time, for Husserl, is not the ego, but rather the impressions that we retain and protend.[17]

Husserl immediately adds that with the constitution of the two continua, we have "a lasting and remaining form-continuity for what streams through it, which, as streaming, is always co-constituted." This form-continuity is simply that of the centering of experience about the now, the central ego being the center of this form-continuity. Since the form-continuity is one of temporally streaming material, this center's constitution always occurs together with the constitution of this material—a constitution that involves placing it in time through retention and protention.

Relative to this streaming material, the ego appears to stream—that is, continually advance toward the future. Relative to itself, however, it does not stream. Remaining between the streaming past and future, the ego remains in the now. Associating itself with the welling-up that appears to arise in this now, the ego thus takes itself as acting in and through this nonextended, abiding nowness. In Husserl's words, the result is "the primal phenomenon of my 'I act,' in which I am a stationary and remaining ego and, indeed, am the actor of the '*nunc stans*' [or stationary now]. I act now and only now, and I 'continuously' act" (Ms. B III 9, 15a, Oct.–Dec. 1931). As he elsewhere describes this, my acts flow away, "but I, the identity of my act, am 'now' and only 'now' and, in my being as an accomplisher, I am still now the accomplisher." In other words, "I, the presently actual ego, am [always] the now-ego" (Ms. C 10, 16b, Sept. 1931; *CMs*, 200). All of this is, of course, correlated to my appearing as the welling source of time. Such an appearance is deceptive, as is the notion that what acts is this non-extended temporal zero-point. What acts, as Husserl elsewhere makes clear, is our embodied selfhood.[18] Our constitution of time, however, is such that we always locate this action in the now that forms the dividing line between our anticipated future and retained past.

Notes

1. *Zur Phänomenologie des inneren Zeitbewusstseins* (The Hague: Martinus Nijhoff, 1966). This text will be referred to as *PdiZ*.

2. According to Rudolf Boehm, the editor of *Zur Phänomenologie des inneren Zeitbewusstseins*, this means that the original text of the 1905 lectures on time consciousness is "not reconstructable" ("Einleitung des Herausgebers," *PdiZ*, xvii).

3. *Die Bernauer Manuskripte über das Zeitbewusstsein (1917/18)*, eds. Rudolf Bernet and Dieter Lohmar (Dordrecht: Kluwer Academic Publishers 2001). This edition will be referred to as *BM*.

4. *Späte Texte über Zeitkonstitution (1929–1934): Die C-Manuskripte*, ed. Dieter Lohmar (Dordrecht: Springer Verlag, 2006). This will be cited as *CMs*.

5. Husserl makes reference to his debt to James in the *Logical Investigations*. See *Logische Untersuchungen*, ed. Ursula Panzer, in *Edmund Husserl, Gesammelte Schriften* (Hamburg: Felix Meiner Verlag, 1992), III, 211, note. This text will be cited as *LU.* As for Hume, Husserl writes that "Hume's problem" is: "How is this naïve obviousness of our certainty of the world in which we live … to be made comprehensible?" Hume, he continues, liberates us from "the naïveté of speaking about 'objectivity' without ever considering subjectivity as experiencing" (*Die Krisis der Europäischen Wissenschaften und die transzendentale Phänomenologie*, second ed., ed. W. Biemel [The Hague: Martinus Nijhoff, 1962], 99).

6. See Roman Ingarden, *On the Motives Which Led Husserl to Transcendental Idealism*, trans. A. Hannibalsson (The Hague: Martinus Nijhoff, 1975), 12.

7. See *Ideen zu einer reinen Phänomenologie und phänomenologischen Philosophie,* Vol. 1, ed. R. Schuhmann (The Hague: Martinus Nijhoff), 1976, 88. This book will be cited as *Ideen I*.

8. *Cartesianische Meditationen*, ed. S. Strasser (The Hague: Martinus Nijhoff, 1963), 112. This text will be cited as *CM*.

9. "To See and Not See," *The New Yorker*, May 10, 1993, 64. A version of this article was later reprinted in *An Anthropologist from Mars, Seven Paradoxical Tales* (New York: Vintage Press, 1996), 244–96.

10. For Husserl, to be a sense is to be a one-in-many. This holds not just for the senses that present the common features of objects—e.g., the redness of a number of red objects. It also holds for the objects themselves insofar as to see them is to apprehend a single referent for a multitude of perceptions. This means that in direct perception the theses of the object's sense and its being are intertwined. The object of a coherent perceptual experience is, in other words, not just grasped as something real, "a real unity." It is also apprehended as a sense. Thus, as Husserl constantly stresses, all "real unities" are "unities of sense" (*Ideen I*, 120). They are such because of the way they are present to consciousness. In the words of the *Cartesian Meditations*, "The object of consciousness, in its self-identity throughout the flowing of experience, does not enter into this flowing from outside. It lies included within it as a sense; it is this [sense] as a result of the intentional performance of the synthesis of consciousness" (*CM*, 80).

11. Thus, we find him still using it in the C and B manuscripts from the 1930s. For a representative sample of such usage see James Mensch, *Husserl's Account of our Consciousness of Time*, Marquette University Press, 2010, 68–69.

12. "Kritik der reinen Vernunft" (1. Aufl.)" in *Kants gesammelte Schriften*, ed. Königliche Preussische Akademie der Wissenschaften (Berlin: George Reiner, 1955), A 102, 4, 79.

13. The intentionality that proceeds along such chains is called a "lengthwise intentionality" (*Langsintentionalität*).

14. *Zur Phänomenologishen Reducktion*, *Texte aus dem Nachlass (1926–1935)*, ed. Sebastian Luft (Dordrecht: Kluwer Academic Publishers, 2002), 186.

15. Ibid., 384.

16. I am grateful to the Director of the Husserl Archives in Leuven for permission to cite from the manuscripts of Husserl's *Nachlaß*.

17. Husserl, in fact, never abandons this point. See, for example, Ms. B III 3, 4a, written in 1931.

18. See *Ideen zu einer reinen Phänomenologie und phänomenologischen Philosophie,* Vol. 2, ed. W. Biemel (The Hague: Martinus Nijhoff, 1952), §§35–42.

4 The Structure of Lived Time

Edmund Husserl (translated by James Mensch)

4.1 The Exclusion of Objective Time[1]

We should start by making a few general remarks with regard to a phenomenological analysis of time-consciousness. As with all such analyses, this involves the complete exclusion of every assumption, stipulation, and conviction with regard to objective time (with regard to all transcendent presuppositions about existents). Objectively speaking, every experience, like every real being and moment of being, may have its position in a single objective time. The same holds for the experience of perceiving and presenting time to oneself. It may be interesting to determine the objective time of an experience, including the experience that constitutes time. It might also be of interest to investigate how the time that is objectively posited in time-consciousness relates to actual, objective time, that is, to determine whether the estimations of temporal intervals correspond to objective, actual temporal intervals or to show how they deviate from them. These, however, are not the tasks of phenomenology. Just as the actual thing, the actual world is not a phenomenological datum, neither is world-time, real time, natural time in the natural scientific sense. This includes its sense as given by psychology understood as a science of the nature of what is mental.

When we speak of the temporal character of perceived, remembered, and expected objects, it may seem that we are assuming the flow of objective time and studying only the subjective conditions of the possibility of perceiving. What we assume, however, is not the existence of a world-time, of a physical duration, etc., but rather appearing time, appearing duration as such. These, however, are absolute givens. It would be senseless to doubt them. Thus, we accept an existing time. But this is not the time of the experienced world. It is, rather, the immanent time of the flow of consciousness. It is so evident that the consciousness of a tonal process, of a melody that I am now hearing, shows a succession [of notes] that it is senseless to doubt or deny this.

Since space and time exhibit well-noted and significant analogies, our exclusion of objective time will, perhaps, be clearer when we draw the parallel with space. The consciousness of space—that is, the experience in which the “intuition of space” as perception and phantasy occurs—belongs to the sphere of the phenomenologically given. Opening our eyes, we see into objective space. As a reflective inspection shows, this means that we have visual contents of sensation that found the spatial appearance, this being an appearance of definite things that are spatially positioned in such and such ways. If we abstract from all interpretations that transcend [what is given] and reduce the perceptual appearance to its given primary contents, the result is a continuum of visual fields that is quasi-spatial, but is neither itself space nor a spatial surface. The result is, roughly speaking, a twofold continuous multiplicity exhibiting relations of "alongside," "above," "inside," etc. We find within it lines that meet, enclosing a part of the field, and so on. These, however, are not objective spatial relations. It is, for example, senseless to say that a point of the visual field is one meter distant from the corner of this table here or is next to it or is above it, etc. It is just as senseless to assert that the appearance of a thing has a position in space or any kind of spatial relations: the appearance of the house is not next to the house, nor on top of it, nor one meter from it, etc.

Similar assertions hold with regard to time. Here, the phenomenological data are temporal interpretations,[2] that is, experiences where what is temporal objectively appears. Moreover, the experiential moments that specifically found the temporal interpretation are phenomenologically given. These are the possible, specifically temporal contents that are there to be interpreted [*Auffassungsinhalte*]. They are what moderate nativism calls the originally temporal. None of this, however, is objective time. One cannot discover the least thing about objective time through phenomenological analysis. The "original temporal field" is not like a piece of objective time; the experienced now is not inherently a point of objective time, etc. Objective space, objective time, and, with them, the objective world of actual things and processes—all these are transcendencies. Mind you, space and actuality are not transcendent in some mystical sense as "things in themselves." Rather, it is precisely phenomenal space, phenomenal spatial-temporal actuality, the appearing form of space, the appearing form of time that are transcendent. None of these are experiences. And the ordered connections that we can find genuinely within experiences cannot be encountered in the empirical, objective order. They are not included in it.

An investigation of the data for assigning location also pertains to a fully developed phenomenology of what is spatial. (Nativism takes up this task in the psychological attitude). Such data make up the immanent order of the "field of visual sensation." An investigation of this field also belongs to a developed phenomenology. These data relate to the appearing objective places in the same way that qualitative data are related to the appearing objective qualities. If, in the former case, one speaks of signs of location, in the latter one has to speak of quality signs. The sensed red is a phenomenological datum that, animated by a certain interpretative function, presents an objective quality. The datum is not, itself, a quality. Not the sensed red, but rather the perceived red is a quality in a genuine sense of being a feature of the appearing thing. Since "red" is the name of a real quality, it is only by equivocation that the sensed red is called "red." If, with reference to certain phenomenological occurrences, one speaks of their "coincidence," it must be noted that it is through its interpretation that the sensed red first receives the value of a moment presenting a thing's quality. Inherently, however, the sensed red does not contain anything with regard to this [objective quality]. The "coincidence" of the presenting [sensed red] and the presented [objective quality] is not at all the coincidence that occurs in a consciousness of identity whose correlate is said to be one and the same thing.

If we call "sensed" the phenomenological datum that through its interpretation makes us apprehend something objective in its bodily presence (the latter being said to be "objectively perceived"), then we must similarly distinguish between a "sensed" and a "perceived" temporal object.[3] The second refers to objective time. The first, however, is not itself objective time (or a position in objective time). It is, rather, the phenomenological datum through whose empirical apperception is constituted the relation to objective time. *Temporal data*—or if you will, temporal signs—are not themselves *tempora*. Objective time pertains to the context of the objectively experienced. "Sensed" temporal data are not simply sensed. They are also [endowed][4] with interpreting characters. To these pertain certain claims and rights—namely those of measuring appearing times and temporal relations against one another on the basis of the sensed data, thus bringing them into such and such objective orders and distinguishing various apparent and actual orders. What ultimately constitutes itself here as objectively valid being is an unending objective time, one where all things and events—bodies and their physical characteristics, psyches and their mental states—have their determinate temporal positions, these being determinable by chronometers.

It may be—we do not have to make a judgment here—that these objective determinations ultimately have their basis in the registering of differences and relations between the temporal data or even in their immediate adequation to the temporal data. But being sensed "at the same time," for example, is not yet objective simultaneity; the sensed equality of phenomenologically given temporal intervals is not yet the objective equality of temporal intervals; the sensed absolute temporal datum is not yet the being-experienced of objective time. (This holds even for the absolute datum of the now). To grasp a content, even to evidentially grasp it just as it is experienced, does not yet signify grasping an objectivity in an empirical sense. Without more ado, it is not a grasping of objective reality in the sense that one speaks of objective things, events, and relations, of objective spatial and temporal positions, of objective actually existing spatial and temporal forms, etc.

If we look at a piece of chalk and close and open our eyes, we have two perceptions. In this situation, we say that we have seen the same chalk twice. We have two temporally separated contents. We also see, phenomenologically, a temporal apartness, a separation. But there is no separation in terms of the object; it is the same. The object endures; the phenomenon changes. In this way, we can sense subjectively a temporal succession where a coexistence can be ascertained objectively. The experienced content is "objectivated." And the object is now constituted from the material of the experienced contents by means of interpretation. The object, however, is not simply the sum or composition of these "contents," which do not enter into it at all. It is more than and, in a certain sense, other than a content. The objectivity belongs to "empirical experience" [*Erfahrung*], namely, to the unity of such experience, to the empirically lawful context of nature. In phenomenological terms, this means that the objectivity does not constitute itself in the "primary" contents, but rather in the interpretative characters and in the regularities pertaining to the essence of these characters. The phenomenology of knowledge is precisely to fully grasp this and to bring it to a clear comprehension.

4.2 The Constitution of Things and Their Appearances. Constituted and Primal Interpretations[5]

Let us consider a primary consciousness such as the perception of this copper ashtray. It stands there before us as an enduring physical being. Reflecting, we can distinguish between the perception itself (concretely, the perceptual interpretation taken with the data there to be interpreted: the perceptual appearing in, say, the mode of certainty) and that which is perceived (that which can be described in evident judgments based on perception). This is also the intended; the intending "lives" in the perceiving. As reflection teaches, the perceptual interpretation in its mode [e.g., that of certainty] is itself something constituted in immanent time. Constituted through the multiplicity of now phases and retentions, it stands there before us in the unity of its presence. Both the contents-there-to be-interpreted as well as the interpretative intentions, to which the mode of certainty belongs, are constituted in this way. The contents of sensation constitute themselves as unities in the sensuous impressions. The interpretations constitute themselves in other impressions, in the impressions of the act that are interwoven with the sensuous impressions. As a constituted phenomenon, the perception, for its part, is a perception of the thing.

The appearance of the thing, its interpretation as an enduring, unchanged or changing phenomenon, constitutes itself in the primary consciousness of time. We are "conscious" of a new unity in the unity of this change: the unity of an unchanged or changing thing, unchanged or changing in its time, in its duration. In and precisely through the same impressional consciousness in which the perception constitutes itself, the constituted also constitutes itself. It pertains to the essence of a consciousness that it is so built up as to be simultaneously a consciousness of an immanent and a transcendent type of unity. It belongs to its essence that one can direct one's regard now to the sensuous sensation, now to the appearance, now to the object. This holds, mutatis mutandis, for all "acts." They all, by virtue of their essence, have a transcendent type of intentionality; but they have this only through what is immanently constituted through "interpretations." In every case, this is what grounds the possibility of relating what is immanent, the interpretation with its immanent content, to what is transcendent. This relating of the immanent [to the transcendent] again yields an "act," an act of a higher level.

Here, we should observe that a complex of sensory contents, which are themselves constituted unities in the original temporal flow, undergo a unity of interpretation in perception. Moreover, this unitary interpretation is itself a constituted unity in the first sense [of being constituted in the original temporal flow]. We are not conscious of the immanent unities in their constitution as we are of what appears in the appearance of something transcendent, of what is perceived in the perception of something transcendent. Yet they must have something essentially in common, since the immanent impression, like the perception, makes something present. In one case, something immanent is made present; in the other, something transcendent is made present "through" appearances. Thus, while the appearances of something transcendent are unities that are constituted in the consciousness of what is within consciousness, "in" these constituted appearances other unities, the appearing objects, should be constituted.

As we have seen, the immanent unities constitute themselves in the flow of the temporal multiplicities of the shadings-off [of the primary impressional contents].[6] Proceeding lengthwise along the flow of consciousness, we find the manifold modified primary contents that are characterized as retentional modifications of the primary content's character as the now. They pertain to every temporal point of the immanent content. These primary contents carry primary interpretations that, in their flowing connectedness, constitute the temporal unity of the immanent content in its receding into the past. "Contents," in the case of the perceptual appearances, are precisely these complete appearances [constituted] as temporal unities. Thus, the perceptual interpretation is constituted in such a multiplicity of shadings-off. This multiplicity becomes unified through the unity of the temporal interpretation. We must, therefore, understand interpretation here in two senses. The first is the interpretation that is immanently constituted. The second is the interpretation that pertains to immanent constitution. This belongs to the phases of the original flow itself. It is a primal interpretation that is no longer constituted. Now, in the immanent flowing-off of the appearances, in the continual succession of interpretations in phenomenological time, which [together make up what] we call perceptions, a temporal unity constitutes itself. It does so because the continuity of the interpretations does not just yield the unity of the changing appearances (as, for example, when we turn something, there is a series of aspects that appear as aspects of the same thing); it also yields the unity of the appearances of an enduring or changing thing.

Immanent time objectifies itself as a time of the objects that are constituted in the immanent appearances. It does so through the fact that the identical reality of a thing appears in the multiplicity of the shadings-off of the sensuous contents, the latter being taken as unities of phenomenological time. More precisely, the reality appears in the phenomenologically grasped temporal multiplicity of the shadings-off of the interpretations of these contents. This is the thing-reality that in every phase continually presents itself in the multiplicity of the shadings-off. The thing constitutes itself in the flowing-off of its appearances, which themselves are constituted in the flow of the original impressions. One necessarily constitutes itself along with the other. The appearing thing constitutes itself because unities of sensation and unitary interpretations constitute themselves. Thus, there is always a constituted consciousness of something and the presentation of the same thing in the continuous succession [of the flow]. The streams of presentations have a flow and connectedness such that what appears in them is dispersed in multiplicities of shadings-off in precisely the same way that a unity of sensation is dispersed in the shadings-off of sensations. This is the reason why the multiplicity of interpretations and the immanent impressions are both equally characterized as presenting.

Something else is immediately apparent when, over and beyond the primal presentations and the primal protentions and retentions that essentially belong to them, the primally present sensuous data also continually bear the interpretive characters of the constitution of spatial things. This is that the phenomenological time, to which both the sensuous data and the interpretation of something as a thing belong, has to coincide with the spatial time of things point by point. By virtue of the contents of sensation and their interpretations that occupy phenomenological time, a point of fulfilled objective time presents itself with every fulfilled point of phenomenological time.

Here, in the vertical lines of the diagram [see figure 4.1], we do not have only the thoroughgoing vertical coincidence that pertains to the phenomenological constitution of time, according to which the primal datum E_2 and the retentional modification O′ and $E_{1'}$ are united in one moment.[7] The retentional shadings-off of the thing interpretations that belong to the series of each vertical line also stand, as thing interpretations, in a thoroughgoing coincidence. There are two coincidings here. The series of the interpretations of something as a thing does not just coincide because it co-constitutes a continuous succession, but also because it constitutes the same thing. The first is a coincidence of the binding essential sameness [of the interpretations]. The second is a coincidence of identity, since an enduring entity is brought to consciousness in the continuous identification pertaining to the sequence. Naturally, there also pertains here the continuous successive identification of the series of one vertical with the next as the protentions, which now have an objective spatial sense as well, are fulfilled.[8]

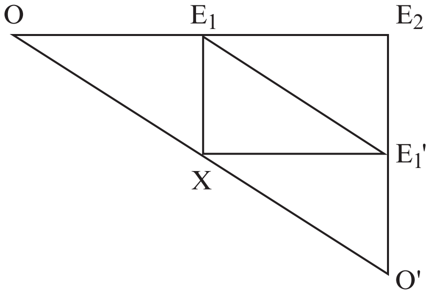


Figure 4.1

We have already indicated the analogy obtaining in the constitution of immanent and transcendent entities. Just as "the shadings-off of sensations" (the primal data for the presentations of unities of sensation in phenomenological time) have their law, their essential character in the primal succession, and just as they constitute the unity of sensation through the modifications represented in the diagram, a similar situation occurs with the shadings-off of things, or more precisely with the [perspectival] "appearances," which now function as the primary data of the primal sequence. The primal succession of the moments of appearance constitutes the (changed or unchanged) appearance as a unity in phenomenological time through the retentions, etc., that ground time. To this, however, one must add that those appearances from the multiplicity of appearances that belongs to the same unchanged thing all have the same ontic essence (an essence of what appears)—this, just as the momentary data that pertain to the same unchanged red have completely the same essence. A fixed law governs the succession of the changes of a thing as it does the changes of the red. Thus, two things are intentionally constituted together: the appearance and what appears, i.e., what appears unchanged or changed in the different appearances.

The question now is, naturally: what kind of characteristics do the appearances of things have; the appearances, that is, of the same thing? This is a question regarding the constitution of the spatial thing, which thus presupposes the constitution of time.

4.3 The Role of "Anticipations" (Protentions) in the Constitution of Phenomenological Time [The Continuous Modification of the Double Intentionality in the Protentional and Retentional Processes of Fulfillment][9]

In the occurring, E_0. . .E_p. . .E_n, protention constantly passes through the series in the sense that every new primally present datum encounters a constant anticipation.

This leads one to say that an anticipation that constantly fulfills itself constantly proceeds along the chain.

It must, however, be noted that the anticipation that is directed to the future is aimed at the coming event or, rather, at the flowing stretch of its occurring. It is not the case that a living anticipation at one point is directed only to the next point, a mere boundary [point], and that with its fulfillment a new anticipation flashes up, which in turn is directed only at the "next point," etc. The anticipation proceeds to the coming event or, rather, to what is coming from it. [It has] a flowing event horizon, a changing stretch. This means that the intentionality [of the anticipation] is continually mediated in its aiming at everything that can be ideally differentiated in what is coming. When we think of the continuum [of the coming] in terms of its phases, it proceeds from one phase to the next. The intentionality, however, proceeds through this phase to the following phase and, through this, to what follows this and so on to all the phases. It can also be said that no matter how we ideally divide up a stretch in thought, at every inner boundary point the intentionality proceeds through this point to the stretch that follows it; and it proceeds through this to every further following stretch.

How is this structured intentionality obtained? We have an [anticipatory] intention that fulfills itself with the occurring of a new primally present datum; but it only does so according to a phase of its intentionality, whereby a continuous stretch remains unfulfilled as an open "horizon." Thus, in the consciousness that has recorded the new primally present (hyletic) datum, a new anticipation does not occur; rather, one and the same anticipation with its intentional continuity goes forward, except that it has, in terms of the series, fulfilled an empty point of its intention.

But this, it will be said, is not sufficient. The constant, punctual fulfillment itself pertains to the intention, given that it is an intention to the occurring of the events that are found in the flow. The intention, however, constantly passes through the new points, preserving in this passage its character as an unfulfilled anticipation; and the intention goes to the fulfillments or rather goes from anticipation to anticipation in the continuum of anticipations, thereby proceeding toward constantly newly fulfilled anticipations (fulfilled according to the phase). What we confront here are two sides of one and the same process. Thus, we observe the same thing with the retentions [where we have] the intention directed to the past primal data and the retention directed to the past retentions. In each of its phases, the continuum of protentional acts is itself a continuum. At one point in the continuum, it is a fulfilled protention and, with regard to the remaining points, it is an empty protention. This fulfilled protention is the fulfillment of a previous empty [unfulfilled] protention. The latter is itself only a nonindependent part of a more extended act, which has a phase of fulfillment. In the progress [of such fulfillments], there is a constant, successive coincidence. Fullness joining with emptiness creates a modified act. This act, however, as fulfillment with respect to the relevant new primally presenting phase (through which it becomes primally presenting) coincides in its empty component with the previous act, while the remaining emptiness coincides with the preceding emptiness. This empty [unfulfilled] consciousness steadily continues in the process. It was already instituted in the beginning, diminishing itself only through constant fulfillment. In a certain sense, the new protention is a modification, in particular a transformation, of the earlier one. But the earlier protention is also a modification with regard to the later, a modification in the sense that the re-presentation is a modification of a presentation, while a "mere intention" is a modification of its total or partial fulfillment, a mediated intention with regard to the less mediated one that corresponds to it.[10]

Every preceding protention relates to every succeeding one in the protentional continuum just as every succeeding retention relates to the preceding one in the same [retentional] series. The preceding protention intentionally includes all the later. It implies them. The successive retention intentionally implies all the earlier.

The later protentions are the fulfillments of the earlier. In the process, each of the earlier fulfills itself. The earlier retentions are fulfillments of the later in a different sense. (A [forward] transition to fulfillment is here impossible. It is only possible with regard to protentions). The earlier retentions are acts in the same sense as the later are, but they have a stronger and richer fullness. In the process, every later retention "fulfills" itself. On both sides, we have a mediated intentionality. A twofold "direction" of intentionality toward the primary and the secondary object—i.e., toward the [retentional] "acts" and toward the primary objects in the how of their modes of givenness—pertains to every mediated intentionality. This does not lead on either side to an infinite regress of the intentionality. Certainly, the difficulty is not the same on both sides, since, in the flow of the primal processes, the empty (relatively empty) protentions precede and the full follow, while the full (relatively full) retentions proceed and the relatively empty follow. The difficulty with regard to the retentions was this: how do we become conscious of the process as a process of retentions (and new appearing, primally given [data])? This would seem to demand that the retentions themselves undergo [an act of] interpretation and that we would need retentions of a higher level [to grasp this act], and so on *ad infinitum*.

Is everything clarified? Do we already have a clear conception of how the primal process looks? How do retentions and protentions intertwine? How do we get the unity of the original consciousness of time in this intertwining? The explication of this constituting stream of consciousness begins with retention; the new that appears remains in consciousness; certainly it modifies itself, but a retentional consciousness takes possession of it as a content there to be interpreted [*Auffassungsinhalt*]. Just so, this retentional consciousness is modified along with its content there to be interpreted, and so on. [Thus, there arises] a stream of retentions of always higher levels, in which, with each phase, there appears a new and modified content.[11]

What characterizes it as "new"? In a certain sense, even the contents there to be interpreted of the protentions are new. Certainly, they appear as contents there to be interpreted that are not "new," not primally presenting. But they also appear as "anticipated," as fulfilling the protentions.

4.4 The Primal Phenomenon of the Living Present. Its Essence as a Fixed Form of a Process Constituting the Temporality of a Concrete Individual[12]

The primal, phenomenal concrete stream of the present is transcendental subjectivity in the primal form of its being. It is the primal streaming present in the ontological form of its streaming emission—a present, and yet again a present. It is a continuous change and, precisely in this change, a present that constantly constitutes itself. We tend to understand "present" in an inauthentic sense. Its proper being, understood as a transcendental being in its primary form, is not something like a present in its normal, if expanded, sense of a streaming, persistent piece [of time] lying between the streaming past and future. Nevertheless, the word "present" is understandably unavoidable. We need the distinct expression: the concrete, original ("primal-phenomenal") present.

In fact, this is the "primal phenomenon" that every transcendental inquiry that follows the method of the phenomenological reduction leads to. Perceptions appear in this present.

It is itself, in a certain sense, perception. It is perception in its totality and in all the components that make up its being; that is, in all the momentarily prominent experiences and aspects of experiences. This follows since we are conscious, originally conscious, of what genuinely belongs to this totality. The same holds for the totality itself. This does not signify that this present is perceived in a mere primary or secondary "noticing," taken as an activity directed to the perceived. When, theoretically interested and active in the transcendental attitude, I return to my transcendental primal ego, to my transcendental primal present, this return, transcendentally considered in the method of the reduction, corresponds to a transcendental, primally presenting process. This process [of the reduction] concludes with a preserving, perceiving transcendental act (in this primal present), an act in which a primal present is objective.

Here, one can object: a present becoming objective, becoming perceived, becoming the goal (the counter-pole) of an ego pole's act aimed at this present (and becoming an individual experience of this primal sphere) is objectively present in a consciousness through an act that is not, itself, objectively apprehended. Thus, the primal phenomenal present that we claimed to be ultimately or primally existent is not really ultimate, given that it is a "phenomenon" for us.[13] Moreover, one could say: my knowledge comes from reflection on my transcendental life. How can I speak about a primal present that is not objective, that is pre-perceived [*vor-wahrgenommen*]? How can I talk about a primal phenomenal being that, as soon as I speak about it, is apprehended, and yet assert that it is anonymous for the ego in which it lies withdrawn as its pole? How are we to understand this anonymity? How are we to understand the anonymity of the ego itself, which we exhibit as the pole of acts and, thence, as also the pole of the "intentional experiences" that are non-acts? How do we arrive at the "capabilities" of the ego, at what it, itself, is? How can we generally justify a method that would allow us to appropriate this primal ego, this primal phenomenal sphere so that we could designate it as a primal phenomenal sphere? These are not the concerns of the beginner. The justification, the self-understanding of the method has to be preceded by the naïvely practiced method. That it has to be this way must be clarified afterward as well. The method [of the reduction] in its absolute being is a transcendental occurrence and, as such, is itself included in the primal phenomenal and, thus, anonymous sphere.

The primal phenomenal being, taken as the living streaming present, is *originally* apprehended. It is a field of original attentive perceivings, perceptions in all its components. It has a remarkable structure that can be followed up in various ways, particularly those that characterize it as streaming. Its basic structure is that of constituting itself as the *nunc stans* [the stationary now] of a unitary streaming. This constitution occurs through an anonymous continuity of intentional modifications of a primary mode. This continuity is not fixed, but is, itself, streaming. A lasting and remaining primal now is constituted in this streaming. It is constituted as a fixed form for a content that streams through it and as a source point for all constituted modifications. In union with this constitution of the fixed form of the primally welling primal now, there is also constituted a two-sided continuity of forms that are just as fixed. Thus, in *toto*, there is constituted a fixed continuum of form in which the primal now is a primal welling middle point for two continua taken as branches of the modes of [temporal] modifications: the continuum of what is just-past and that of futurities. This is a lasting and remaining form-continuity for what streams through it, which, as streaming, is always co-constituted. In the streaming through this form, there is a remarkable synthesis that occurs as a constant streaming process. That which first appears as primally welling up in the now and, then, in passing through the form-system of the just-past, constantly remains the same, but the same in the continually different modes of the just-past, becomes constituted as an individual being through this process.

I shall pass over the account of the constitution of the identity of what comes from the future, i.e., its constitution in what we are conscious of in the concrete present. I explicated its essential structure under the heading of “The Phenomenology of Internal Time Consciousness.” This is, more precisely, the phenomenological constitution that constitutes the being of the primal phenomenal present as such.

This analysis allows us to differentiate the concept of originality, and, thus, the perceptional modes of givenness. We distinguish the primal impressional mode of givenness of what appears as now, as primally welling up, from the retentional and protentional modes of givenness. At the same time, we distinguish the whole streaming continuity of these primal impressions, retentions, and protentions from what is *originally* given within this continuity. In the originally given, [there is] the primally perceived in its form of the primal now, which is itself primally perceived. We also have what is originally given in the retentions, namely, the having-been-just-past in the form of the just-past that originally pertains to it, etc. If everything originally given is termed perceived, the having-been-just-past is also perceived. It is a matter of perception that the individual, abstractly regarded as a point, appears in the now point, is now, directly changes into the just-past and, in the change of this just-past into a just-past of this first just-past, etc., yet remains the same individual, the same in the changes of its temporal modalities. Precisely through this process, the same [temporal point] becomes constituted; constituted, however, as an individual point that is distinct from every new point that constitutes itself in the continually streaming departure [that occurs] in the persisting form of the primal now, the just-past, etc.

By means of this type of continual synthesis, a continuous duration constitutes itself, one where every phase is an identical temporal point. There is, thus, constituted an identical temporal form with identical temporal points as phases of this form and identical “concrete” unities that exist as individual unities in this form. Each such unity has its own duration; each persists in this form; each exists in a temporal modal fashion in its mode of givenness. Each thus constitutes a persisting duration in the continuous change of its temporal modalities. These temporal modalities as such, and time itself, including the temporal duration of what endures (i.e., being as enduring), are all *originally given*. Essentially, a unity can constitute itself (and, essentially, must constitute itself as a unity) only by the entire content of each primal now constituting a plurality of differentiated, coexistent unities, each of which has its manner of continuing development. The unity can constitute itself in this continuing development only if there occurs a continuity of similarity in the fulfilling content. The conditions of association of contents through coexistence and succession have to be satisfied. Essentially, then, time and temporal duration become constituted in the streaming concrete primal present only as the [temporal] form of concrete individuals that coexist or succeed one another. Since these individuals have to be already constituted for us to unfold the structure of the primal present, our regressive inquiry [into its structure] must begin with them as what is first for us.[14]

Notes

1. Edmund Husserl, *Zur Phänomenologie des inneren Zeitbewusstseins* (The Hague: Martinus Nijhoff, 1966), §1, 4–8. (Original used with kind permission from Springer Science+Business Media B.V.)

2. "*Zeitauffassungen*." "*Auffassung*" will be translated throughout as "interpretation." [—Trans.]

3. "Sensed" would then indicate a relational concept that would inherently be silent on whether the sensed is sensual, indeed, or whether it is at all immanent in the sense of the sensual. In other words, it would remain open whether what is sensed is itself already constituted and is, perhaps, totally different from the sensual. —But it is best to leave aside this whole distinction. Not every constitution has the schema: contents there to be interpreted—interpretation [Auffassungsinhalt—Affassung].

4. *Behaftet*: added by the German editor. Brackets indicate additions by this editor. [—Trans.]

5. Edmund Husserl, *Zur Phänomenologie des inneren Zeitbewusstseins*, §6, 90–94.

6. These shadings-off (*Abschattungen*) are described by Husserl as the fading of the primary content as it is retained; this retention of it is itself retained, and so on. See *Zur Phänomenologie des inneren Zeitbewusstseins*, pp. 62–3, where he describes this as a "fading away [*Abklingen*], a certain sinking down [*Herabsinken*] from the highest sensory apex in the now to what can no longer be discerned." We interpret this fading as the departure of the original impressional content into pastness. This is similar to our interpreting something getting smaller as spatial departure. Like the spatial object, "in receding into the past, the temporal object contracts and in the process also becomes obscure" (ibid., 26). [—Trans.]

7. In figure 4.1, the horizontal line, OE_2, represents the onward flow of time. The diagonal lines, OO′ and E_1E_1', represent the sinking down of primary contents through their retentional modifications, and the vertical lines represent the momentary presence in consciousness of the primal impressional datum, here E_2, and the retentions, here E_1' and O′ of the earlier primal impressions. X has been added by the translator. Husserl introduces the time diagram in §10 of *Zur Phänomenologie des inneren Zeitbewusstseins*. [—Trans.]

8. The point is that not just the earlier impressions protend the later, so O protends E_1, which protends E_2., the later moments fulfilling the earlier; the same also holds for the retentions of these moments, namely X, which retains O, and E_1', which retains E_1. Thus, X protends and is fulfilled by E_1' even as

E_1, protends and is fulfilled by E_2. The succession of the verticals is thus a succession of fulfillments. [—Trans.]

9. Edmund Husserl, *Die Bernauer Manuskripte über das Zeitbewusstsein (1917/18)*, eds. R. Bernet and D. Lohmar (Dordrecht: Kluwer Academic Publishers, 2001), 8–11. (Original used with kind permission from Springer Science+Business Media B.V.) The subheading in brackets has been added by the editors. [—Trans.]

10. The second of each pair represents a relative fullness. Thus, the earlier protention is less fulfilled than the later. [—Trans.]

11. The modification is that the content appears more faded with each successive retention. See note 6. [—Trans.]

12. Edmund Husserl, *Späte Texte über Zeitkonstitution (1929–1934): Die C-Manuskripte*, ed. Dieter Lohmar (Dordrecht: Springer Verlag, 2006), §3, 6–9. (Original used with kind permission from Springer Science+Business Media B.V.) The heading has been added by the editors.

13. What would be ultimate would be the act aimed at this present. But such an act, unless a further act were aimed at it, would not be a phenomenon for us. What stops the regress that threatens here is the fact that at the ultimate level time-constituting phenomena are not constituted. They appear without being the object of a further act. [—Trans.]

14. The distinction here is the Aristotelian one between what is first for *us* as opposed to what is first *in itself*. [—Trans.]

II Contemporary Philosophies of Lived Time

> At the railroad station he noted that he still had thirty minutes. He quickly recalled that in a cafe on the Calle Brazil . . . there was an enormous cat which allowed itself to be caressed as if it were a disdainful divinity. He entered the cafe. There was the cat, asleep. He ordered a cup of coffee, slowly stirred the sugar, sipped it . . . and thought, as he smoothed the cat's black coat, that this contact was an illusion and that the two beings, man and cat, were as good as separated by a glass, for man lives in time, in succession, while the magical animal lives in the present, in the eternity of the instant.
>
> —J.-L. Borges, "The South"

How long is "now"? In the tradition of James and Husserl, philosophers examine subjective time through the phenomenological analysis of the experience of temporality. Whether "continental" or "analytic" in philosophical flavor, these analyses acknowledge from the outset that the awareness of time raises special questions. The "now" of awareness seems to contain an immediate consciousness of temporally extended phenomena like change, motion, duration, sequence, and order. While the instant is "thin," its accompanying consciousness is temporally thick, seeming to involve events that cannot cohabit a single moment. The philosophical project is to identify what is necessary and fundamental for thick awareness. Three distinct positions are discussed in the chapters in this section: "retentionalist," "extensionalist," and "cinematic." These labels are not self-explanatory, so in this introduction we will try to distinguish them and provide a coordinated framework for dialogue. With respect to the subjective experience of Now, what is "thick" and what is "thin"?

Events in the world are thin. The lightning flash lasts its milliseconds and then ceases to exist. In our experience of a brief, surprising event, we discern the three phases of the Husserlian schema, as anatomized by James Mensch in the previous chapter: first, a startling "something," "data" intruding like an uninterpreted exclamation, "!?." But this shock of the new is immediately subject to interpretation: lightning? camera flash? fireworks? hallucination? Very soon after, a single satisfying answer appears: lightning, which interpretation may soon be further confirmed as the expectation of a thunderclap is fulfilled. The initial shards of experience are constituted as an "intentional object." Routine experience also comprises the three phases of data, interpretation, and constitution, but normally these intertwine in a continuous flow. The banal coffee cup on the table is emanating routine confirmations of its cup-ness. Aspects of its appearance can be lightly sampled for the sake of our interaction, just to make sure the handle is right for grasping, the contents at a certain level (for estimating weight and trajectory suitable for a sip, etc.). In this case the flow of data is sporadic, even though the object is continuously one and the same. Much of experience is like this.

This morning, however, I've reached for a book and knocked over the coffee cup. An exasperating stain spreads across an earlier draft of this commentary. The mishap has its uses, for in this episode we can discern many strands of time, which we will do well to distinguish. Picture the episode like this: |, the cup upright; /, the cup tipping toward disaster; _, the cup down and its contents spilled across the desk. The brief chronicle of the event, including a few moments before and after, might be rendered like this:

| | | | | / _ _ _ _ _

Time appears conventionally as clock time, ticking from left to right. Each stroke of the cartoon is like a frame in a film. It has its exact date, a fact which can be measured down to the tiniest increments. We can use the timeline to tag each "frame" of the three scenes depicted: "before," frames 1 through 5; "during," frame 6; "after," frames 7 through 11. Of course, this continuous process could be subdivided into infinite increments, but for heuristic purposes we will assume that the eleven moments of the cartoon are atomic, defining instants that cannot be further divided:

[|] [|] [|] [|] [|] [/] [_] [_] [_] [_] [_]

Subjectively, at least part of our experience seems to run in parallel with the objective timeline. Assuming that I'm conscious of the cup throughout the episode, I am at least aware of events in some of the frames, in approximately their real order, lagging a short time (one frame, perhaps) behind the events themselves. Of course, like the events themselves, the experience of the events is a continuous flow. The isolation of experiential snapshot frames is just for illustration. Nonetheless, we can identify this aspect of experience as cinematic. Consciousness tracks the events of the world, with greater or lesser accuracy. The "cinematic theory" of subjective time holds, approximately, that subjective time is simply the mind's continuous update of conditions unfolding in objective time. In chapter 7, Ian Phillips introduces one form of cinematic temporality:

> [T]he temporal structure of experience is determined by the temporal properties of the objects and events one confronts. The intrinsic temporal properties of the stream of consciousness are taken up from the temporal structure of the world. (this volume, p. 142)

Subjective time, on this view, is simply subjectivity *in* time, rather than a special capacity of consciousness. We can use curly brackets to suggest the subjective "frames":

{ | } { | } { | } { | } { | } { / } { _ } { _ } { _ } { _ }

Cinematic theory likens consciousness to a video camera, but a very smart one. A camera might record something like the data of phenomenology, but we are always manufacturing interpretations as well. At each frame, the meaning of the scene is richly articulated. The soaked pages of frame 9 are far more than a retinal Rorschach blot, not a mere spot but a spot pregnant with implications for the usability of the pages, and so forth. Background knowledge is brought to bear on my understanding of the scene. But if my perception is strictly cinematic, then it does not depend on my experience of its temporal context. It is as if each instant of consciousness is confined to a snapshot of that instant in isolation. Although we can interpret the contents of the snapshot, we don't use the neighboring frames as part of our constitution of the present.

The cinematic theory faces an immediate challenge concerning temporal thickness. How will stroboscopic awareness accommodate the experience of change, motion, and duration? Each of these seems to require components separated by a subjective temporal interval, a starting point and then a subsequent condition. The cinematic theory will need to deny appearances, claiming that we are in error to think that an experience of change requires awareness of two distinct moments, "before" and "after." Consider frame 6, {/}. The frame shows a coffee cup at a precarious angle, a bulge of coffee hanging over the edge of the cup. Nothing in the frame moves or changes, and yet it is a picture of movement. With background knowledge of liquids and gravity, frame 6 is readily understood, even if not experienced, as a spill in progress, without any surmises about either the frames before or after. The same can be said for all the frames. The stability (lack of change) in frame 2 follows from a little folk physics of containers. We don't need to know that the cup looked the same in frame 1 or frame 3.

While cinematic snapshots might convey change and its absence, "pure duration" poses an additional challenge. Frame 4 may be indiscernible from frame 1, yet part of our experience at 4 is that of a cup that has endured an extra three frames. Here, cinematic theory must rely on objective time for temporal differences. As a matter of fact, frame 4 samples the static situation three frames after frame 1, and that is sufficient, even in the absence of any detectable difference in the two snapshot-experiences. Immediate awareness can do no more. Other senses of duration are inferential addenda. The clock, for example, tells us that minutes have passed, but we detect the passage of time through changing snapshots of the clock face.

In short, for cinematic theory, unique "temporal" thickness is an illusion. The density of consciousness is due to conceptual knowledge combined with sensible clues to past and future to be found here and now at the scene of the time. In chapter 7, Ian Phillips further explores the obstacles to a cinematic theory with a close analysis of some untested assumptions brought to bear against it.

An alternative to the cinematic theory is the view explicitly detailed by Husserl, a "retentional" view of subjective time. Setting aside any appeal to clock time, isn't there nonetheless an immediately perceived difference between, say, frames 7 and 8? They may look the same,

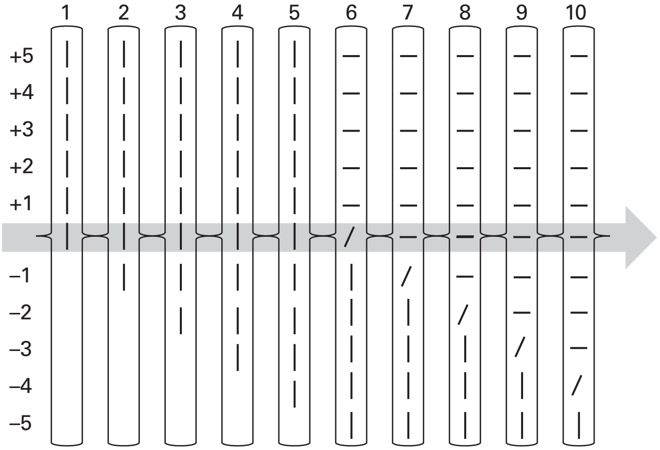


Figure II.1

The experience of time according to retentionalism. The light arrow outlines the primal impressions at each time point. Protentions at each time point are above the primal impressions, while retentions are below. From moment to moment the protention-primal impression-retention complex "sinks" toward the past.

but the temporal context for the two snapshots has altered. Frame 7 immediately follows the mishap, while in frame 8 more time has elapsed. The awareness of elapsed duration simply doesn't seem like an inference, based either on interpretation of the current frame nor some appeal to explicit recollection. The awareness seems more like perception, though of a special, nonsensory type. At frame 7, frame 6 is perceived still, but as "past." For Husserl, as we have seen in part I, this perceptual capacity indeed spreads several seconds into the past. Moreover, "protention" or immediate anticipation spreads toward the future. We see this view also in James, as well as others among Husserl's precursors. Accordingly, the cartoon of subjective time grows more complex. In figure II.1, we follow Husserl's convention of imaging the thickness of temporality as a vertical elaboration of the horizontal time line:

The light arrow outlines the subjective time line previously depicted in the cinematic theory. These are the events experienced as they are happening, the aspect of consciousness Husserl called the "primal impression." But each of the numbered frames includes anticipation, up to +5 frames into the future, and retention, holding –5 frames into the past. The mug spills at frame 6. Until then, I anticipated that the mug would continue upright for at least five frames into the future. Once the mug spills, my anticipation shifts, and I expect coffee to remain spilled for some frames forward. As time progresses, the moment of the spill sinks away from the present, as does the even older retention of the upright mug prior to the spill.

Now a slice of the present is a stack of retained/anticipated frames sandwiching a unique "primal impression," the immediate source of data to inform a temporally extended perception of the evolving scene. Since the stack is always shifting, every moment is temporally unique, both as a whole configuration and in all its parts. Frames 2 and 3, for example, can be distinguished, although their visual appearances might be indiscernible. Moreover, the retention of frame 2 changes as time advances from frame 3 forward. With each tick, retained frame 2 alters its temporal inflection. In short, every element of consciousness is subject to continuous change. William James's Heraclitan observation that you can't step in the same stream of consciousness twice is abundantly true in the retentionalist view. Once again, the heuristic frames pigeonhole what is really a continuum, now imagined in two dimensions. Each moment of experience is a continuum of past-present-future, and the whole is a flowing continuum of experience in time. The diagram also misleadingly implies a rigid threshold for retention and protention, rather than various forms of shading off into indefiniteness. Husserl often compared temporal perspective to spatial perspective: as objects recede into the past, our discernment of details fades. This too has been oversimplified here.

The retentional view is considerably more complex than the cinematic alternative. One apparent shift here is in the span of the immediate perception of time. The content of time consciousness is dramatically different, with the cinematic view limiting content to what is immediately present, compared to the spread of temporal awareness envisioned by the retentionalist. Unfortunately, retentionalism gets more complicated still. The entire stack of retention/primal impression/protention appears in present, current awareness, and thus the whole assembly makes its relentless transit into the retained past. There are retentions of past retentions, retentions of past protentions, and so forth. Diagrammatically, another dimension would be needed to schematize just one frame of this recursive infolding of temporality. All of this is constituted through the interpretation—of what? "Data," particularly the mysterious notion of "primal impression," is ambiguous in retentionalism. In chapter 5, Shaun Gallagher and Dan Zahavi take this issue as an opportunity to clarify a rich new version of retentionalism, in which the immediacy of the primal impression is always filtered through its retentional and protentional context, in a recursive process they compare to a fractal curve. Thus the primal impression is not raw "data," but already a constituted subjective reality reaching toward the future, an active construction rather than a passive impression.

The intricacy of retention/primal impression/protention leads some theorists to seek a middle way between retentionalism and the cinematic view. In chapter 6, Barry Dainton refers to this alternative as extensionalism. Extensionalism relies on a "specious present" of a small duration—perhaps half a second—during which a short sequence of events is somehow co-present. In the simplified frame world of this introduction, the now of awareness spans a larger interval than the dense series of frames representing objective events:

. . . { | / _ } . . . .

. . . [|] [/] [_] . . . .

The diagram suggests a middle path between retentionalism and the cinematic theory. Like retentionalism, a single subjective frame, {| / _}, has temporally extended content. But the specious present is not a simple temporal blur of a sequence of events. The specious present of the coffee spill retains the temporal distinctions among the three stages of the episode. Somehow, throughout the extent of the subjective present, the three elements |, /, and _, are experienced as fully "now" and yet in their correct order. James, as usual, marshals apt metaphors to describe the structure of the specious present:

> [T]he practically cognized present is no knife-edge, but a saddle-back, with a certain breadth of its own on which we sit perched, and from which we look in two directions into time. The unit of composition of our perception of time is a *duration*, with a bow and a stern, as it were—a rearward—and a forward-looking end. It is only as parts of this *duration-block* that the relation of *succession* of one end to the other is perceived. We do not first feel one end and then feel the other after it, and from the perception of the succession infer an interval of time between, but we seem to feel the interval of time as a whole, with its two ends embedded in it. The experience is from the outset a synthetic datum, not a simple one; and to sensible perception its elements are inseparable, although attention looking back may easily decompose the experience, and distinguish its beginning from its end. (1890, 609–10)

If the elements of the specious present are all co-present, how are "bow" and "stern" distinguished? Dainton suggests that elements of experience have an "inherent and directed dynamic character":

> Suppose I see a bird fly overhead. It crosses my field of vision in a second or so. I do not merely see the bird occupying a succession of different locations at different times. I see the bird moving. The perceived movement is itself a dynamic and directed intrinsic feature of my visual experience, and just as essential to it as color, size, or shape. (2001, 105)

This "inherent directional dynamism" is a sort of mental momentum that can order items in awareness without reflection. A puddle of coffee does not leap into a precariously tilted cup, nor does the tilted cup right itself—this order runs contrary to the inherent dynamism of the scenario. In this way the three stages of the coffee spill might simultaneously appear to me as fully perceived right now, yet temporally ordered.

On the one hand, inherent dynamism resembles the cinematic view in its appeal to intrinsic assumptions about the way the world works. Roughly speaking, mental momentum prereflectively mirrors the physical laws of inertia. But the temporal spread of the subjective now in extensionalism preserves a phenomenological presupposition that the before and after of change can be directly and simultaneously perceived. On the other hand, Dainton's dynamic extensionalism can sound quite like the retentional view, in its enactive and dynamic reformulation. For example, Gallagher and Zahavi write:

> Our experience of the present is always dynamic and (because) it is always structured by protention–primal impression–retention. Pre-reflectively, consciousness has this structure. There is no impression of the present taken as a knife-edge; rather, as Husserl suggests, primal impression is already fulfilling

> (or not) protentions that have already been retained, and in doing so is already informing the current protentional process. This structure constitutes a specious present. (this volume, p. 92)

From this point forward the phenomenology requires subtle distinctions, and the supporting arguments and thought experiments reflect the continual creativity of the authors in this section. Looking over the three positions, we find different accounts of the phenomenology of subjective time, three views of "what it is like" to experience a toppling coffee mug, and every other aspect of conscious life. All three celebrate the continuous flow of experience. For all, consciousness is always on the move, and for all of them states of consciousness are intricate assemblies of "lower-level" features combined with more abstract "higher-level" understandings of the current scene. Examining a single, overly simple frame of experience, however, discloses significant alternative views of the phenomenology of time. The cinematic theory aims for a minimalist account of the contents of temporal consciousness. Cinematic awareness is mainly perceptual awareness of the scene present to us here and now. Time is an abstraction like gravity, rather than a primitive and essential aspect of every state of consciousness. In retentional theory, the here and now is elaborately temporal in every respect. The elapsed time to and from anticipated and retained events is a fundamental feature of perception. For extensionalism, immediate past and future join with the present in an extended temporal window of awareness. Inside the window the order of events is preserved, but the "look" of each event remains unchanged for the duration of the window.

Accordingly, the first foray into the contemporary landscape of subjective time is an examination of the experience of time itself. A simple appeal to introspection is not enough to distinguish the varieties of temporal experience. Instead, the authors in this section work ahead of time, examining the necessary conditions for temporal experience of any sort, and behind time, examining the consequences of fundamental theories of subjective time.

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5 Primal Impression and Enactive Perception

Shaun Gallagher and Dan Zahavi

Philosophers and cognitive scientists have recently argued that perception is enactive (e.g., Varela, Thompson, & Rosch 1991; Noë, 2004; Di Paolo, 2009).[1] To put it simply, perception is action-oriented. When I perceive something, I perceive it as actionable. That is, I perceive it as something *I can* reach, or not; something *I can* pick up, or not; something *I can* hammer with, or not, and so forth. Such affordances (Gibson, 1977, 1979) for potential actions (even if I am not planning to take action) shape the way that I actually perceive the world. One can find the roots of this kind of approach in the pragmatists (e.g., Dewey, 1896), but also in phenomenologists like Edmund Husserl, Martin Heidegger, and Maurice Merleau-Ponty. Merleau-Ponty (1962) is most often cited in this regard, but Merleau-Ponty himself points back to Husserl's analysis of the "I can" in *Ideen II* (Husserl 1952), and to his analysis of the correlation between kinesthesia and perception (1973b; see Zahavi, 1994 and Gallagher & Zahavi, 2008 for further discussion).

With this enactive view in mind, we revisit Husserl's account of time-consciousness. In his analysis, the very basic temporal structure, protention–primal impression–retention, is said to characterize perception, as the most basic form of cognition as well as consciousness in general. As such, the temporal structure of perceptual consciousness should in some significant way reflect or enable its enactive character. Our question is this: if perception is enactive, then at a minimum, shouldn't its temporal structure be such that it allows for that enactive character?

In the first part of this essay, we provide a brief account of Husserl's classical analysis. We then proceed to focus on the concept of primal impression by considering various objections that have been raised by Jacques Derrida and Michel Henry, who basically argue in opposite directions. Derrida emphasizes the relationality of time-consciousness and downplays the importance of the primal impression, whereas Henry emphasizes the irrelationality of time-consciousness and downplays the importance of protention and retention. In a further step, we consider some of Husserl's later manuscripts on time, where he revises his original privileging of the primal impression. In the final section, we turn to the question of an enactive temporal structure.

5.1 Husserl's Classical Analysis of Time-Consciousness

One of the basic questions to which Husserl seeks to provide an answer in his famous lectures on time-consciousness is the following: How it is possible for us to be conscious of temporal objects, of objects with a temporal extension? How is it possible to be conscious of objects such as melodies, which cannot appear all at once, but unfold only over time? Husserl's well-known thesis is that a perception of a temporal object (as well as the perception of succession and change) would be impossible if consciousness merely provided us with the givenness of the pure now-phase of the object, and if the stream of consciousness were a series of unconnected points of experiencing, like a string of pearls. If our perception were restricted to being conscious of that which exists right now, it would be impossible to perceive anything with a temporal extension and duration, for a succession of isolated, punctual, conscious states does not as such enable us to be conscious of succession and duration. But this consequence is absurd. Thus, consciousness must in some way transcend the punctual now, and be conscious of that which has just been and is just about to occur. But how is this possible? How can consciousness be conscious of that which is no longer or not yet present?

According to Husserl, Brentano held the position that it is our re-presenting (*vergegenwärtigende*) acts that permit us to transcend the now-point. We perceive that which is now, and we imagine, remember, or anticipate that which does not yet or no longer exist (Husserl, 1966a, 10–19). Husserl rejects this explanation, however, since it implies that we cannot *perceive* objects with temporal duration. Basically, his alternative is to argue that the basic unit of perceived time is not, as James (1890) had termed it, a "knife-edge" present, but a "duration-block," a temporal field (a "specious present") that contains all three temporal modes: present, past and future.[2] Let us assume that I am hearing a triad consisting of the tonal sequence C, D, and E. If we pay attention to perception the instant tone E sounds, we will not find a consciousness occupied exclusively with this tone alone, but a consciousness of the broader sequence E, D, and C. When I hear the tone E, I am still conscious of the tones D and C, but not as remembered. Rather, I am still *hearing* these tones as part of an ongoing sequence. This is not to say that there is no difference between our consciousness of the present tone E and our consciousness of the tones D and C. D and C are not simultaneous with E; they are past tones, and, just so, they are *intuited as past*, and it is exactly for this reason that we can say that we *hear* the triad in its temporal succession and not merely as isolated tones replacing each other abruptly.

Husserl employs three technical terms to describe the structure of this temporal field. There is (1) a *primal impression*, which is the component of consciousness that is narrowly directed toward the now-phase of the object. Husserl is very clear about the fact that the primal impression cannot be thought independently of its temporal horizon (Husserl, 1966b, 315, 337–38)—it never appears in isolation but is an abstract component that, by itself, cannot provide us with awareness of a temporal object. It is accompanied by (2) a *retention*, which is the component that provides us with a consciousness of the just-elapsed phase of the object, allowing us to be aware of the object or event as it sinks into the past, and by (3) a *protention*, the component that, in a more-or-less indefinite way, intends the phase of the object about to occur. The role of protention is evident in our implicit and unreflective anticipation of what is about to happen as experience progresses.

According to Husserl's analysis, experience of any sort (perception, memory, imagination, etc.) has a common temporal structure such that any moment of experience contains a retentional reference to past moments of experience, a current openness (primal impression) to what is present (which may be, e.g., a currently activated note in a remembered or imagined melody), and a protentional anticipation of the moments of experience that are just about to happen. Consciousness involves the generation of a field of lived presence. The concrete and full structure of this field is determined by the *protention–primal impression–retention structure of consciousness*. Although the specific experiential contents of this structure from moment to moment progressively change, at any given moment this threefold structure is present (synchronically) as a unified whole.

> In this way, it becomes evident that concrete perception as original consciousness (original givenness) of a temporally extended object is structured internally as itself a streaming system of momentary perceptions (so-called primal impressions). But each such momentary perception is the nuclear phase of a continuity, a continuity of momentary gradated retentions on the one side, and a horizon of what is coming on the other side: a horizon of "protention," which is disclosed to be characterized as a constantly gradated coming (Husserl, 1962, 202).

Thus, on Husserl's account, a perception cannot merely be a perception of what is now: rather, any perception of the present phase of an object includes a retention of the just-past phase and a protention of the phase of the object about to occur (Husserl, 1966b, 315). Phrased differently, perceptual presence is not punctual, it is a field in which now, no-longer-now, and not-yet-now are given in a horizonal gestalt. This is what is required if perception of succession and duration is to be possible.

Both retention and protention have to be distinguished from the proper cognitive acts of recollection and anticipation. There is an obvious difference between retaining and protending the tone which has just passed and is just about to occur, on one hand, and remembering one's tenth birthday or looking forward to next Christmas, on the other. Whereas the latter are full-fledged intentional acts which presuppose the work of retention and protention, retention and protention are structural components, implicit moments of such acts of consciousness. They do not provide us with new intentional objects, but with a consciousness of the present object's temporal horizon. Whereas the retention and protention occur passively without any active contribution from our side, explicit anticipation and recollection are acts we can initiate voluntarily. Retention, in contrast to recollection (memory proper), is an immediate intuition or holding-in-presence of something that has just been present; recollection is a presenting (or "re-presenting" [*Vergegenwärtigung*]) of a past event (Husserl, 1966a, 41, 118, 330).

Since the presenting function of perception or memory, or any such cognitive act, depends upon the contribution of retention as a structural feature, and its ability to retain that which has just been present, it would be wrong to identify the intuitively given with that which in a narrow sense is present, namely the punctual now-phase of the object. It is, in part, for this reason that Husserl claims the analysis of retention has led to a significant widening of the phenomenological field (Husserl, 1966b, 324–325; 1973a, 162).

Let us emphasize that temporal experience, for Husserl, is not an object occurring *in* time, but neither is it merely a consciousness *of* time; rather it is itself a form of temporality, and ultimately the question to ask is whether it makes sense to ascribe temporal predicates to time itself. Perhaps this worry can explain some of Husserl's occasionally somewhat enigmatic statements. Even if we ascribe some kind of temporality to the stream of consciousness due to its dynamic and self-differentiating character, we should not conflate the temporality that is intrinsic to consciousness itself with the kind of temporality that pertains to the objects of consciousness. Husserl would reject the claim that there is a temporal match, or isomorphism, between the stream of consciousness and the temporal objects and events of which it is conscious. The relations between protention, primal impression, and retention are not relations among items located within the temporal flow; rather, these relations constitute the flow in question. In short, we have to distinguish the objects that are constituted as temporal objects in the way they are structured by protention, retention, and primal impression from the relation between the constituting structures of consciousness itself. Just as my experience of a red circle is neither circular nor red, there is a difference between the temporal givenness of the intentional object and the temporal givenness of the experience itself. They are not temporal in the same manner. It makes, as Husserl writes, no sense to say of the time-constituting phenomena (the primal impressions, retentions, protentions) that they are "present," "past," or "future" in the way empirical objects are (Husserl, 1966a, 75, 333, 375–376). Rather it is their very conjunction which makes possible the senses of present, past, and future.

5.2 Some Critical Perspectives

Husserl's analysis of inner time-consciousness has given rise to a number of heated debates within phenomenology. Derrida, for example, attempted to demonstrate that all meaning, being, and manifestation, including the self-givenness of subjectivity, far from being original and simple, are products of an irreducible process of differentiation (Derrida, 1967, 68, 70). Derrida's argumentation is decisively inspired by his reading of Husserl. It was Husserl's own analyses which, according to Derrida, made it clear that it is impossible to speak of the simple self-identity of the present (Derrida, 1967, 71).

According to Derrida, it would be impossible to understand the relation between retention and primal impression, and to comprehend the perpetual retentional modification, if the primal impression were a simple and completely self-sufficient ground and source. The primal impression is always already furnished with a temporal density, and the retentional modification is not a subsequent addendum to, but an integrated part of, the primal impression. Rather than being a simple and undivided unity, the present can only appear as present due to the retentional modification, the irreducible otherness (nonpresent) of the past. Presence is differentiation; it *is* only in its intertwining with absence (Derrida, 1990, 120, 123, 127).

> One then sees quickly that the presence of the perceived present can appear as such only inasmuch as it is *continuously compounded* with a nonpresence and nonperception, with primary memory and expectation (retention and protention). These nonperceptions are neither added to, nor do they *occasionally* accompany, the actually perceived now; they are essentially and indispensably involved in its possibility (Derrida, 1967, 72).

For Derrida, it consequently proves necessary to distinguish the pure primal impression, which is an empty a priori possibility, a theoretical limit-case, and the phenomenological present, which appears only as genetically complex, modified by retention and protention. We might infer that there must be something like a primal impression, but it is never experienced as such. The primal impression will always be gone before it can be fixed by consciousness. To be punctual and to be experienceable are incompatible determinations. For this reason it is necessary to ascribe a transcendental, that is, a constitutive significance, to a nonpresence in self-awareness (Derrida, 1990, 166, 1967, 5).

To be more precise, self-presence must be conceived as an originary *difference* or *interlacing* between now and not-now, due to the intimate relation between primal impression and retention. Consciousness is never given in a full and instantaneous self-presence, but presents itself to itself across the difference between now and not-now. Presence is possible thanks to the retentional trace. It emerges on the background of a nonidentity; it is haunted by the alterity of the absent and always presupposes an *othering* (Bernet, 1994, 216, 235, 283).

> As soon as we admit this continuity of the now and the not-now, perception and nonperception, in the zone of primordiality common to primordial impression and primordial retention, we admit the other into the self-identity of the *Augenblick* [instant]; nonpresence and nonevidence are admitted into the *blink of the instant*. There is a duration to the blink, and it closes the eye. This alterity is in fact the condition for presence. (Derrida, 1967, 73).

One somewhat disturbing implication of this is that consciousness appears to itself not as it is, but as it has just been. Initially, the initiating moment is unconscious, and it only gains self-presence *nachträglich* (belatedly) through the retentional modification.[3]

Now, whereas Derrida argued that Husserl failed to draw the full implications from his discovery of the retentional modification, we find the exact opposite criticism in Michel Henry, namely that Husserl assigned too great significance to the work of retention. Whereas post-Husserlian phenomenology has generally tried to rectify what was believed to be an imbalance in Husserl's account of the relation between immanence and transcendence, namely his disregard of *exteriority*, Henry has accused Husserl of never having managed to disclose the true *interiority* of subjectivity in a sufficiently radical and pure manner. Thus, according to Henry, the basic problem in Husserl's phenomenology is not that it somehow remained unable to free itself from immanence, but on the contrary, that it kept introducing external elements into its analysis of this immanence. As Henry suggests, it is downright absurd to accuse Husserl of having advocated a philosophy of pure presence, since Husserl never managed to conceive of a presence liberated from the horizon of nonpresence (Henry, 1989, 50). To put it differently, Henry argues that Husserl mistakenly sought to analyze the self-presence of consciousness in terms of the ecstatic-centered structure of protention–primal impression–retention. According to Henry, however, this introduces a retentional mediation into the core of self-manifestation, thereby furnishing it with a complexity that is utterly foreign to its nature (Henry, 1990, 49–50).

Against this background, it is hardly surprising Henry rejects Derrida's claim that the self-manifestation of the primal impression is due to the intervention of the retention, and that subjectivity only gains self-presence in temporal adumbrations. Indeed, Henry goes so far as to claim that the dimension of primary self-manifestation is nonecstatic, nontemporal, and nonhorizonal (Henry, 1963, 576, 349). It is nonhorizonal insofar as the manifestation does not presuppose or entail a reference to anything transcendent or absent. It is nonecstatic in the sense that the living ego never appears to itself across a recollection or oblivion; and it is immediate in the strict sense of being neither mediated nor delayed. We are ultimately dealing with a self-presence characterized by its complete unified self-adherence and self-coincidence (Henry, 1963, 858), and this unity is neither constituted (by anything else), nor is it extended in protentions and retentions (Henry, 1965, 139).

Although both Derrida and Henry end up criticizing Husserl's theory of inner time-consciousness, they both remain deeply influenced by his account.[4] At the same time, however, both also seem to end up defending positions that are themselves too radical. The question is whether Husserl's own account might not provide us with a sound position that avoids the opposing excesses of both Henry and Derrida.

At first sight, Derrida's description of the relation between primal impression and retention appears somewhat misleading. Although one might characterize the relation between primal impression and retention as a question of internal differentiation, it is strictly speaking erroneous to characterize it with terms like "delay" and "absence." As it was pointed out above, retention and protention are not past or future in regard to the primal impression. They are "together" with it, and the self-manifestation of enduring consciousness consequently possesses the full structure of protention–primal impression–retention. Thus, it is not the retention, but that which is given in it, namely, the retained, which is past, an absence kept in presence. Ultimately, Derrida's argumentation contains a puzzling tension. On the one hand, he wants to stress the intimate connection and continuity between primal impression and the retention. It is a falsifying abstraction to speak of them in isolation and separation. But, on the other hand, he also wants to describe the retention as being different from and foreign to the primal impression. Only this will allow him to speak of impressional self-awareness as being mediated and constituted by the alterity of the retention.

Whereas Derrida argues that retention has priority over primal impression, Henry argues that primal impression has priority over retention. The question, though, is whether either of these alternatives is really attractive. Taken in isolation, the primal impression is an abstraction and theoretical limit-case. It is in fact never given alone. The concrete and full structure of the lived presence, according to Husserl, is protention–primal impression–retention (Husserl, 1966b, 317, 378). It is "immediately" given as an ecstatic unity and is not a gradual, delayed or mediated process of self-unfolding. Lived presence has an internal differentiation, an original complexity, but to speak of it as being mediated or delayed is to remain determined by a conception that sees primal impression and retention as two different and separate elements. One has to avoid the idea of an instantaneous, nontemporal self-presence, but one must also stay clear of the notion of a completely fractured time-consciousness, which makes both consciousness of the present and of the unity of the stream unintelligible.

5.3 Husserl's Revision

So far we presented a brief survey of Husserl's standard depiction of the structure of inner time-consciousness, centered on the three components of primal impression, retention and protention. We then looked at two quite different phenomenologically motivated criticisms of Husserl's account and considered what a likely Husserlian response would amount to. Let us now move forward and take a look at some of Husserl's later texts on time-consciousness, in particular his so-called Bernau Manuscripts, which were written around 1917–18. What we will find there is Husserl's own revision of the original tripartite account. The main difference is that the primal impression (or as Husserl calls it in the Bernau Manuscripts, the "primal presentation"), rather than being the origin and point of departure, is considered the result of an interplay between retention and protention. Compare for illustration the two following quotations. The first is from the original lectures on time-consciousness, the other from the Bernau Manuscripts:

> The primal impression is something absolutely unmodified, the primal source of all further consciousness and being. Primal impression has as its content that which the word "now" signifies, insofar as it is taken in the strictest sense. (Husserl, 1966a, 67).

> The now (i.e., the primal presentation) is the boundary between two different "re-presentational" acts, the retentions and protentions. (Husserl, 2001, 4).[5]

In short, whereas retentions and protentions in the early lectures were defined vis-à-vis the primal impression, in his later research manuscripts, Husserl argues that the primal impression must be considered the line of intersection between the retentional and protentional tendencies that make up every momentary phase of consciousness. Just as in his earlier account, Husserl continues to claim that the primal presentation by itself doesn't present at all, it is not self-sufficient, rather its presenting occurs only in connection with retentions and protentions. But in addition, and this is where the Bernau Manuscripts are more radical, Husserl also seems to suggest that the complicated interlacing of retentions and protentions is constitutive of presence. The primal impression is not only not self-sufficient, it is a constitutive product rather than something with a constitutive contribution of its own. This more radical claim is, for instance, brought to light in Husserl's idea that the point of departure, rather than being the primal impression (or primal presentation), is the empty anticipation:

> First there is an empty expectation, and then there is the point of the primary perception, itself an intentional experience. But the primary presentation comes to be in the flow only by occurring as the fulfillment of contents relative to the preceding empty intentions, thereby changing itself into primal presenting perception. (Husserl, 2001, 4)

In short, the now is constituted by way of a protentional fulfillment (Husserl, 2001, 4, 14). Occasionally, Husserl even describes the matter in a way that doesn't mention the primal impression at all:

> Each constituting full phase is the retention of a fulfilled protention, which is the horizonal boundary of an unfulfilled and for its part continuously mediated protention. (Husserl, 2001, 8)

5.4 The Return of the Primal Impression

Taking Husserl's considerations in the Bernau Manuscripts as inspiration, let us reconsider the question that was also at the center of Derrida's and Henry's criticisms, namely the status of the primal impression. We propose to develop the analysis in the direction of genetic and enactive phenomenology.

If we remain with a static phenomenology, the notion of the primal impression plays an important role in the structure of time-consciousness. If, however, we take a more genetic view, the notion of an isolated primal impression seems to be an abstraction and not something that exists in itself. As we have seen, Husserl himself and some of his commentators indicate just this: that the concept of the primal impression is an abstraction. As Klaus Held (1966, 19) puts it, "from a phenomenological perspective, there is no such thing as an infinitely short momentary perception"—that is, experientially there is no such thing as an isolated primal impression. On the other hand, however, one could argue that there must be something like a limit or division between retention and protention, aspects which do characterize our experience, but which need to be differentiated.

Lanei Rodemeyer (2006, 33) suggests that primal impression might be considered an overlap between retention and protention. In that case, too, it is nothing in itself but the product of retention and protention, and a paradoxical one, since as an overlap it seemingly must be both retention and protention at once. Rodemeyer suggests that Husserl is consistent in conceiving of the experienced now as more than a mere point—"the experiencing now can never be atomized" (2006, 34). This is certainly right, but we shouldn't forget that Husserl doesn't equate the experiencing or the experienced now with primal impression. Rather, in his view the experienced now has the triadic structure of protention–primal impression–retention.

Any momentary phase of consciousness, which itself is an abstraction, is composed of protention–primal impression–retention. Primal impression is not a momentary phase of consciousness—it's part of the structure of any momentary phase. In that case, it is something like an abstraction within an abstraction—it's the structure of a piece of consciousness that has been lifted out of the flow. It is the part of the structure that focuses on the now point of the temporal object. But this focus is not equivalent to a conscious attention, since any conscious attention would itself, in any momentary phase, have the structure of a momentary phase of consciousness, which would include a primal impression.

Let's widen the scope of the discussion. Primal impression is supposedly the consciousness of the now point of the temporal stimulus (S)—for example, in Husserl's favorite example, the musical note that is currently being sounded, or more precisely, the current moment of the note that is present. Now with respect to describing what we experience, from the perspective of phenomenology it is inappropriate to appeal to neurophysiology, which tells us that there is always some delay or distortion introduced between the current moment of a stimulus as it objectively exists, and our awareness of it—a delay or temporal distortion introduced by the mechanisms of neural processing. That is, it takes time for the current moment of S to register through the neural processing and consciously appear as being now. Our experience of S as being now, in this strict momentary sense, is always after the fact—the result of a neurophysiological retention. One might say that our access to the present is always through a small bit of the past, or that we never experience the objective present as such.

These considerations are clearly bracketed out by Husserl, and we can effect this bracketing simply by saying that *the current moment of the note* refers to the current moment of the experienced note. It's not the note as objectively sounded, but the note as experienced. Without appealing to the objective processes of neurophysiology, however, we may still look to certain considerations in the neuroscience of movement, and do so in a way that is more than an appeal to analogy. As some have argued (Berthoz, 2000; Gallagher, 2005, 2011) the protention–primal impression–retention model applies to movement and nonconscious motor processes, as well as it does to consciousness. We could say that human experience and human action are both characterized by a ubiquitous temporality. In this regard, when we look at action we can say that at any one moment the body is in some precise posture—as captured by a snapshot, for example—but that posture is a complete abstraction from the movement since in each case the body is not posturing from moment to moment, but is constantly on the way, in the flow of the movement such that the abstract postural moment only has meaning as part of that process. One could argue that *objectively speaking*, at any moment the body actually is in a specific posture. But if that postural moment is anything, it is the product of an anticipated trajectory, of where the action is heading. Furthermore, we can define that abstract postural moment only when it is already accomplished—but that means, only in retention, and as an end point of what had been a movement characterized primarily by anticipation.

We should think of consciousness in the same way—as Husserl does—as a flow, where it is intentionally directed in such a way that when I am hearing the current note of a melody I'm already moving beyond it, and such protentional/anticipatory moving beyond is already a leaving behind in retention. What we have as the basic datum of experience is a process, through which the primal impression is already collapsing into the retentional stream even as it is directed forward in protention. Hearing a melody (or even a single note in some context—and there is always a context) never involves hearing a currently sounded note (or part of a note), *and then* moving beyond it; rather, the "and then" is already effected, already implicit in the experience.

One way to express this is to say that talk of any one of the three components in isolation runs into an abstraction. Our experience of the present is always dynamic because it is always structured by protention–primal impression–retention. Prereflectively, consciousness has this structure. There is no impression of the present taken as a knife-edge; rather, as Husserl suggests, primal impression is already fulfilling (or not) protentions that have already been retained, and in doing so is already informing the current protentional process. This structure constitutes a specious present, and our experience of that is what one might call a *secondary* impression—that is, not a primary impression of a knife-edge present, but a secondary (constituted) impression of a specious present. What I experience in this immediate now is a complex presence.

To put it differently, the proposal is not that we should eliminate the primal impression. The point is rather that we should abandon the idea that primal impression is a direct, straight, and simple apprehension of some now-point of S that is unaffected by retention and protention. If I perceive a currently sounding note, for example, what I perceive is already modified by my just-past and passing awareness of whatever came directly before. In that sense, primal impression is already modified by the retentional performance of consciousness. There is no primal impression that is not already qualified by retention. It is not that in a now phase of consciousness I have a retention of a past phase *plus* a primal impression of a current S. It is not an additive function. The full experience of a melody is not well described by saying that I first experience (in primal impression) note A, and then (in a new primal impression) note B, as I retain note A. Or more precisely, the full experience is not given by

… iA … followed by … iB plus r[iA] …,

where i = primal impression and r = retention.

Rather, iB is already qualified (impacted, transduced, modulated) by the just-previous experience. For example, in Bach's *Concerto in B Minor* the note B minor sounded at a certain point will sound different from the note B minor sounded at a certain point in Vivaldi's *Concerto in B Minor*. So the primal impression of B is never simply iB; it is iB that works its way through r[iA], that is, through the relevant retentional train of experience. That means that iB would be a different experience if it were preceded not by iA, but by i[~A], just as much as r[iA] would have to be different if in fact it were r[i{~A}].

Consider further the effect of protention (p). First, the primal impression of A, (iA), when occurrent, is producing a determination of what my protentional horizon is—for example, a protention of B … C … D …, and so on. That is, whatever I anticipate must be modified by what I am currently experiencing. Furthermore, the primal impression of B, (iB), when occurrent, is already qualified by the previous protention (currently retained), whether that was a protention of B (now fulfilled), or something else (now unfulfilled). Generally speaking, then,

(1) primal impression constrains the current protention, and
(2) primal impression is constrained by the previous protention.

With respect to (2), this means that the occurrent primal impression is partially either the fulfillment or lack of fulfillment of the previous protention. With respect to (1), the primal impression provides partial specification of what I am anticipating. Primal impression includes a protentional specification.

Again, it is not

… iA *plus* p[B … C … D …] …,

which is then simply followed by

… iB *plus* r[iA + p{B … C … D}] *plus* p[C … D …] ….

Rather, the primal impression of B, (iB), already contains specification of the previous (now retained) protention (with continuing reference to C and D as forthcoming) as fulfilled (or as the case may be, as unfulfilled). My occurrent primal impression of B would be different if instead of a protention of B … C … D in the previous phase of experience I had anticipated silence or a different note. The primal impression of B confirming a previous protention of B is different from the primal impression of B disconfirming a protention of ~B.

One objection to this may be that we have confused the content of experience with the formal temporal properties of the experience. That is, someone could object that the analysis of time consciousness, which is about how one experienced note follows another, is not about the difference between how we hear Bach and Vivaldi. But this objection ignores the fact that what I experience has an effect on the temporality of my experience. If, for instance, I am bored by Bach and find Vivaldi vivacious, then Bach's *Concerto in B minor* will seem to drag on—time will seem to slow down—in contrast to my listening to Vivaldi's concerto. If I'm hungry, or mad, or in pain, retentionally and protentionally experience will be temporally different from my satiated, happy, pain-free listening experience. To that extent, content has an effect on the specifications of the formal structure. As Merleau-Ponty suggests, there is an "influence of the 'contents' on time which passes 'more quickly' or 'less quickly,' of *Zeitmaterie* on *Zeitform*" (1968, 184).

Temporal masking is another example of contents determining the experienced temporal order of things. For example, the tonal arrangement of sounds presented in a sequence can affect the perception of that sequence. If in the sequence of tones ABCDBA, the tones A and B are of a particular low frequency, the order of C and D will be masked. That is, you will not be able to distinguish the order of C and D. You can also vary the tones A and B, so that C will appear to come before D, or so that D will appear to come before C (see Bregman & Rudnicky, 1975). But it's not simply that the conscious retention of A and B determines the phenomenal order of C and D, since the later sounds of B and A are also required to get these effects. That is, the sounds that follow C and D in the objective sequential order will also determine the way C and D play out on the conscious level.[6]

Consider, as another example, that in many cases the meaning of a word in a sentence is deferred until a phrase or the sentence is complete, so that the word itself, as it is read or sounded, motivates a certain anticipation toward the fulfillment of its meaning. The word "cases" in the previous sentence is an example. It doesn't refer to containers (e.g., cases of wine), or to grammatical cases (cases of a noun or pronoun); but its meaning is already anticipated before that ambiguity gets resolved, and the remainder of the sentence fulfills that anticipation. If the content of the paragraph that preceded this paragraph had been about visiting a wine store, or about a grammatical point, then it could have biased my anticipation of the meaning of the word "cases." Such things often slow down our reading and make us go back over text to get clarification.[7] Of course one can still say that there is some level of formal temporalization that remains invariant—whatever the content, or whatever the phenomenological velocity or experienced serial order, or the implicit temporality of the object itself, I do experience a sequence in which some S precedes another. But which S that happens to be, and what order it comes in, and how fast it happens to swim by, make all the difference in experience.

In one respect we can say that primal impression targets the current moment of the object S—but not without already being infected by (being influenced by) the retentional train of what has just happened, and by the protentional horizon of whatever is anticipated. To talk of primal impression as intuiting the current moment without insisting on the effects of retention and protention already at work, shaping primal impression, is to talk of an abstraction. If we say that primal impression is part of the structure of the living present—that's true, but it's not enough. We also have to say that the primal impression is itself structured by its very dynamic participation in its relations to retention and protention (and vice versa, of course). My primal impression of the current moment is influenced by the retentional train—it's not just the abstract beginning point of that train as if the business of retention was strictly about the past and had no influence on the present. In addition, my primal impression of the current moment is already influenced by protention—not only the current protention (although perhaps that one especially), but also by previously retained protentions.

It thus starts to look like time-consciousness has a fractal character. Having distinguished primal impression from retention and protention, in the protention–primal impression–retention structure, any closer examination of primal impression (or retention or protention) finds that same structure repeated—again, not in an additive way, but in a kind of fractal effect. This is not an overlap (as Rodemeyer suggests), but an effect that multiplies itself in such a way that any attempt to define primal impression in itself always finds the effects of retention or protention already included. It is consistent with Husserl's indication that "it pertains to the essence of conscious life to contain an intentional intertwining, motivation and mutual implication by meaning," although whether it does so "in a way which in its form and principle has no analogue at all in the physical" (1977, 26) is an issue that we set aside here (see Thompson, 2008, 356, for discussion).

Here, perhaps, is one way to think of this, and it's why we suggest the image of the fractal: the structure of the living present—the now phase of consciousness—is protention–primal impression–retention. But each element also reflects this structure again—primal impression, by itself, is an abstraction, but to think it *in* this structure is to think it *with* (or *having*) this structure—primal impression, in its intentional functioning, reflects the retentional and protentional components, and vice versa.

What this amounts to is that there is no primal impression—no current intuition of the present S—without it already being anticipatory (on the basis of what has just occurred), so that my primal impression of the present is already involved in an enactive anticipation of how S will work out. Protention, primal impression, and retention are in an *enactive* structure in regard to S in the sense that a certain anticipatory aspect (already shaped by what has just gone before) is already complicating the immediacy of the present. Consciousness is not simply a passive reception of the present; it enacts the present, constituting its meaning in the shadow of what has just been experienced and in the light of what it anticipates.

This view is not equivalent to treating primal impression as an "overlap"; it doesn't deny that there is a primal impression; it doesn't conceive of primal impression as simply the passive product of retention and protention; but it does conceive of retention and protention as contributing to the constitution of primal impression (and vice versa)—consistent with the idea of a self-constituting flow. The unity of consciousness at this level is not a static unity, or an additive kind of unity, but an enactive unity. There is no primal impression without retention and protention; there is no retention or protention without primal impression.

What the primal impression is, then, and how it relates to retention and protention, are not independent from the intentional nature of consciousness, or from the specific content that we experience. This means that the temporal structure of consciousness should be considered as in-the-world, and in very pragmatic terms. We take this to be a positive way to account for the temporality of consciousness that lines up well with Husserl's conception of embodied experience as an "I can." In contemporary terms, we can think of this as an *enactive* phenomenon. My hearing of the melody, for example, is not a passive reception of the sound. My hearing of any one note is a hearing directed toward the next note—that is, I only hear one note as the anticipation of the next note, or the next bit of silence—as something that is leading somewhere—and I never hear it just on its own. Again, as Husserl put it, "every living is living towards (*Entgegenleben*)." This anticipatory intentionality is not an apprehension of an absence (*entgegenwärtigung)*, in the sense that it is directed toward the not-yet; it is rather an apprehension of the possibilities or the affordances in the present, of what S *can be* for my experience, possibilities that will be fulfilled or not fulfilled as our enactive perception trails off in retention.

The important question, in contrast to the inclinations of Derrida and Henry, is not whether any one element has priority. Primal impression, retention, and protention are not elements that simply add themselves to each other. They are rather in a genetic relation; they have a self-constituting effect on each other.

Moreover, they, together, constitute the possibility of an enactive engagement with the experienced world (the object, the melody, etc.). Just as I perceive the hammer as affording the possibility of grasping it, or in a different circumstance, as affording the possibility of propping open my window, I likewise perceive the melody as affording the possibility of dancing or sitting in peaceful enjoyment, and so on. The point, however, is not about hammers versus melodies. It's about the temporality of affordances and enactive engagements. Nothing is an affordance for my enactive engagement if it is presented to me passively in a knife-edge present; that is, nothing would be afforded if there were only primal impressions, one after the other, without protentional anticipation, since I cannot enactively engage with the world if the world is not experienced as a set of possibilities, which, by definition, involves the not-yet. And just as nothing would be possible if there were only primal impressions without a retentional-protentional structure, so too if there were no primal impression. If there were only retentions, everything I experience would already have just happened; we would be pure witnesses without the potential to engage. If there were only protentions, there would only be unfulfilled promises of engagement. Meaning itself would dissipate under any of these conditions.

Thus, the enactive character goes all the way down, into the very structure of time-consciousness, and one doesn't get this enactive character without an integration of all three components. What we are suggesting here is that experience has an enactive character, not only on the act or action level, but in its most basic self-constituting, self-organizing level, in its very temporal microstructure.

Notes

1. Following Varela, Thompson, and Rosch (1991), we take "enactive" to signify that perception (and cognition more generally) is characterized by a structural coupling between the agentive body and the environment, which is both physical and social, which generates action-oriented meaning.

2. In James (1890, Vol. I., 609–10) one finds a related account. For a comparison of Husserl's and James's philosophy of time, cf. Cobb-Stevens (1998) and Gallagher (1998).

3. For a criticism of this idea, cf. Zahavi (1999 and 2003).

4. Henry in *Phénoménologie matérielle* describes Husserl's *Vorlesungen zur Phänomenologie des inneren Zeitbewußtseins* as the most beautiful philosophical work of the twentieth century (1990, 31).

5. We note some shifting terminology here. In many other places, Husserl makes it clear that while acts of recollection or expectation are certainly re-presentational acts (*vergegenwärtigenden Akten*), retentions and protentions are not. Perhaps we can attribute this slippage in terminology to the fact that the Bernau Manuscripts are working notes rather than a finished document.

6. The effect here is similar to the *phi* phenomenon, where the color of a dot that appears later has an effect on my experience of the apparent color of the apparently moving dot.

7. Other examples of effects of content on experienced temporal sequence can be found discussed in Gallagher (1998).

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6 The Phenomenal Continuum

Barry Dainton

6.1 Making Sense of Temporal Experience

Think of what it is like to see and hear a large firework rocket go off. Shortly after ignition, one hears the *whooosh* as the rocket streaks into the night sky, and a few moments later the loud BANG as it erupts into a rapidly expanding shell of glittering, colored sparks. Change, succession and persistence seem to be vividly and immediately present in our sensory experience in cases such as these. We *hear* the rocket's whoosh and *see* the resulting light-trails spread across the sky (whose ongoing enduring *blackness* we also see: persistence can feature in our immediate experience too). So far, so familiar: few would deny that this is how our experience seems, and no one would deny that we often talk and think as though we see and hear change and succession ("I saw him sitting still"; "I saw her car approaching"; "I heard the wind roaring"; and so forth). The conundrums and controversies begin as soon as we try to make sense of any of this. If we really are capable of directly apprehending temporally extended phenomena, how is this possible? What must our consciousness be like—what features and structures must it possess—for this to be possible?

Abstracting from the many nuances and points of detail, the main approaches to the problem of experienced change fall into three categories.

Some seek to sidestep the difficulties by denying that change and succession do in fact feature in our immediate experience.[1] Proponents of this view generally accept the familiar doctrine that our immediate experience is confined to a momentary (or near-momentary) present, while also maintaining that the contents of these momentary phases of experience are in fact entirely static or change-free, and then seek to explain away the appearances to the contrary. Some proposals in this category are ingenious and worthy of comment, but I will not be discussing them here.[2] Nor will I be discussing a more radical option. If it could be shown that experiences either do not exist, or are identical with physical states or processes that are themselves completely devoid of phenomenal features, then the problem of explaining or understanding our immediate experience of change would be solved at a stroke: if experience is ultimately unreal, so too is our so-called experience of change.

However, this radical reductionism (or nihilism) with regard to the phenomenal is wholly implausible, or so I believe, though I will not try to defend this view here. I want to focus instead those who believe that our experience of change, succession, and persistence is real and irreducible, and their attempts to explain how this can be.

These explanations fall into two general categories, which elsewhere—for example, Dainton (2008, 2010b)—I have labeled "extensionalist" and "retentionalist."[3] Since both camps accept that change features in our immediate experience, they also accept that such experience is *not* confined to a momentary "now"; they hold, rather, that it extends over a brief interval (or what seems to be such), usually known as the "experiential" or "phenomenal" or "specious" present. Despite some misgivings, I will go with the latter terminology here. Although the apparent duration of a typical specious present is generally taken to be quite small, it is most decidedly nonmomentary: it is enough, for example, to encompass the whoosh of a rocket, or the flight of a shooting star. The key difference between the extensionalist and retentionalist camps lies in how they conceive of the relationship between the specious present and ordinary clock-time.[4]

Extensional theorists take the specious present to extend through ordinary time in much the way that it seems to. In contrast, although retentional theorists agree that the contents of a specious present appear to be temporally extended—and *are* temporally extended, for direct realists—they hold that the acts or episodes of experiencing in which these contents are apprehended are themselves objectively momentary.[5] The two views are depicted in figures 6.1a and 6.1b. The horizontal rectangle in figure 6.1a represents a brief, temporally extended "chunk" of a stream of consciousness; this stream-phase is a single extensional specious present. The corresponding rectangle in figure 6.1b represents the content of the depicted specious present; the single retentional specious present is itself depicted by the thin vertical line: this momentary episode of experiencing carries the seemingly extended

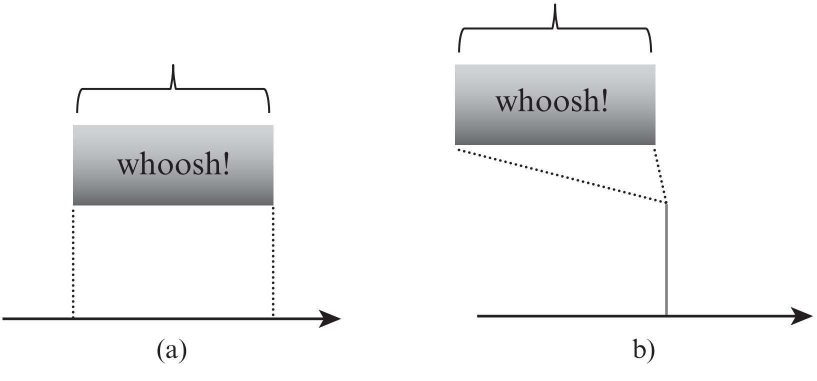

Figure 6.1
(a) A single extensional specious present; (b) A single retentional specious present.

content. The brackets above the rectangles indicate that the contents within each specious present are phenomenally unified; that is, they are experienced together. It is important to note the distinctive character of this unity. Although the contents so unified are apprehended *together*, they are *not* experienced as simultaneous—the contents within a single specious present seem to occur in succession.

These very divergent conceptions of individual specious presents give rise to equally divergent conceptions of the composition of streams of consciousness, which both camps agree should be thought of as a succession of specious presents. Retentional streams of consciousness—I will use this expression, and its extensional analog, as shorthand for "streams of consciousness as construed by retentional theorists"—are composed of closely packed momentary episodes of experiencing, a selection of which is shown in figure 6.2b, where each vertical line depicts a distinct instantaneous episode of experiencing. To avoid unrealistic repetitions or duplications, retentional theorists usually hold that contents in neighboring specious presents are apprehended under different "temporal modes of presentation." In a simple case, if you were to hear the succession of tones C–D–E, C would initially appear as fully present. Although this C-tone also features in subsequent specious presents, in these it is not represented as fully present, but under the temporal mode "less present" (or "more past").

Extensional streams are most plausibly construed as a series of *overlapping* specious presents, a few of which are shown in figure 6.2a. This "overlap extensional model"—see Foster (1979) and Dainton (2000)—is the version that is best able to accommodate the seamless continuity our typical streams of consciousness exhibit (in the eyes of many, if not all). The vertical separation shown in figure 6.2a serves no purpose other than to leave the overlap structures more clearly visible than they would otherwise be. The overlaps in question consist of *part-sharing*. If the experienced succession of tones C–D unfolds over two specious presents SP_1 = [C–D], SP_2 = [D–E], the D-phase in the former is numerically identical with D-phase in the latter.

Elsewhere I have explored some of the different variants of retentional and extensional models in more detail and explained why I think the extensional model is the more plausible—see Dainton (2000, chapter 7, and 2003, 2008). I will not be repeating these

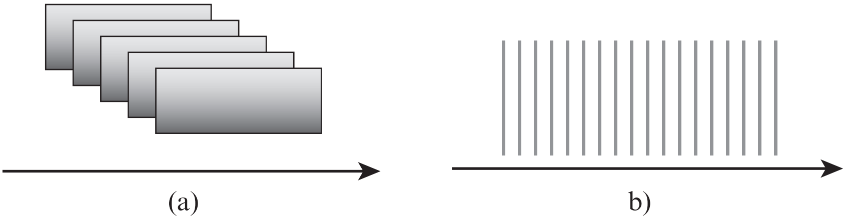

Figure 6.2
(a) An extensional stream of consciousness; (b) A retentional stream of consciousness.

arguments here; rather, my primary focus will be on a cluster of issues relating to the structure and composition of our streams of consciousness over very brief temporal intervals.[6] But before proceeding to the main business, I will venture just one observation. Irrespective of their other features, retentional models are quite complex—in a way my brief presentation here does not begin to do justice—but also profligate. Whereas extensional streams of consciousness are straightforwardly one-dimensional entities, retentional streams are in an important respect *two-dimensional*. For if the retentional theorists are right, a stream of consciousness that extends through an hour of ordinary clock time has an additional degree of temporal extension: a distinct retentional specious present exists *at each distinct moment* over the course of this hour, and each of these specious presents has a complex temporal structure—each contains experienced change, succession, or persistence. This additional dimension may be short-lived (objectively speaking) and only of the phenomenal variety, but it undeniably has a temporal character, subjectively if not objectively.

One might well find this objectionable, and for different reasons. Is it really possible for a momentary episode of experiencing to have a phenomenal content that vividly presents change and succession—such as the *whoosh* of a rocket or the *bang* of an explosion? To claim that this is *logically* impossible would surely be rash: perhaps there are possible worlds where the laws of nature are quite different from our own, and in which experience is distributed through objective time (or what might pass for such) in all manner of peculiar fashions. But the notion that this is a real possibility for *our* experience, in *our* universe, can easily seem implausible. All the evidence suggests that experiential and neural processes are closely connected, and neural processes occur at finite speeds—for example, a typical neuron can only fire about 200 times per second, and action potentials are transmitted though axons at rates varying between 1 and 100 meters per second. The clock cycles and internal signal speeds of everyday home computers are faster by far. If the physical processes that produce our experience are as slow as this, isn't it ludicrous to suppose they could generate the dense successions of instantaneous conscious states—each possessing its own complex, internal temporal features—the retentional model requires?

Although I have considerable sympathy with this line of thought, on balance I think this conclusion is premature. For as things currently stand, I do not think we know enough about the relationship between the physical and the phenomenal to pronounce with confidence on the kind of experiences that momentary (or very nearly momentary) physical systems in our universe can generate. After all, if the models taken seriously by string theorists are along the right lines, there is a great deal of concealed *spatial* structure in our universe: each dimensionless point in ordinary three-dimensional space is attached to a small but complex spatial structure that extends over six (or seven) additional "hidden" spatial dimensions (see figure 6.3). If spatial structures of this kind are possible in our universe, the odd-seeming temporal structures and compressions posited by retentional theorists cannot be dismissed as *wholly* absurd or beyond the pale.

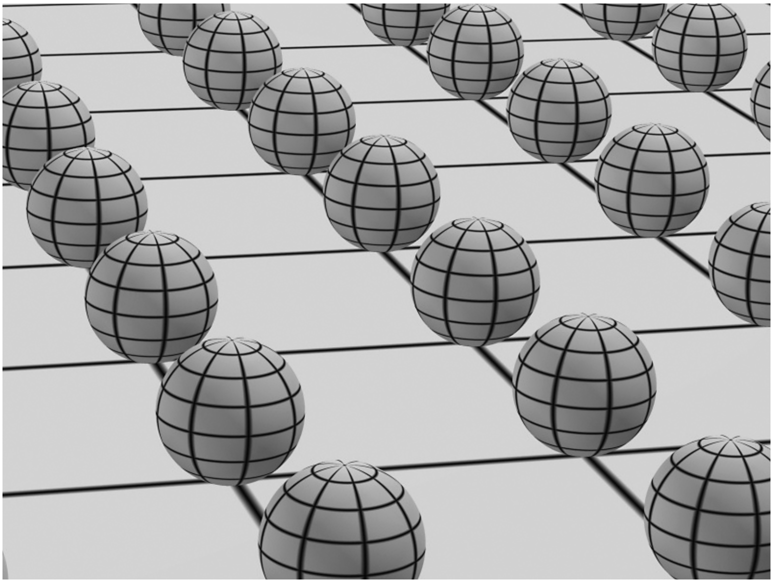

Figure 6.3
A standard way of providing the additional spatial dimensions posited by string theorists with pictorial flesh.

But there is another point to note in this connection. Those physicists who are prepared to countenance the hidden additional dimensions of string theoretical models only do so because they see no other way of reconciling general relativity theory and quantum theory. Integrating these hard-to-reconcile theories into a single theoretical framework is what justifies the postulation of the additional degrees of complexity. Retentional models *also* involve the postulation of what is—in effect, an additional dimension, albeit of the temporal kind.[7] For this additional ontological complexity to be justified, these retentional models need to be supplying something which cannot be had at less cost. But are they? The competing extensional model accounts for the relevant data—our experience of change and succession—in a far less costly way: there is no need for either the additional temporal dimension, nor the temporal modes of presentation to which most retentional theorists appeal. So if the extensional approach is viable, why take the retentional approach seriously? Even if the structures it posits are logically possible, we lack sufficient justification for supposing they obtain in our world. Or so extensional theorists can reasonably argue.

6.2 Content and Circularity

Why opt for the more complex and costly position retentional approach at all, given the extensional alternative? If, as retentionalists generally suppose, phenomenal unity is by its nature confined to the momentary present, then the retentional models are the only game in town. Extensionalists respond by pointing out that while it is often *assumed* that the unity of consciousness is a purely synchronic affair, explicit and effective arguments for this assumption are thin on the ground. The retentional approach would almost certainly be vindicated if some of the more extreme versions of presentism turn out to be true—our temporal experience cannot have temporal extension if the universe itself is strictly momentary. But although there has been a renewed interest in it, presentism remains a highly controversial view of time, one many regard as untenable.[8]

In two recent papers, Michael Pelczar has opened up a new front. Pelczar's main aim is to establish that it is at least *possible* for a subject to experience change or succession without thereby having a succession of experiences. As Pelczar appreciates, this is tantamount to establishing that it is possible for change or succession to be experienced within the confines of retentional specious presents. En route to his main conclusion, Pelczar also delivers some criticisms of the extensional approach. The latter provides a problematic conception of (what we might term) the *temporal microstructure* of the phenomenal continuum; if we want an adequate account of the relationship between our streams of consciousness and their elementary constituents, we must look instead to some version of the retentional approach, or so Pelczar argues.

Now, as I noted in section 6.1, granting that it is (logically) possible for momentary experiences to possess contents that seem dynamic does not, in itself, do significant damage to the extensionalist's cause: the greater simplicity of extensional accounts is reason enough to prefer them, at least in the absence of countervailing considerations. However, Pelczar's microstructural arguments have the potential to do a good deal of damage—more perhaps than he realizes. While I do not think his arguments ultimately succeed, addressing them is instructive, in more ways than one.

In developing his case, Pelczar relies heavily on what he holds to be a universal feature of experience in all its modes, a feature he calls "subjective dynamism." He suggests the content of every (human) experience is invariably of *something* following *something*. Such a content can represent a change—an object moving from A to B, a tone rising in pitch—but it needn't, for it can simply represent something *remaining unchanged* for a few moments. The claim is that all human experience is necessarily dynamic in one of these ways: we never have an experience as of a strictly durationless and entirely static state of affairs; indeed, we cannot conceive of our experience taking such a form. Although some might want to question the doctrine that human experience is *essentially subjectively dynamic* (as we might put it), the doctrine does have good deal of plausibility, and for present purposes I propose to accept it.[9] What I will be focusing on is what Pelczar goes on to do with the doctrine: he argues that while retentional models can accommodate subjective dynamism without any difficulty, extensional models cannot.

One of his objections runs thus:

> The real problem with Dainton's account is one of circularity. If all experiences are subjectively dynamic, it is no use trying to understand a subjectively dynamic experience as a sequence of suitably related experiences, since each of the related experiences must itself already be subjectively dynamic. One might as well define a line segment as a sequence of suitably related shorter segments. (2010a, 52–3)

We can agree that anyone who defines a line segment in terms of other (shorter) line segments is not being as informative as someone who defines a line segment in different and independent terms. So is Pelczar complaining that the extensional overlap model purports to provide, but in fact fails to deliver, a *reductive* account of subjectively dynamic experience—one that explains how dynamic phenomenal features arise from nondynamic phenomenal features? If so, the complaint is misplaced.

The extensional overlap model—at least as I have elaborated and defended it (2000, 2001, 2008)—was intended to be a phenomenological account of the most basic temporal features of our consciousness. I certainly made some claims about the ways in which briefer experiences are interrelated when they form parts of more extensive streams of consciousness, but in so doing I took the dynamic phenomenal features of stream-phases as a basic datum, and made no attempt to explain these features in other terms. Indeed, these same dynamic features play a crucial role in the overlap model. Consider a specious present consisting of a succession of two tones, C-D. The relationship of diachronic co-consciousness is a symmetrical relationship, so in addition to C's being co-conscious with D, D is also co-conscious with C. So why is it that we hear C flowing into D, rather than D flowing into C? The answer, I suggested, lies in the fact that tones such as C and D possess an intrinsic directional dynamism:

> Contents that are symmetrically joined by co-consciousness must themselves possess an inherent directional dynamism. The C-tone is not a static auditory quality, but a flowing quality, likewise for D and E. This immanent flow is an essential ingredient of any auditory content, just as essential as timbre, pitch or volume. It is because these contents possess this inherent and directed dynamic character that we hear C as enduring for a brief while and then seamlessly running on into D, which in turn runs on to E. The same applies to bodily sensations, such as pains or tickles, as well as to olfactory and gustatory contents. It applies to the visual case also. Suppose that I see a bird fly overhead. It crosses my field of vision in a second or so. I do not merely see the bird occupying a succession of different locations at different times. I see the bird moving. This perceived movement is itself a dynamic and directed intrinsic feature of my visual experience, and just as essential to it as colour, size or shape. (2001, 105)

In *Stream of Consciousness* I argued along the same lines, and in similar terms. The solution to the puzzle of why a perceived ball's movement seems to unfold in one temporal direction rather than the other lies in the fact that "the phenomenal contents of these experiences are temporally patterned: they possess an internal temporal organization, an intrinsic and directed animation" (2000, 176). Perhaps I could have made it clearer or more explicit, but in these writings I took dynamism and flow to be intrinsic and irreducible phenomenal features of our experience.

6.3 Reductio?

So the overlap model is immune to the charge of circularity, at least in the form just discussed. But in other passages Pelczar develops the charge in a rather different way:

> The extensional account of phenomenal change may be adequate for experiences as of jumpy or discontinuous change, but it fails as an account of experiences as of smooth or continuous change … when I listen to a steadily ascending musical tone, my experience does not decompose into a series of briefer sub-experiences, unless these are themselves experiences as of smoothly ascending tones that fit together to form the overall sound experience. There is no point trying to apply the extensional analysis to these sub-experiences, since the same problem will arise again: the only series of experiences that constitutes any experience as of smooth change is a series of experiences as of smooth changes. (2010b, 279)

Pelczar's point needs a little unpacking. What are the *briefest* of experiential parts in an extensional stream of consciousness? Given the standard assumptions that time is composed of an infinite number of durationless instants, and that (truly or maximally) continuous processes are similarly structured, the briefest parts of a continuous stream of consciousness will themselves be strictly instantaneous. For extensionalists, if an episode of experiencing has a dynamic content it must possess some temporal extension, which means that a strictly momentary experiential episode *cannot* contain dynamic contents. But suppose the plausible-seeming essential dynamism claim is true, so that each and every experiential content contains some form of succession. The extensionalist might now seem to be in serious trouble.

First of all, it looks as though the extensional theorist has no option but to hold that experiences whose contents are dynamic are composed of experiences whose contents are entirely static or change-free. In which case, it turns out that extensionalists *are* in fact committed to a highly implausible reduction of dynamic phenomenal features to static phenomenal features. If I read him right, this is the problem to which Pelczar is drawing our attention in the passage above.

However, there is a second and (perhaps) even more dangerous difficulty lurking in the vicinity. As we have just seen, for extensionalists, strictly momentary experiences will not and cannot possess dynamic contents. But according to the essential subjective dynamism doctrine—which I am currently taking to be true—all experiences possess dynamic contents, and do so necessarily. It follows at once that in the extensional framework, momentary *experiences* cannot exist at all. If the briefest and most basic parts of a stream of consciousness cannot exist, then neither can streams themselves. It seems the extensional approach reduces to absurdity.

Faced with this catastrophic result, the retentional approach—which is founded on the notion that momentary episodes of experiencing can and do possess subjectively dynamic contents—may well start to look more appealing, and Pelczar is drawn to it for this reason. But bearing in mind that this approach is not without difficulties of its own, it would be unwise to follow him in this direction before examining the responses available to the extensionalist.

6.4 Subjective Dynamism: A Brief Assessment, and a Qualification

A key element in the menacing *reductio* is the doctrine of essential subjective dynamism. If we could reject this doctrine, at least one of the extensionalist's problems would be no more. After all, if it is possible for experiences to have contents that are nondynamic in character, the most obvious candidates for having such contents are experiences that are momentary, and if the extensionalist were in a position to acknowledge the existence of momentary experiences, there would no longer be any danger of extensional streams of consciousness vanishing into thin air. But it remains the case—for better or worse—that the dynamism doctrine has a great deal of plausibility. There is no denying that many of the most common and prominent contents to be found in a typical human stream of consciousness—the sensory, perceptual, and imagistic ingredients—appear to be deeply dynamic. When we observe the smooth motion of a bird gliding through the sky, the contents of the resulting experiences appear to be motion-involving all the way down. Even the briefest discernible phases of these visual experiences have a content that presents (or represents) *a bird in motion*. This is one reason for supposing that such contents cannot be reduced to contents that are entirely static and motion-free: motion is a fundamental and irreducible feature of much visual experience.[10] Analogous considerations hold in the case of auditory contents. When we listen to an extended tone, even its briefest phases have some apparent duration, and these phases invariably have dynamic contents: of a *tone continuing on* (in a simple instance). Indeed, an auditory sensation entirely lacking in duration seems inconceivable. As is evident, the subjective dynamism claim is not to be abandoned lightly.

However, even if many forms of experience are essentially dynamic, it may be that some forms are not. The doctrine that change and succession are essential features of our consciousness—and hence that consciousness itself is essentially temporal in character—has a long history and is widely accepted. But there are dissenting voices, among them that of Ralph Walker. In his *Kant* he poses the question: "If non-spatial forms of experience are possible, might non-temporal forms be possible as well?" and replies in the affirmative: "Certainly it is more difficult to imagine what they would be like. … But I think that with a little effort we can imagine it." (1978, 34) Walker goes on to outline a number of imaginary scenarios, some more extreme than others. In the more modest variants, subjects whose thoughts change as ours do inhabit entirely static and changeless worlds; in the more radical variants, the conscious lives of the subjects are static and changeless as well. In all of the scenarios, the subjects are able to see an array of solid three-dimensional objects (or what look like such) stretching out ahead of them. Some of these objects carry messages in the form of inscriptions whose meaning is apprehended by the subjects who are in a position

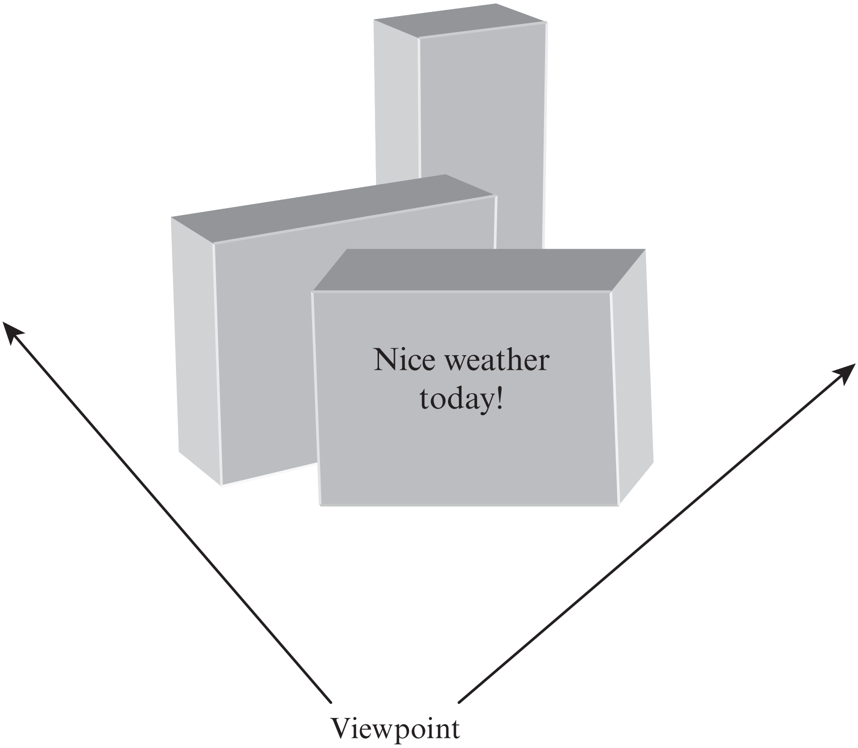

Figure 6.4
Life in a timeless world?

to read them—a situation of this sort is depicted in figure 6.4, which reveals what is seen by one particular subject. Walker concedes that life in a timeless universe would be very strange and limited, but it would nonetheless *be* a life:

> Life would not be exciting; but at least it would not be boring either. For us pleasure resides very largely in getting things done, not in having done them, and none of this would be available in our imaginary world. Aristotle thought that such an existence would be fun all the same; this may be doubted, but at least one could entertain a great variety of thoughts and a great complexity of mathematical argumentation, so long as one did it all at once. And tastes, after all, do vary. (1978, 41)

Walker does not dwell on the precise character of the experience of his timeless subjects—his primary concern is the characteristically Kantian one of establishing that it makes sense to suppose that the experience of these subjects can legitimately be construed as experience of an objective world. But it is not difficult to make explicit what Walker leaves implicit. The timeless subjects evidently have *visual* experience, and are capable of *consciously apprehending propositions*, whether in the form of their own conscious thoughts, or in the form of the inscriptions they can see on the objects in their environments. Is a visual experience whose content is entirely static and motion-free possible? Is the claim that visual experience could take this form an intelligible one? I think it probably is. Arguably, our experience takes this form when we view a strobe-illuminated scene. Doesn't a stroboscope *freeze* motion? An ordinary camera flash, used to illuminate an otherwise dark room, can provide us with a single, very brief, almost momentary-seeming visual experience whose content is entirely static. Of course, in the normal run of things these brief experiencings do not exist in isolation, but occur as parts of more extended experienced patterns (e.g., of darkness-LIGHT-darkness …), and it may very well be that our human sensory systems are incapable of delivering such contents in solitary form. But even if *we* are incapable of enjoying experiences of this type, it seems conceivable that there could be subjects who are not so constrained—subjects such as the inhabitants of Walker's imaginary world. And it is not only visual contents that can be so brief as to be seemingly instantaneous: think of what it is like to experience a needlelike pain.

The case of conscious thinking, or the conscious apprehension of meanings, is rather more difficult. First, because the phenomenology here is both more varied and harder to characterize with any confidence. Second, because the issue of whether meanings (or propositions) really are apprehended in consciousness is a very controversial one. We needn't enter this dispute here, because it is comparatively uncontroversial that we frequently have experiences that *seem* to involve the experience of meaning, such as whenever we engage in conscious thinking, or listen to a conversation, or read a newspaper. Now, some of these experiences seem to be dynamic in character—think of what it is like to absorb the content of prolonged rapid speech, or to apprehend the content of one's own thoughts when they are "voiced" in the acoustic imagination. But other apprehensions of meaning seem virtually instantaneous. Think of what it is like to take a glance at a short written sentence (such as the one shown in figure 6.4)—in such cases, isn't the content grasped as a whole, all at once? Conscious thought can be like this too: when the realization suddenly dawns that *yet again I've failed to reply to X's email* doesn't it do so as a whole, and all at once?[11]

So it may be that Walker's timeless subjects really are possible; a strong case can certainly be made for supposing that they are at least conceivable. For our purposes, however, the relevant lesson is that the contents of our streams of consciousness may well be heterogeneous. Whereas many of these contents are essentially dynamic in nature (perceived movements, extended tones), others are not (pinpricks of pain, quasi-instantaneous thoughts). Objectively speaking, the episodes of experiencing in which these nondynamic contents are apprehended are (very probably) not strictly momentary—they very likely occupy a brief interval of ordinary clock time. Subjectively speaking, the relevant experiences seem to possess *minimal* temporal breadth: they are very brief, they do not seem to persist through any clearly discernible interval of time, and—crucially—they do not appear to be composed of successive phases, and they are change-free. If such experiences exist, the essential subjective dynamism claim is not universally valid: it applies to some forms of experiences, but not all.

We may now have a more accurate grasp of the general temporal characteristics of the different forms of our experiences, but we are by no means out of the woods. Since Pelczar's challenge is directed at experiences whose contents are essentially and irreducibly dynamic, it does not apply to the nondynamic forms of experience we have been considering latterly. But even if some of our experience is not dynamic in character, there is no denying that the greater part of it is. The continuous flow of bodily sensation is irreducibly dynamic in character, as is the vast bulk of our ordinary auditory and visual experience, much of our mental imagery, and our conscious thinking—some of which is continuous in character, rather than staccato. And so a serious problem remains. How can the extensional theorist avoid holding that our streams of consciousness are ultimately composed of parts that are strictly instantaneous? For if their constituents *are* instantaneous then disaster looms: the extensional approach does not permit experiences that are momentary to have contents that are dynamic.

There is only one obvious way forward. Since the difficulty for the extensionalist derives from the assumption that the ultimate (or briefest) constituents of our streams of consciousness are strictly momentary, it is this assumption we need to scrutinize.

6.5 The Essentially Extended Continuum

The doctrine that continua such as space and time are composed of infinitely many densely ordered zero-sized points has been the orthodox view in recent years—ever since the work of Weierstrass, Dedekind, Cantor and others in the nineteenth century put the real number continuum on solid foundations. Prior to these advances, the real numbers were ill-defined, and there were serious and well-founded worries regarding the intelligibility of actual (as opposed to merely potential) infinities. But competing views have always had their defenders, and some of these views are relevant to the case in hand.

Relevant, but not always helpful. According to (one form) of *nonstandard analysis*, the orthodox conception is correct insofar as it recognizes that a continuum such as the geometrical line or Euclidean plane is composed of points, but it is mistaken regarding the *number* of points. Between every pair of locations on the real number line, *R*, nonstandard analysis recognizes a vast number of points over and above those that are ordinarily thought to exist in *R*. But while these additional points are certainly of use in some contexts, since they are zero-sized they will not help with our current difficulties. What the extensional theorist needs is a way of dispensing with the services of points altogether, not increasing their number. Is this a viable option?

It is indeed. The most obvious—and most obviously promising—way of eliminating points is to follow in the footsteps of Whitehead, Broad, Russell (for some phases of his career), and before them Aristotle, in adopting a conception of continua as *essentially* *extended*. A continuum of this sort is divisible into smaller or lesser parts—in some instances, endlessly so—but by virtue of the fact that it is *essentially* extended, no matter how small the parts are, they always have a finite, nonzero size. Ordinary objective space and time can be conceived in this way, and so too can phenomenal continua. For present purposes, what matters is that extensionalists who construe the temporal structure of our own streams of consciousness in this manner have a simple and direct response to Pelczar's *reductio*. If our own streams are essentially extended, they are not composed of strictly momentary experiences: irrespective of how finely they can be subdivided, their briefest experiential parts or phases will still possess some finite temporal extension. And since this is so, *all* their constituent parts or phases can possess dynamic contents in the extensional manner.

There are some analogies here with Zeno's paradox of the arrow. Over the course of its flight to its destination, at each instant the arrow occupies a specific location, filling a volume that exactly matches the arrow's own size. Since instants are durationless, and motion takes time, if we consider the state of the arrow at each these instants, it looks to be at rest. But of course the arrow's flight, as standardly conceived, is composed of nothing but a continuous series of such instants. How can the arrow be in motion, when at every point along its trajectory it is at complete rest? The standard response to Zeno runs thus: "Motion isn't something that takes place *at* a single point, it is essentially *interval*-bound; an object is in motion at a time *t* if it is at different locations at the times neighboring *t*. The intrinsic properties of the object at *t* itself are irrelevant to its state of motion." In a similar manner, the extensional theorist can hold that *experienced change* (or motion, or succession) is not determined solely by the phenomenal features our streams of consciousness possess at an instant *t*: what matters is the content and character the stream possesses over the brief interval in which *t* occurs. If this interval contains experienced change, then we can legitimately say that the relevant subject is experiencing change *at t*, just as we can legitimately say that the arrow is in motion at *t*, though in both cases the truth-makers of these claims essentially involve what is occurring around *t*. But there are also important differences between phenomenal and physical motion that need to be acknowledged. It may be legitimate to view an arrow's flight through physical space as being composed of a series of instantaneous and so motion-free states, but if a phenomenal continuum is essentially extended—as we are currently supposing—it cannot be regarded in an analogous manner: the briefest experiential parts (or phases) of a stream of consciousness of this kind will have some nonzero duration, and the contents of these brief phases will (in cases involving experienced change or movement) have an intrinsically dynamic character. Also, in the experiential case, the stream-phases in the immediate neighborhood of *t* are phenomenally unified—they are diachronically co-conscious. There is no obvious counterpart of this mode of unity in the case of purely physical motion.

Taking our own phenomenal continua to be essentially extended may provide extensional theorists with a coherent way of accommodating essentially and irreducibly dynamic contents over brief intervals, but it has other advantages too. Not least of these is sheer phenomenological plausibility. It is because so much of our experience does seem dynamic, down to the smallest intervals, that we can discern that the essential dynamism claim can seem so plausible; strictly momentary stream-phases play no obvious role in much of our everyday sensory experience. I suggested in the previous section that there may be some forms of experience that are not essentially dynamic—pinpricks of pain, sudden apprehensions of meaning, and the like. If so, then in the essentially extended scheme, these will have the status of (what we might call) *phenomenal atoms*: experiences of very brief but nonetheless finite duration that do not possess any smaller experiential parts. More on this shortly.

Should we conclude that *all* phenomenal continua are of the essentially extended type? Given that we are sure of so little about the relationship between the experiential and the nonexperiential, this would (probably) be premature—I suggested in section 6.1 that for all their peculiarity, individual specious presents of the retentional variety could nonetheless be logically possible. But for the purposes of meeting Pelczar's challenge, it is sufficient to establish that the essentially extended model is a genuine alternative, a way our own experience *could* be. If our own experience *is* of the essentially extended variety, then experience that is irreducibly dynamic in character poses no threat to the extensionalist. The various considerations—also outlined in section 6.1—that count against the retentional model can then come into play. Given the greater economy and simplicity of the extensional model, not to mention its superior consilience with a naturalistic view of the world, it is difficult to see why we should take the retentional model seriously, at least when we are in the business of considering the character and structure of experience in the real world.

Although the essentially extended conception resolves some issues, it also gives rise to new questions, some of which are challenging in themselves, and I will be addressing these shortly. But before moving on, it is worth registering a more general motivation for taking the essentially extended conception seriously: dispensing with the services of points and instants allows us to avoid the baffling conundrums to which acknowledging zero-sized entities inevitably leads. Consider, first, the spatial case. Anyone who holds that visual experience is composed of continuum-many dimensionless points faces some awkward questions. Since these points are zero-sized, they lack area or volume, so how can they have color? It might seem they can't, but if the basic constituents of our visual sensations are colorless, where do the colors we experience come from? In a different vein, what would happen if a single line of points stretching from the top to the bottom of your visual field were suddenly removed? The elimination has divided your visual field into two parts—it is no longer a continuous expanse of color—but would you notice? Given that the points are all zero-sized, how *could* their removal make any difference to the phenomenal character of your experience? These puzzles have diachronic analogs. Suppose, contrary to fact, that a momentary temporal slice of your stream of consciousness was annihilated three seconds ago. Would the character of your experience during the relevant period have been any different? Since the temporal slice was of zero-size (or temporal breadth), it is difficult to see how its absence could have made a discernible difference. Suppose three billion such slices were removed over the course of this three second interval; again, since each slice is of zero-breadth, it is difficult to see how their removal could impinge on the character of your experience.[12] At an intuitive level, it is not clear how a stream of consciousness can be *composed* of points if these same points can be removed in vast—infinite—numbers without discernible impact. Of course, there are ways of responding to these questions.[13] But by holding that phenomenal continua are essentially extended, and so point-free, these troublesome puzzles can be avoided altogether.

6.6 Durations and Variations

All essentially extended continua may have one feature in common—a rejection of zero-sized points—but in other respects they can differ considerably. The following are probably the most important areas of divergence.

1. *Minimum independent durations (MIDs)* When a continuum contains smaller or briefer parts, these parts may be able to exist by themselves, but they may not: depending on the case, the parts may only be able to exist in more extended wholes. The MID for a particular form of experience (and subject), is the briefest whole capable of independent existence.
2. *Homogeneity* As traditionally conceived, space is homogeneous. Its smaller nonzero-sized regions have the same intrinsic properties as its larger regions (its smaller parts are not any less *spatial*). The contents of visual fields can be similarly homogeneous: every part of a clear blue sky looks equally blue. Other continua are not homogeneous in this manner. At the macroscopic scale, water looks and behaves like a smoothly flowing liquid, but at the microlevel it consists of molecules that, taken individually, lack the properties characteristic of liquids. The performance of the movement of a concerto is a temporally continuous process, but the briefer phases are not all alike: they do not (usually) all contain the same notes, and some periods may be entirely silent.
3. *Mereological complexity* The number of smaller and/or briefer parts a continuum possesses; some continua are divisible into only a finite number of parts, others are divisible into an infinite number of parts (all of finite size).

These dimensions of flexibility are useful in the present context, because when it comes to the microstructure of phenomenal continua, there is a great deal that we do not yet know. I will limit myself to very brief observations on the first two headings, and spend rather longer on the third.

6.6.1 Minimum Independent Durations

There is some evidence for the existence of MIDs in our own experience. Although it is well established that brief stimuli—for example, pairs of 1 msec clicks or flashes of light—can be perceived *as* distinct when separated by as little as 30 msec, it would be a mistake to conclude from this that 1 msec flashes of light produce visual sensations that also have a duration of 1 msec. Research on the (equally well-established) phenomenon of visible persistence has revealed that very brief visual stimuli tend to give rise to visual experiences that are—objectively speaking—considerably longer: typically in the 100–200 msec range.[14] In a series of tests designed to distinguish the durations of auditory and visual stimuli and the durations of the resulting experiences, Efron (1970a, 1970b) concluded that there are minimal perceptual (or experiential) durations in vision of around 120–240 msec, and 120–170 msec in the case of audition. Since the contents of experiences of these MIDs are long enough to present succession or persistence, it seems that the experiences in question are not mereologically simple; rather, they consist of a succession of experiential parts (or phases) that are unable to exist in isolation. That there are MIDs of this order of magnitude may well be entirely contingent: MIDs may vary from species to species, and for all we know there may be subjects, perhaps merely *possible* subjects, whose experience is not constrained in this way at all. Alternatively, there could be subjects whose MIDs are considerably longer than our own. The distinction between MIDs and minimally brief or "atomic" experiences would be very much more obvious for such subjects than it is in our own case—though, as we shall see below, there are further complications here.

6.6.2 Homogeneity

Much of our experience seems to be mereologically homogeneous. When listening to a continuous tone, the briefer parts of the tone—to the extent that we can discern them at all—seem to possess the same phenomenal generic features as the more extended wholes of which they are part: the briefer parts have the character of *an auditory tone continuing on*. But perhaps this is not in fact the case. Phillips has argued (2009, chapter 7) that homogeneity may well fail at the smaller timescales. In the case of perceived movement, for example, although the second hand of the clock seems to us to be in constant motion, do we need to suppose that we are perceiving the hand as moving at particular speeds over very short intervals, such as a few nanoseconds? Given the limitations of our visual systems, this is not very plausible. A more economical alternative is that our visual systems represent the hand as simply *being in motion*, rather than moving at a highly specific (real-valued) angular speed. Hence Phillips's more general proposal: so far as short intervals are concerned, perceived objects possess purely *determinable* properties, but do not possess corresponding *determinate* properties.

The notion that anything—phenomenal objects or contents included—can be purely determinable will not be to everyone's liking; see Gillett and Rives (2005). But again, we needn't attempt to adjudicate this debate here: what matters is that the extensional approach has the flexibility to accommodate this divergence.

6.6.3 Mereological Complexity

Continua of the essentially extended kind may lack zero-sized points or durationless instants, but they nonetheless possess smaller constituent parts, and (in principle at least) they can do so in different ways. Some are infinitely divisible—they are such that every one of their proper parts also has proper parts. Others are only finitely divisible: continua of this sort possess *atomic* parts—constituents which cannot be further subdivided, and which differ from points and instants by virtue of *not* being zero-dimensional. We can label these two important types of continua "atomless" and "discrete," respectively.[15] The issue of whether *phenomenal* continua are atomless or discrete is, as we shall see, quite a complicated one. To start with, I will focus exclusively on the possible chronomereological structure of temporally extended phenomenal continua themselves, ignoring questions relating to the spatial subdivisions to be found in certain types of experience (e.g., our ordinary visual fields). I will also start off by leaving the relationship of phenomenal continua to ordinary objective time out of the picture; this simplifying assumption will be lifted in due course.

We saw earlier that there might well be exceptions to the essential subjective dynamism doctrine: there are certain forms of experience—pinpricks of pain, quasi-instantaneous visual experiences—that do not obviously house change or succession. If this is correct, then instances of such experiences may be "phenomeno-temporal atoms" (henceforth *PT-atoms*), defined as experiences that lack experiential proper parts and do not consist of a succession of distinct experiential phases.

However, as we also noted earlier, much of our experience, particularly our sensory experience, has a dynamic, flowing character, and does not (or does not obviously) consist of PT-atoms. It may be that continuous-seeming experiences of this sort are truly atomless, and hence infinitely divisible. This is certainly how, say, the experience of an extended violin tone, or smooth movement, usually *seems*: there is no obvious grittiness or grain in the contents of experiences of this ilk. Despite this, it could nonetheless turn out—in some cases if not all—that these dynamic contents do in fact have an atomic structure, even though this structure is not readily discernible. If so, then given that it seems unlikely that dynamic phenomenal features are reducible to their nondynamic counterparts, these PT-atoms will of necessity have dynamic contents. We thus need to acknowledge that two distinct types of PT-atom might both be realizable: those whose contents are nondynamic (e.g., pinpricks of pain, conscious thoughts), and those whose contents are dynamic (e.g., continuous-seeming auditory sensations or perceived movements). It seems quite conceivable that experiences possessing these differing mereological structures could coexist within a single stream of consciousness. A subject whose sensory experience is entirely atomless and so infinitely divisible could have conscious thoughts in the form of indivisible PT-atoms; perhaps there could be subjects for whom some forms of sensory experience are atomless and others are discrete.

We have been concentrating thus far on purely experiential structures. How do these correspond with the mereological structure of objective time? To make matters more concrete, let us consider first a single specious present, which (we can suppose) extends over an interval of one second, and focus on the experience E of a continuous-seeming auditory tone that extends over the entirety of this interval. If we assume that time itself is infinitely divisible, this one-second interval is divisible into an infinite number of temporal subintervals. Since each of these subintervals has a counterpart in *E* itself, from a purely objective perspective *E* also possesses an infinite number of subintervals. But does *E* possess *experiential* parts corresponding to each of these objective subintervals? If *E* is atomless, the answer is "yes": this brief stretch of experience has the same infinitely rich mereological structure as time itself. If, in contrast, *E* is discrete, then the answer is "no." In the latter case *E* consists of a finite number of PT-atoms, each of which is entirely lacking in experiential proper parts, and each of which has some finite temporal extension.

The notion that there could be an experience that is both atomic and temporally extended can seem strange if one is encountering it for the first time. But what we are dealing with here is nothing more than the temporal analog of the spatially "extended simples" which many contemporary metaphysicians are happy to admit into their ontologies.[16] And with good reason: superstrings may be small, but they are not pointlike—they are spatially extended (through the three macrospatial dimensions); if it turns out that the fundamental physical particles are all superstrings, then our entire universe will be composed of extended simples. A spatially extended simple occupies smaller subregions of space without possessing any parts that do likewise; in an analogous fashion, a temporally extended simple occupies briefer temporal regions without possessing any parts that do likewise.

While there are certainly some compelling reasons for acknowledging the possibility of extended simples, doing so gives rise to some intriguing metaphysical conundrums. We saw above that the phenomenal character of PT-atoms can be dynamic (in the case of flowing sensory experience) or nondynamic (in the case of momentary-seeming sensations or conscious thoughts). Since the dynamic PT-atoms will consist of a succession of phases—for example, of a tone continuing on, or rising in pitch—the relationship between the experience and the interval of time it occupies is not unduly mysterious. The successive phases of an atomic tone-sensation do not have the status of experiential parts—just as a truly elementary (or atomic) physical object lacks physical parts—but each of these phases nonetheless has its own distinctive temporal location, an interval of objective time it can call its own.

But what of the *nondynamic* experiences and their contents? Since these do not consist of a succession of experiential phases, their relationship with the time through which they extend is not so obvious. Suppose the content of a nondynamic PT-atom *E* is a single pinprick of pain that extends through the temporal interval *T*. What is going on, experientially, at each of the briefer subintervals to be found in T? One option is to hold that the pain-content is possessed by *E* as a whole, and that consequently there is no determinate answer to this question. Since the content of the experiential whole is not shared by all of its briefer temporal phases, this could reasonably be regarded as a breakdown in content-homogeneity. An alternative is to hold that the whole pain-content is instantiated during *each* of *T*'s subintervals. This restores homogeneity, but the cost might seem high. Instead of just one pain-sensation, haven't we now got a multitude? Not if we construe the relevant property instantiations in the way that some construe *universals*. If all the scattered instances of (say) the property of sphericity can be numerically identical, why can't the same apply to all the exemplifications of the property (of a given type of) pain to be found at the various subintervals within *T*? If the latter are numerically identical with one another, we have one sensation, not many.[17] Future work on the properties of extended simples, both spatial and temporal, may reveal different and (perhaps) more appealing options.

There is, no doubt, a good deal more to be said on each of these topics, but we have seen enough for it to be clear that the extensional approach is a flexible one: (i) it can accommodate forms of experience that come in MIDs, and those that do not; (ii) it can accommodate experience whose contents are homogeneous down to the smallest of timescales, and those that are not; (iii) as we have seen latterly, the contents of extensional streams of consciousness can possess a variety of chronomereological structures, and some of these structures may have implications for content-homogeneity.

Of course, having acknowledged this spectrum of possibilities, the question "Which are realized in our own experience?" becomes more pressing. Perhaps there are some subjects—real or merely possible—whose streams of consciousness possess an actual infinity of ever-smaller parts, but it can easily seem implausible to hold that our own experience is similarly fine-grained. This claim is certainly in tension with the widely accepted doctrine that the Planck duration of 5.391×10^{-44} seconds is the smallest physically meaningful temporal interval. It can also be argued that positing an infinitely rich structure in our sensory fields goes well beyond what is needed to account for what we find *in* these fields. If you are fortunate enough to possess 20–20 vision you will be able to distinguish lines separated by an angle as little as a single arc-minute (or a sixtieth of a degree), but lines separated by much less will not appear as distinct. (To make matters more concrete: our visual systems are able to resolve up to around 110 lines drawn on a finger-nail sized object at arm's length).[18] Since our other senses are similarly restricted, why posit the additional structure? But while these considerations have very considerable weight, they are not conclusive. The Planck time may be an unbreachable limit in contemporary physical theories, but future theories may tell have a different story to tell; perhaps more importantly, those who view phenomenal properties as nonphysical might reasonably argue that the phenomenal realm can be continuous in ways that the physical realm is not. This point aside, from the fact that our powers of discrimination are limited it does not automatically follow that our experiences (or their contents) are similarly restricted: perhaps our experiences have features that go beyond our ability to discriminate.[19] These are issues are difficult to resolve, and we needn't attempt to resolve them here: it suffices to note that the extensional theorist has a good deal of room to maneuver, even within the framework of the essentially extended assumption.

Where some will see a useful flexibility and welcome challenges ahead, others may see a series of difficult, perhaps insoluble problems. There is no doubt that the problems in this area are difficult. As for whether they are soluble or insoluble, time will tell. In this connection it is worth noting, however, that the retentional alternative faces analogous difficulties. It is true that if the contents of individual specious presents are not distributed over intervals of ordinary objective time, questions about *how* they are distributed over such intervals simply do not arise. Nonetheless, questions can still be asked about the temporal microstructure of the relevant experiential (or retentional) contents. When a continuous-seeming movement is registered in a retentional specious present, precisely *how* is this accomplished? Is the moving object represented as occupying an infinite number of distinct locations, or are retentions more coarsely grained? If the latter, how many distinct retentions exist in a typical specious present? Are their contents homogeneous or not? Do they represent all parts of the movement in a fully determinate way, or in a less than fully determinate way? There is no need to press further: it is clear that issues relating to mereological complexity and content-homogeneity arise on both the extensional and retentional approaches.

6.7 Initial Experiences

We are now in a better position to engage with Pelczar's main argument, or at least the one he develops in most detail, which I have yet to mention. On the face of it, the aim of the argument is quite limited: Pelczar takes it as establishing that an experience of succession need not require a succession of experiences. As I noted in section 6.1, establishing the bare possibility of retentional specious presents does not in itself undermine the extensional theorists' account of the structure of our actual streams of consciousness. Nonetheless, as we shall see shortly, it turns out that if sound, this argument would undermine the extensionalist's cause to a very significant degree. In a simplified but more easily grasped form, the argument runs thus:

A1 Your first experience (of the day, say) could be an experience as of change.

A2 If your first experience could be an experience as of some change taking place, then a momentary experience can be an experience as of change.

A3 Therefore, a momentary experience can be an experience as of change.

From a commonsense standpoint it is certainly plausible to suppose that one's first experience of the day could be an experience as of change—e.g., hearing the ringing of an alarm clock. This verdict of common sense is decisively reinforced if we follow Pelczar in assuming that the contents of our experience are essentially dynamic. If all experiences (or experiential contents) are either as of change or as of persistence, the same applies to your first experience. What is more, there is no reason to think your first experience must be as of persistence rather than change. Consequently A1 looks to be true: your first experience *could* very well be as of change. A question now arises. Out of all the experiences that you have had since waking this morning, which was the *very first*? If streams of consciousness are divisible into momentary temporal phases, then the earliest momentary phase in today's stream is the obvious and natural candidate for being your very first experience of the day. Since this experience is both momentary and as of change, A3 is true. And if A3 is true, a succession of experiences is not necessary in order to have an experience as of change (or succession).

This surprisingly simple line of reasoning is enough to establish that retentional specious presents are possible. Since in extensional models the experiencing of change involves the instantiation of a succession of phenomenal properties over an interval of time, it clearly cannot take place in a strictly momentary experience. Accordingly, experiences as of succession that can occur within momentary experiences cannot be accommodated within the extensional framework. If Pelczar is right, our very first experience in any given stream of consciousness falls into this category. More worryingly—for the extensional theorist, at least—a little reflection suggests the reasoning applies more generally. Consider a stream of consciousness S which extends from t_1 to t_2, and to simplify, let us suppose—as is not too unrealistic—that the contents of this stream are continually changing, even if only in small ways, during this interval. Now take any moment *m* between t_1 and t_2 and consider the experience in S which occurs at this time. Given our assumptions, this experience will be an experience as of change and (plausibly) momentary. This reasoning does not in itself demonstrate that the extensional model is incoherent, but it does threaten to make it redundant. If change and succession, as experienced from moment to moment, are necessarily to be found in dense successions of retentional specious presents—in the guise of change-presenting momentary experiences—what room is there for any other mode of experienced change?

The argument I expounded above in A1–A3 is close to the one Pelczar develops, but it contains a simplification that can now be removed. Can we humans enjoy states or episodes of consciousness that are strictly momentary? Such states may not be logically impossible, but Pelczar believes—quite plausibly—that there are empirical reasons for supposing that even the briefest of human conscious states always has a finite temporal extension. Accordingly, rather than formulating his argument in terms of strictly momentary states, Pelczar employs what he calls "presentaneous experiences." An experience is presentaneous if either (a) it is momentary, or (b) it extends over a temporal interval t_1-t_2 but does not vary in its phenomenal characteristics over the course of this interval.[20] The argument now runs:

A1 Your first experience (of the day, say) could be an experience as of change.

A2* If your first experience could be an experience as of change, then a presentaneous experience can be an experience as of change.

A3* Therefore, a presentaneous experience can be an experience as of change.

Presentaneous experiences may be nonmomentary, but they are not candidates for being extensional specious presents that feature experienced change. Since this argument can also be applied to the first experience after any arbitrarily selected moment during the time span of a stream of consciousness, it too threatens to generalize, and render extensional specious presents surplus to requirements.

There are several lines of response open to the extensional theorist, but one point can be made straightaway. Pelczar's argument hinges on the type of content we can reasonably ascribe to the very first experience in a stream, and he maintains that these initial experiences are either (a) momentary, or (b) have some brief duration while possessing uniformly change-free contents. Extensionalists will want to take issue with both options. If phenomenal continua are essentially extended, they do not contain momentary parts, and so (a) is ruled out. Furthermore, in streams composed exclusively of extensional specious presents, directly experienced changes involve a succession of qualitatively *varying* contents being apprehended in an episode of experiencing that itself extends through time, contrary to (b); experiences that present change in this sort of way clearly do not fall into the category of presentaneous experiences. Given this, isn't Pelczar simply guilty of begging the question against the extensionalist when he claims that initial experiences *must* be presentaneous? Is he not simply ignoring the possibility that our awareness can encompass an interval of time?

Although I think the main thrust of Pelczar's argument can be countered in this way, more needs to be done: the extensional theorist still needs to be able to provide a plausible positive account of the initial phases of our streams of consciousness—or generally, about our initial experiences after an arbitrary midstream time *t*. Since there remains a good deal to be discovered about the microstructure of our experience, we cannot at present be sure of very much in this domain; fortunately, as we saw in section 6.6, the combination of the extensional model and the essentially extended view of the continuum leaves a good many possibilities open.

If we assume that phenomenal continua are essentially extended, we can be sure of one thing: the very first part of a stream—or the first experience after any arbitrarily selected midstream time *t*—will *not* be a momentary experience, it will be an experience with some temporal extension. Given the essential dynamism assumption, this experience will be as of change or persistence. We saw in section 6.61 that there are empirical reasons for supposing that our own experience—or at least some varieties of it—may come packaged in minimum independent durations (or MIDs). If so, then the initial experiences within our streams will inevitably be of this minimum length, which may well be different on different occasions, or for different forms of experience, and no doubt different subjects. However, this (probably contingent) fact about human experience gives rise to further questions. If these minimum units are of the order of 150–250 msec they are quite long enough to contain briefer subphases, which will themselves present change or succession. Quite how many briefer experiences a 250 msec stretch of a stream of human consciousness can contain will depend on the mereological complexity of the experience in question, and here the various distinctions drawn in section 6.63 become relevant. If the stream-phase is atomless, and hence divides into further brief (but always finite) experiential parts without end, then there will be an infinite number of experiential subphases. If the stream-phase is atomic—if there is a limit beyond which this particular stretch of experience cannot be further divided into experiential parts—then the experiential subphases it contains will be finite in number. The possibilities do not end here: the 250 msec stream-segment could conceivably be heterogeneous in character, with some of its experiential parts being atomless (e.g., the experiencing of an auditory tone) whereas others are atomic (e.g., a conscious thought).[21]

Subjects whose streams of consciousness are endlessly divisible into ever-briefer experiences are interesting in several respects, not least because of the intriguing way in which their streams initially get going. Consider a stream of consciousness S, belonging to just such a subject, which starts at t_0 and continues on for some hours; let us focus on the first complete specious present in S, which we can suppose extends between t_0 and t_1, with t_1 occurring one second after t_0. If we look at S from the later-to-earlier direction, there will be an infinite sequence of experiential subphases commencing at t_1 and extending into the past in the direction of t_0. To make matters more concrete, we can think of these subphases as stretching from t_1 back to t_0 via the series of locations l_1, l_2, … , l_n, which are generated in a Zeno-like fashion by successive halving of our one-second interval thus:

$l_1 = t_1 - 1/2s$

$l_2 = (t_1 - 1/2s) - 1/4s$

$l_3 = ((t_1 - 1/2s) - 1/4s) - 1/8s$

etc.

l_n

In other words, l_1 is half a second earlier than t_1; l_2 is a quarter of a second earlier than l_1; l_3 is an eighth of a second earlier than l_2, and so on. There are at least two points to register here. First, the temporal interval between t_0 and each successive *l*-location gets smaller and smaller as we close in on t_0, but by virtue of being parts of an essentially extended continuum, the series does not terminate with (or at) a durationless point. Second, provided we assume that time and experience are both infinitely divisible, the sequence l_1, l_2, … , l_n is an infinite one, from which it follows that it has no last or final member. If we now reverse our temporal perspective and consider what lies *ahead* of t_0, we see that there is an infinite number of subphases demarcated by the succession of *l*-locations. Since this succession has no first member, there is no such thing as the *initial* experience in the stream S. Evidently, for streams structured in this way, there is no *first experience* at all, and so Pelczar's argument does not get off the ground. To arrive at a complete account of stream-structure that is appealingly clear and unambiguous we need make just one further assumption: that the phenomenal content of each phase or subphase of this subject's experience is fully homogeneous in character—for example, of a note smoothly rising in pitch, or the second hand of a clock moving at a certain rate—no matter how brief the phase is. If content is homogeneous in this way, our streams of consciousness harbor no mysteries in their smaller and briefer parts.

Streams of consciousness with this sort of structure and content may well be logically possible. But although it can easily seem that *our* experience is of this kind, it may well not be. If the mereological complexity of our experiences (or their contents) approximates to what we are able to discriminate, then it is finite rather than infinite, in which case there are hard empirical questions to be answered about the shortest intervals of genuine change-presenting experience that we are capable of enjoying. If phenomenal contents are not homogeneous on shorter timescales, there are equally hard questions to be answered about the kinds of contents these short stream-phases possess. After only a little reflection, questions such as these can easily seem *impossibly* difficult to answer. What is the character of our experience over a 1 nanosecond interval? How would one possibly go about finding out? If the extensional approach gives rise to such questions, shouldn't we seek an alternative? There are several points to bear in mind here.

First, the fact that these questions are likely to prove very difficult to answer does not mean there *are* no answers. Second, as I noted at the end of section 6.6, the alternative retentional approach gives rise to analogous questions relating to the fine-grained structure and content of retentions, questions that look equally difficult to answer. Third, hard questions about the microstructure of experience do not arise solely in the temporal case. Consider the continuous blue expanse that fills your visual field when you look at a clear sky at a given moment. What are *its* smallest experiential constituents? If we divided this phenomenal *spatial* field into a billion smaller parts, what sort of visual content do they have? Into how many experiential parts can an itch or a tickle be divided? Last but not least, the difficulty of these microstructural questions stems from the broader difficulty of understanding how the experiential and physical realms are related. One of the reasons it is so difficult to comprehend how phenomenal states or processes can *be* physical is the difficulty of seeing how the frenzied activity of the trillions of elementary physical particles in our brains could constitute a homogeneous expanse of (say) phenomenal blue—or (if you prefer) an experience of a blue expanse. Reconciling the manifest features of the phenomenal with the microstructure of the physical is a dauntingly difficult task. Reconciling the *temporal* microstructure of our experience with the microstructure of the physical world is just one part of this task. It is too early to know whether the reconciliation will be accomplished. In any event, I hope it is now plain why it would be wrong to make too much of the fact that the extensional approach to temporal experience gives rise to some hard questions: these hard questions are simply part and parcel of the more general problem of understanding the relationship between experience itself, in all its forms, and the wider world.

6.8 The Continuum Strikes Back

If my arguments so far have been successful, contrary to what Pelczar has suggested, the extensional theorist has nothing to fear from the seamless continuity which we find in many parts of phases of our streams of consciousness. But there are strong grounds for thinking that it is otherwise with the retentional alternative: anyone who adopts this conception of the temporal structure of experience has very real problems in accommodating phenomenal continuity.

That our streams of consciousness exhibit strong and significant continuities is widely—if not universally—accepted. Since "continuity" can mean different things in different contexts, so too can accepting that "consciousness is continuous." So far as the latter claim is concerned, two senses are particularly relevant; I will label them as follows:

Moderate continuity A stream of consciousness is moderately continuous over an interval of time if it contains experience throughout this interval.
Strong continuity A stream of consciousness is strongly continuous over an interval if each of its briefer phases is experienced as flowing into the next.

Moderate continuity is simply freedom from gaps. In addition to freedom from gaps, strong continuity requires genuine phenomenal *connections* between adjacent brief stream-phases (or their contents). There is every reason to believe such connections exist. Recall again the character of your experience when listening to a continuous tone, or observing continuous motion. Do you not hear each brief phase of the tone flowing smoothly into the next? Doesn't every phase of the movement segue into its successor? These directly experienced transitions between what we are experiencing from one brief interval to the next are what I have in mind in talking about "phenomenal connections" here. Precisely how this mode of connectedness should be characterized is a non-trivial issue, but it is nonetheless plausible to suppose such connectedness is pervasive feature of typical streams of consciousness, from moment to moment—and Pelczar for one is eager that we should acknowledge its existence.

The extensional overlap model can accommodate phenomenal connections, and hence strong continuity, without difficulty. Consider a short stream-segment consisting of phases P_1–P_2–P_3–P_4, where each "P" is half the duration of a single specious present, and each phase is experienced as flowing into the next, so as to form three partially overlapping specious presents SP_1, $SP_{2,}$ and SP_3, as shown in figure 6.5.

Each of these brief phases is phenomenally connected with its immediate neighbors; the resulting overlaps ensure that successive specious presents are themselves phenomenally connected, and so able to form strongly continuous stretches of experiencing. This overlap mechanism is plainly well capable of accommodating phenomenal connections between all the brief phases of streams of consciousness of any length and complexity.

In the case of retentional model the situation is very different. Moderate continuity poses no difficulty: retentional theorists generally assume that a stream consists of a dense,

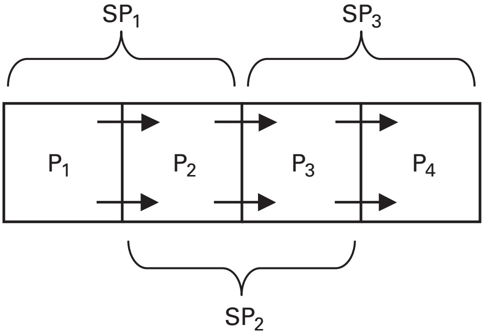

Figure 6.5

In the extensional model strong continuity is secured by overlap and part-sharing. Stream-phases (such as P_1 and P_2) which are strongly connected are linked by horizontal arrows.

gap-free succession of specious presents. It is strong continuity that poses the problem. The defining feature of the retentional approach is the doctrine that phenomenal unity—or equivalently in this context, diachronic co-consciousness—is confined to experienced contents that in objective terms are momentary and simultaneous. As a result, it is impossible for contents in distinct but neighboring specious presents to be directly phenomenally unified. The retentionalist's confinement of diachronic co-consciousness inevitably fragments our streams of consciousness—for, in effect, each specious present is an entirely discrete episode of experiencing in its own right. How could it be otherwise? Given the total absence of direct phenomenal connections between neighboring stream-phases, this fragmentation is inevitable.

Of course, this fragmentation only matters if it leads to phenomenological consequences that are both detectable and unrealistic. It can easily seem that it must. If diachronic phenomenal unity is confined to the contents within individual specious presents, and never bridges the gap between distinct specious presents, how could all the successive brief phases in a stream be experienced as flowing into the next in the way they seem to be? Doesn't the experience of uninterrupted flow—experience of the sort that we enjoy all the time—require phenomenal unity to run from one specious present to the next?

It does indeed—or so I think—but one must be careful of moving too quickly here.

Recall our simple stream-segment P_1–P_2–P_3–P_4. We have seen that the extensional theorist can easily accommodate the experienced transitions between neighboring stream-phases, in the form of three specious presents:

SP_1: [P_1–P_2], SP_2: [P_2–P_3], SP_3: [P_3–P_4]

But the retentional theorist looks to be able to register the existence of exactly the same experienced transitions, in the form of the following sequence of retentional specious presents:

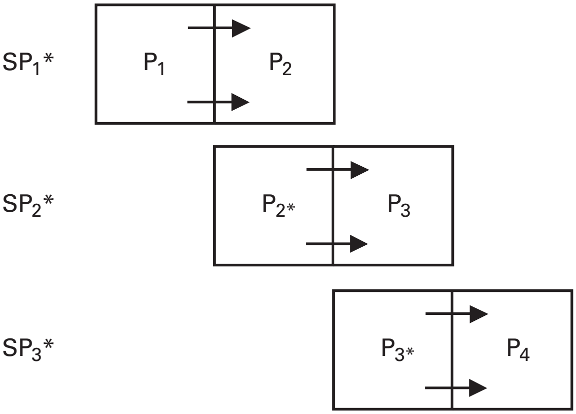

Figure 6.6
The retentional case: overlap via duplication rather than numerical identity.

SP_1*: [P_1–P_2], SP_2*: [P_2–P_3], SP_3*: [P_3–P_4]

Since the same experienced successions are available on both approaches, where is the extensionalist's advantage? What is *missing* if we construe things along retentional lines?

Well, in one sense, this objection is perfectly correct. If we view experienced successions solely in terms of types of qualitative content, then the two sequences are largely equivalent.[22] But if we focus instead solely on the interrelations between *token* experiences, they are quite different, as is plain when figure 6.6 below is compared with the earlier figure 6.5, which shows the extensional equivalent.

Whereas in the extensional case, the initial phase P_2 of SP_2 is numerically the same token experience as the second half of SP_1, the initial phase of SP_2* is an entirely new token experience—designated "P_2*" in figure 6.6 to make this plain—one that is numerically distinct from P_2. And similarly for P_3 and P_3*. The question to be considered, of course, is whether these differences in token-identities impinge on the character of experienced continuity.

A powerful case can be made for answering in the affirmative. A phenomenologically relevant difference emerges when we take a closer look at the *kinds* of experienced transitions which are to be found in our ordinary streams of consciousness. First, and more obviously, *pairs* of immediately successive brief stream-phases are experienced together—they are diachronically co-conscious—with the first phase experienced as flowing into the second, in the manner of P_1 and P_2. A second, only slightly less obvious, aspect concerns the way in which successions of these paired phases are interrelated within the stream. If one hears a rapid "do-re-mi", it is perfectly clear that the "re" which is experienced as following directly on from "do" is the *same token experience* (or same instance of auditory content) that one experiences as flowing into "mi". As far as I can see, few features of our experience are *more* obvious than this. And what goes for "do-re-mi" applies for other tri-phase successions (as we can call them) which unfold over sufficiently brief intervals. It certainly applies in the case of hearings of "so-fa-la" or "tra-la-la," but also in the visual realm. Think of the sort of experience one has as one watches a skier smoothly negotiating a slalom. Focusing on the experiencing of three successive brief phases of their run, which we can label m_1, m_2, and m_3, isn't it clear that m_1 flows into m_2, and that m_2 (and not some copy or surrogate of it) flows into m_3? Doesn't the same apply to the successive brief phases of all directly perceived transitions, in all sensory modalities?

Let us call experienced successions of this sort *phenomenally mediated*. In more general and schematic terms, a tri-phase succession is phenomenally mediated if it comprises three experiential phases, X_1, X_2, and X_3, where X_1 is experienced as flowing into X_2, and X_2 is experienced as flowing into X_3. Crucially and distinctively, in a phenomenally mediated succession the central phase X_2 is not *duplicated*: the X_2-phase that X_1 is experienced as flowing into is numerically identical with the X_2-phase that is experienced as flowing into X_3. If the phases of a phenomenally mediated transition are very brief they will all fit within the confines of a single specious present; if they are rather longer they will be spread over at least two specious presents which will overlap by sharing a common part or phase, for example, SP_1 = [*do-re*], SP_2 = [*re-mi*]. The fact that tri-phase phenomenally mediated successions of this sort feature so prominently in experience provides us with compelling evidence that specious presents *can* overlap in this sort of way.

The relevance of these considerations to the point at issue should be plain. The extensional overlap model has no difficulty in accommodating this sort of succession: tri-phase phenomenally mediated successions and overlapping extensional specious presents are one and the same, as is clear from figure 6.5. Retentional models fare far less well. Phenomenally mediated successions that are sufficiently brief to fall within the confines of a single specious present pose no difficulty: they can be directly experienced as forming phenomenally mediated successions. But crucially, tri-phase successions which cross the bounds of a single specious present cannot possibly be experienced in the required way.

In the terms of our earlier case, whereas the extensionalist can accommodate P_1 flowing into P_2 and P_2 flowing into P_3, the retentionalist is unable to: P_1 can be experienced as flowing into P_2, but it is not P_2 that is experienced as flowing into P_3, but rather the qualitatively identical but numerically distinct P_2^* (as shown in figure 6.6). Precisely the same considerations apply to stream-phases which are of different apparent durations, e.g., a third or a quarter or a tenth of the duration of the specious present. In reality, these too can belong to chains of phenomenally mediated successions which last for considerable periods—indeed, they compose much of our ordinary experience—but again, such successions can only be accommodated in retentional models in fragmented and abbreviated form: no such succession can extend beyond the confines of an individual specious present.

The necessary curtailment of phenomenally mediated successions in retentional models is surely unrealistic from a phenomenological point of view. Reflect again on the continuous character of ordinary perceptual experience, of how each brief phase flows into its successor in the same kind of way. To put it simply, the retentional approach is incompatible with the *homogeneous* character of phenomenal succession.[23] Since in our actual conscious lives phenomenally mediated successions are not confined to apparent spans of time of the order of a second or so—and this applies to the contents of our imaginations as well our perceptual experience—the character of the experience of a subject whose experience *is* so confined is very probably quite different from anything we can imagine. For this reason, accurately imagining what it would be like to be a subject frivolously brought into existence, allowed to exist for a single second, and then abruptly annihilated, is harder by far than it can initially seem. Of one thing we can be reasonably sure: the experience of such a subject would be quite unlike *our* experience.[24]

6.9 Concluding Speculations

Some retentional theorists have been aware of the need to say more about how the contents in successive co-streamal specious presents are unified.

Husserl himself tentatively ventured several remedies, and ultimately turned to a timeless transcendental Ego as a unifying agent.[25] But since explicit attempts to address the continuity issue are thin on the ground, I think it fair to say that retentional theorists have not, on the whole, recognized the potential seriousness of the problem confronting them. As for why, I suspect one reason may well be because they have taken false comfort from the conception of the continuum to which they typically subscribe.

Retentionalists generally assume—for example, Broad (1938, 1959) and Dobbs (1951)—that the specious presents composing a single stream of consciousness are closely packed in the manner of the points in the orthodox mathematical continuum.[26] On the assumption that this is the case, it can easily seem that a retentional stream of consciousness is *bound* to be continuous in the fullest of senses. As for why, consider figure 6.7, which depicts a retentional stream of consciousness with the internal structure of individual specious

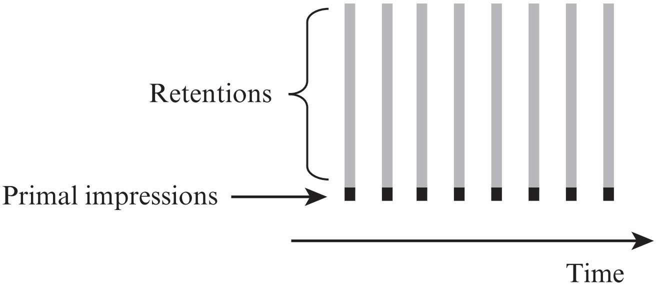

Figure 6.7
The composition of retentional specious presents.

presents laid bare. As can be seen, each specious present comprises a momentary fragment of ordinary sensory (nonretentional) consciousness—in Husserl's terms, a "primal impression"—along with a collection of retentions (i.e., representations of the recent past). As previously, individual specious presents are depicted as thin vertical lines, whose contents are simultaneous in ordinary objective time.

The gaps between the vertical lines in figure 6.7 make the structure and composition of the retentional phenomenal continuum easier to discern, but they are unrealistic. In reality, the specious presents are supposed to be as closely packed as the points on a geometrical line, so that between every two points there is not just another point, but an infinite number of further points. A more accurate representation is supplied by figure 6.8, where the gapless character of the continuum of primary impressions (or sensory experience, properly so-called) is made explicit.

If our streams of consciousness have *this* degree of continuity at the primary sensory level, haven't they as much continuity as one could wish for? What could be more continuous than a geometrical line? But appearances can be deceptive; it may not be obvious, but even when continuous in this way, such a series of momentary sensory contents (or primal impressions) possesses no more than moderate continuity. We have already seen why: each retentional specious present is a discrete (momentary) phase of experience, clearly and cleanly separated—phenomenally *disconnected*—from its neighbors. Figure 6.8 is thus misleading: the retentionalist's continuum of primal impressions is, in reality, massively fragmented. As has long been recognized, a succession of experiences is not the same thing as an experience of succession; the retentional phenomenal continuum provides the former, but not the latter.

The lack of contact, in any intuitively intelligible sense of the term, between neighboring points is a widely acknowledged feature of continua that are isomorphic with the real number continuum. By virtue of being dense, between any two points in such a continuum there is always yet a further point; if any two points are always separated by more points—an infinity of them, in fact—it is evident that simple contact between points is impossible. Or

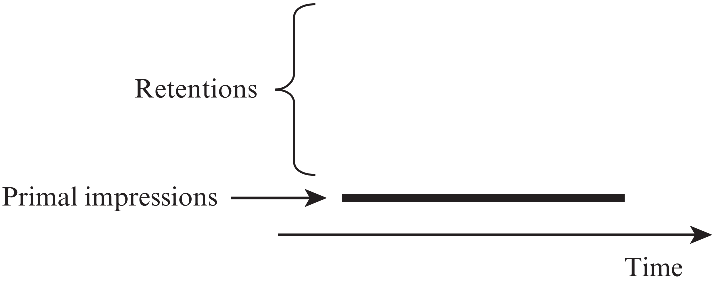

Figure 6.8

A dense continuum of momentary sensory experiences (or "primal impressions").

at least, it is impossible for them come into immediate contact in the way the objects and contents that we encounter in our ordinary experience do. A continuum constituted from isolated points of this sort lacks the kind of unity—the kind of *continuity*—that phenomenal continua possess. And of course, the one binding agent that might convert a collection of isolated points into a genuine continuum, the phenomenal unity relationship—in the form of diachronic co-consciousness—is by necessity absent in the retentional framework.

That the orthodox mathematical continuum is devoid of real unity has long been recognized and lamented by mathematicians themselves; here is Poincaré on this theme:

> The continuum thus conceived is no more than a collection of individuals arranged in a certain order, infinite in number, it is true, but external the one to the other. This is not the ordinary conception, in which it is supposed that between the elements of the continuum exists an intimate connection making of it one whole, in which the point has no existence previous to the line, but the line does exist previous to the point. Multiplicity alone subsists, unity has disappeared—"the continuum is unity in multiplicity"—according to the celebrated formula. …. The real mathematical continuum is quite different from that of the physicists and from that of the metaphysicians. (1952, 18, translation modified)

In a similar vein, Weyl observed, "Certainly, the intuitive and the mathematical continuum do not coincide; a deep chasm is fixed between them." (1994, 93).[27] The lesson for us is clear. The mathematical continuum may be adequate for the modeling of many phenomena in the physical world, but it is less than adequate when it comes to capturing the characteristic features of phenomenal continua. For this reason, it is fruitless for retentionalists to appeal to its features when addressing the charge that their models do less than full justice to the continuities we find in our own experience.[28]

Notes

1. I take "immediate experience" to include conscious thought, memories, and mental images, in addition to perceptual and sensory experience. Change and succession are by no means confined to the latter: the contents of our memories and imaginations, not to mention our inner soliloquies, can also be highly dynamic.

2. For example, see Le Poidevin (2007, chapter 5); for further discussion of this general approach, and some particular instances of it, see Dainton (2010b, §4.2).

3. There is a further option. According to the proponents of "cinematic realism"—as I label it in Dainton (2010b, §4.1)—our streams of consciousness are composed of dense successions of instantaneous snapshot-like phases whose contents are entirely static, but that together generate the dynamic characteristics we find in our ordinary experience. Although it has some appeal—don't rapid sequences of static images on a cinema-screen give rise to the appearance of motion?—this approach is hopelessly flawed, for the reasons set out in (2010b), and so it will not figure further here.

4. This need not be the only difference: quite what an account along extensionalist or retentionalist lines amounts to will depend on the general conception of experience and its contents that is being presupposed in a particular instance. Does consciousness in general have an act-object structure? What

is the correct view of perceptual experience: naïve realism, Lockean-style representationalism, or one of the other alternatives? So far as I can see, the retentional and extensional approaches are compatible with a range of different views of both the general structure of consciousness and the nature of perceptual experience. Hence, in what follows, I try to use the terms "experience" and "content" in as neutral way as possible. Accordingly, the "content" of (say) a perceptual experience could be an external material object, or it could be a realization of a pattern of sensory qualia—to mention just some of the relevant possibilities.

5. Whether or not we have any awareness of these momentary episodes of experiencing *themselves*, in addition to the awareness we have of their contents, is another issue upon which a divergence of opinion in the retentionalist camp is possible; since this issue is peripheral to my main concerns here, I will not be investigating it further. Influential variants of the retentional approach have been elaborated by Husserl (1991), but also by Broad (1938, 1959); recent sympathizers include Grush (2005a, 2005b), Gallagher (1998, 2003), Lloyd (2004), Strawson (2009), Kiverstein (2010), and Zahavi (2007). The extensional approach has been defended by Foster (1979, 1982), Sprigge (1983), and Dainton (2000, 2001, 2008), and can be traced back to Stern (1897). See Dainton (2010b) for further background and discussion. Although traces of both approaches can be found in James's classic discussion in the *Principles of Psychology* (1890), in a number of important passages James seems to side with the retentional school.

6. Although in sections 6.8 and 6.9 I will return to a theme—the difficulties retentional models have in coping with phenomenal continuity—that I have discussed previously.

7. For further elaboration of this claim see Dainton (2001, §7.5); some retentionalists—cf. Broad (1959)—fully acknowledge that the account they are offering involves two temporal dimensions. Retentionalists who hold that we have, at each moment, a direct awareness of the *past itself* (or a brief stretch of it), rather than *representations* of the past, are less vulnerable to the "extra dimension" charge, but their position has plausibility problems of a different kind.

8. See Dainton (2010b, §5.5) for further discussion of the divergence of views on phenomenal unity, and Dainton (2010a, §7.8) for more on the incompatibility between presentism, in its different forms, and the extensional approach.

9. In fact, Pelczar cites some earlier writings of my own by way of support for this subjective dynamism thesis. Although I do find the doctrine a plausible one, I will later be suggesting in section 6.4 that it may need qualifying.

10. For further considerations pointing in the same direction see Dainton (2010b, §4).

11. Geach held this view of judgments—see Soteriou (2007) for an illuminating discussion.

12. The details of the story can be spelled out in a variety of different ways. We might, for example, suppose that the annihilations leave a momentary experience-free *gap* in your stream of consciousness; or, alternatively, we can stipulate that no experience-free gap occurs. It seems plausible to suppose that your experience would have precisely the same character either way—this is a further puzzling feature of the envisaged predicaments. Of course, if we suppose that envisaged removals significantly impact on (or even destroy) the phenomenal unity of the state in question, then the consequences would be

dramatic indeed. But it is not obvious that the removal of zero-sized parts would necessarily impact upon phenomenal unity in this manner; indeed, it is not clear why or how the removal of such parts could or should have any impact in this regard.

13. For example, according to the orthodox measure-theoretical way of thinking of point-constituted continua, while a countable infinity of points does not add up to a finite quantity, an uncountable infinity of points can—in which case, removing an uncountably infinite number of points could make a detectable difference. For more on point-related puzzles see Arntzenius (2008) and Dainton (2010a, §17.5).

14. For useful overviews on these topics see Pockett (2003) and Long and O'Saben (1989).

15. Atomless or *gunky*, in the jargon of contemporary metaphysicians. The use of the term "gunk" as a label for continua that are divisible into ever-smaller (but never point-like) parts is comparatively recent—it dates back to Lewis (1991)—but the view itself is by no means new: Aristotle probably subscribed to a (finitist) version of it, as did Broad, Russell, and Whitehead (at during some periods of their careers anyway). See Bostock (2010) for a critical survey of Russell and Whitehead's attempts to define points in terms of the (for them) more basic concept of extended regions.

16. For example, Markosian (1998), Parsons (2000), Simons (2004), and McDaniel (2009).

17. My thanks to Jonathan Lowe for this suggestion. For more on property instantiation in extended simples see Parsons (2000), McDaniel (2007, 2009), and Spencer (2010).

18. For further detail see Sheng et al. (1997).

19. Fara (2001) suggests that although we judge the hour hand of a clock to be stationary, in fact its movement may register in our visual experience even though we are unable to notice this.

20. This is the argument as Pelczar sets it out in (2010b); essentially the same argument, using different terminology, is also deployed in his (2010a). Pelczar's more precise definition of a presentaneous experience runs thus: "consider a moment of time at which you instantiate one or more phenomenal properties, or a period of time such that there are phenomenal properties F1, F2, … , Fn such that at every moment in that period, you instantiate F1, F2, … , Fn and no other phenomenal properties besides these. Call the experience or (collectively) experiences you have at that moment or during that period a 'presentaneous experience'" (2010b, 276). A case could be made for holding that a presentaneous experience might exhibit phenomenal flow, and thus a kind of change, despite the lack of variation of intrinsic properties, but I will not press this point here.

21. I am focusing here on the properly experiential parts of this brief stream-phase. As we saw in section 6.6, there is a further factor: if time itself is infinitely divisible, then any nonmomentary experience *E* will contain an infinite number of temporal parts; whether these temporal parts can legitimately regarded as *experiences* (or properly experiential parts) will depend on whether *E* is atomless or atomic.

22. Largely but not completely: in most retentional models, contents reappear in neighboring specious presents under different "temporal modes of presentation"; to simplify, I am leaving temporal modes of the picture at the moment: they do not affect the essentials.

23. For a more thorough elaboration of this point see Dainton (2012).

24. Earlier, when distinguishing between strong and moderate continuity, I said that it was "widely—*if not universally*—accepted" that our streams of consciousness exhibit significant continuities. Galen Strawson is one of the more prominent of the skeptics in this regard. In 'The Self' he suggested that our streams of consciousness are in fact radically discontinuous—"always shooting off, fuzzing, shorting out, spurting and stalling" (1997, 421)—and he dismisses James's use of the stream metaphor as "inept." In a more recent discussion to which I cannot do full justice here—see Part V of *Selves* (2009)—Strawson changes tack: he concedes that his experience may not be entirely typical in respect of its apparent discontinuities, but he argues that this is of no import. Even if your experience from moment to moment seems to you to be deeply continuous, these appearances are irrelevant: it may in fact be radically *dis*-continuous. What is most distinctive about Strawson's position is his espousal of the following three claims: (a) a version of the retentional model is essentially correct, (b) our streams of consciousness are in fact radically discontinuous, far more so than most of us believe, (c) the discontinuities in our streams cannot be discerned by introspection—or at least by most of us, there may be exceptions (e.g., Strawson himself, skilled practitioners of certain kinds of mediation). I don't think we should follow Strawson in accepting these three claims. For the reasons just given, I think if our streams really did contain regular and repeated ruptures in strong connectedness, they would not seem as continuous as they do. Nonetheless, I think Strawson has seen what many have missed, namely that if (a) *were* true, then (b) would be too. He has correctly appreciated that the retentional model breaks our streams of consciousness down into innumerable entirely discrete fragments of experience. My guess is that most earlier retentionalists did not fully appreciate that their conception of temporal awareness has this consequence.

25. See the discussion of Husserl's later C-manuscript writings in Kortooms (2002).

26. The rational number line possesses the property of denseness—in the technical sense—but it only contains a *countable* infinity of points. The real number line, which also includes all the decimals, contains an *uncountable* infinity of points. When retentionalists talk of specious presents forming a "continuous" continuum, it is not clear they have more than density in mind, in which case a stream of consciousness will contain a countable but not an uncountable infinity of distinct specious presents. However, if—as is commonly, but not necessarily correctly, assumed—the moments of time are isomorphic with the real numbers, there will be an uncountable infinity of instants in any temporal interval. In which case, to avoid gaps in the phenomenal continuum—in the form of instants that lack specious presents—retentional theorists may hold that there is an uncountable infinity of specious presents in any stream of consciousness. For the point presently at issue it is irrelevant whether streams have the structure of the reals or the rationals: the same difficulties arise in both cases. Also worth noting in this connection: as a student of—and later (in 1883) assistant to—Karl Weierstrass, there can be no doubt that Husserl was very familiar with the recently developed mathematical conceptions of the continuum; it was Weierstrass, along with Dedekind and Cantor—later (1886–1900) Husserl's colleague at Halle—who put analysis and the theory of real numbers on firmer foundations in the nineteenth century. See Ortiz Hill (1997) for more on Husserl's relationship with Cantor, and Bell (2006) for more on competing conceptions of the continuum.

27. In this passage, Weyl explains why attempts to understand our streams of consciousness in terms of the orthodox point-constituted continuum fail: "Continuous observation would thus consist of infinitely many mutually related systems of infinitely many memories, one packed inside the other, the earlier being the 'contained' one. But, clearly, we experience none of this; and besides, such a system

of point-like moments of experience fitted endlessly into one another in the form of a completely apprehended unity is absurd. The view of a flow consisting of points and, therefore, also dissolving into points, turns out to be false. Precisely what eludes us is the nature of the continuity, the flowing from point to point. … Each one of us, at every moment, directly experiences the true character of this temporal continuity. But, because of the genuine primitiveness of phenomenal time, we cannot put our experience into words" (1994, 91–2).

28. My thanks to Richard Gaskin, Adam Pautz, Ian Phillips, Galen Strawson, and the Institute of Advanced Study, Durham, for providing an ideal environment for thinking about these (and other) issues.

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7 The Temporal Structure of Experience

Ian Phillips

7.1 Overview

This chapter defends a naïve view of the relation between the temporal structure of the objects of experience, and the temporal structure of experience itself. According to the naïve view, when all goes well, your stream of consciousness inherits the temporal structure of the events that are its contents. You "take in" the temporal structure of the events you witness in witnessing them. As a result, the temporal structure of experience matches the temporal structure of its objects. In cases of illusion, it is as if this is so. Thus, in every case, the temporal structure of experience matches the *apparent* temporal structure of the objects of experience.

Such a view faces both philosophical and empirical objections. The most prominent philosophical objection is that the naïve view is incompatible with a principle often labeled the "principle of simultaneous awareness" (Miller, 1984, 109), roughly the claim that if we are aware of a succession or duration, we must be aware of it at some one moment. Elsewhere, I have argued that this principle is false. Here I want to take that for granted. However, this attitude raises a worry. Extant theories of temporal consciousness take the principle of simultaneous awareness as their point of departure. If we discard it, it is unclear why we need a philosophical theory of time consciousness at all.

The answer is that time is special. Temporal properties are the only properties manifestly shared by both the objects of experience and by experience itself. Experience, at least in its subjective aspect, is not colored or shaped; it does, however, manifestly have a temporal structure. As a result, the question arises of the relation between the temporal structure of experience and the temporal structure of its objects. No such question obviously arises for color or shape. The naïve view is the natural answer to this obligatory question. Having fleshed out these opening remarks, I develop the naïve view, show why it is intuitive, and respond to a major empirical objection to it, namely its alleged inability to account for postdictive phenomena.

7.2 The Traditional Problematic

Traditional debates about time consciousness are best understood as competing attempts to make sense of temporal experience constrained by what Miller (1984, 109) labels the "principle of simultaneous awareness" (PSA):

PSA If one is aware of a succession or duration, one is necessarily aware of it at some one moment.[1]

PSA quickly leads to skepticism about the very possibility of temporal experience, as the following two passages testify.[2]

> If we speak strictly and philosophically … no kind of succession can be an object either of the senses, or of consciousness; because the operations of both are confined to the present point of time, and there can be no succession in a point of time; and on that account the motion of a body, which is a successive change of place, could not be observed by the sense alone without the aid of memory. (Reid, 1827, 387)

> Any sound has some duration, however short. If so, how can it ever be true that we really *hear* a sound; for to hear is to hear at a moment, and what we apprehend by way of hearing—or more generally perceiving—can only exist at the moment of hearing, and *ex hypothesi* at least part of the sound said to be heard is over at the moment of hearing, and strictly speaking it is *all* over. … Therefore, it seems, it is impossible to hear a sound. (Prichard, 1950, 47)

Puzzlement, and indeed skepticism, about temporal experience remains rife in the literature. In his recent monograph, Le Poidevin concludes that "order and duration are not in any straightforward sense objects of perceptual states" (2007, 99). Nor are such views confined to philosophers: Gallistel argues (in somewhat Kantian fashion, and citing phenomenological paradox) that, unlike color and shape, "duration is not itself a sensible aspect of events" but "exists only in recollection" (1996, 336).

Puzzlement about temporal experience has prompted two basic non-sceptical responses: memory theories and specious present theories. According to the memory theorist, "What gives rise to the experience of pure succession [in a case where a C and an E are heard successively] … is the conjunction of the perception of E with the very recent memory of C" (Le Poidevin, 2007, 92). On this picture, raw, basic experience lacks temporal content; temporal experience is woven from a combination of this raw material and memory.[3] According to the specious present theorist, in contrast, at any instant we are aware of an extended period of time: our basic experience at a moment literally embraces extended temporal structure (e.g., Tye, 2003; cf. Broad, 1923). For the specious present theorist, the confinement of experience to an instant does not prevent it acquainting us with temporally extended goings-on as such.

Both theories have received a great deal of critical attention, and, correspondingly, increasingly complicated revisions.[4] Elsewhere, I have argued that no form of either theory can successfully account for our experience unless it rejects PSA.[5] Yet to reject PSA is to reject the puzzle that motivated the construction of these theories in the first place. Thus, once it is recognized that PSA needs to be rejected to account for our temporal experience, we need to reconsider why we want a philosophical theory of temporal consciousness in the first place. If there is no problem, why do we need a solution?

In the next section, I press this question, and argue that the starting points in the literature are inadequate. Instead, I suggest that we should frame our thinking about temporal consciousness in terms of the special question that time raises for us regarding the relationship between the temporal structure of the objects of experience, and the temporal structure of experience itself. The naïve "theory" is the natural answer to this question. The aim of the rest of this chapter is to explore whether we need to depart from it. At least with regard to one very prominent source of contemporary hostility, I argue that we have no reason to do so.

7.3 Starting Again

If we attempt to justify theorizing about temporal experience unmotivated by the strictures of a controversial theoretical assumption such as PSA, it is natural to begin with the appearances. Many have felt that the way our temporal experience seems to us on reflection is somehow paradoxical (cf. Gallistel, 1996, quoted above), and therefore demands a theoretical response. This is one way to read the opening of Kelly's discussion of what he calls the puzzle of temporal experience. "How is it possible," Kelly writes, "for us to have experiences as of continuous, dynamic, temporally structured, unified events given that we start with (what at least seems to be) a sequence of independent and static snapshots of the world at a time" (2005, 210)? It is, however, perplexing why such a starting point would be forced upon us simply by reflecting upon our experiences. It is much more plausible to think that Kelly's puzzle arises because we implicitly or explicitly endorse a philosophical assumption such as PSA.

We might think that Kelly's how-possible question could stand alone, without any need to point to a particular source of puzzlement. Thus, Dainton opens his *Stanford Encyclopedia* entry on temporal consciousness as follows.

> In ordinary conscious experience, consciousness of time seems to be ubiquitous. For example, we seem to be directly aware of change, movement, and succession across brief temporal intervals. How is this possible? (2010)

However, it is not clear why we should accept that a genuine how-possible question arises. Cassam suggests that "to ask a how-possible question is to ask how something which looks impossible given other things that one knows or believes is nevertheless possible" (2007, 1).[6] But as yet we have no grounds for thinking that time consciousness is in any way mysterious, let alone for thinking it impossible. Of course, it is possible to argue that Cassam's conception of how-possible questions is too restrictive. But even if this is right, the philosopher of time consciousness has more work to do, as is plain if we contrast Dainton's opening with the following passage.

> In ordinary visual experience, consciousness of colour seems to be ubiquitous. For example, we seem to be directly aware of surface colours, film colours, and coloured lights in various locations. How is this possible?

For all that has been said in this passage, it is quite obscure what kind of philosophical response is required, if any at all. The challenge for the philosopher of time consciousness is to show what *special* problem or question arises in the case of temporal experience.

What then is special about time in relation to experience? The obvious answer is that unlike color, shape, and other visible properties, experience itself manifestly has temporal properties. Experience itself, at least in its subjective aspect, is not colored, nor does it have a shape. But it does manifestly have a temporal profile: the stream of consciousness is composed of events, processes, or both, which persist through time and occur before and after one another.[7] This special fact about time raises a special question: what is the relation between the temporal structure of experience and the temporal structure of the objects of experience? This is not a how-possible question. It is simply a how-question: how (in fact) does the flow of experience relate to the flow of what is experienced? This question is an unobjectionable starting point for our inquiry into temporal experience.

7.4 The Naïve Answer

The most natural answer to the question of the relation between the temporal structure of experience and the temporal structure of the objects of experience is that our experience inherits the temporal structure of the events which are its contents. The temporal structure of the world imposes itself on our stream of consciousness.

Natural as it is, the answer just offered is too naïve. Temporal illusions are not only possible but commonplace. Sometimes we misperceive events as occurring in an order different to their actual order. Sometimes we misperceive two events as having relative durations distinct from those they actually have. Nonetheless, an answer in the same spirit survives acknowledgment of illusion. The answer is that in good cases, we "take in" the temporal structure of the events we witness in witnessing them. In bad (i.e., illusory) cases, it is as if this is so. Thus, in general, the temporal structure of experience matches the *apparent* temporal structure of the world presented. It is this claim that I call the naïve view of temporal experience, or naïveté for short.

It is important to note that the precise commitments of the naïve view depend on precisely what the contents of our temporal experience are. The naïve view holds that for any apparently presented temporal property, the corresponding experience itself has that temporal property. Note two consequences. First, just because the objects of experience have certain temporal properties does not mean that experience will inherit those properties. For inheritance to take place, the objects must be presented *as having those properties*. Thus, for instance, the very fine-grained temporal structure of events will not be inherited insofar as such fine-grained structure is beyond our powers of perceptual discrimination.

Second, insofar as it is controversial whether experience presents us with a certain kind of temporal property, it is controversial which properties are inherited by experience. For instance, many assume that experience can present events as having absolute, metrical durations, for example, as lasting two seconds. In my view, this assumption is mistaken (for discussion see Phillips, 2013). However, we can all agree that the naïve view is committed to the following conditional: if you experience an event as lasting two seconds, your experience of it must itself last two seconds. For present purposes, I focus on naïveté in relation to less controversial temporal properties: successiveness, temporal order, relative duration and simultaneity.[8]

Why is the naïve view so intuitive? The reason is that naïveté reflects how our experience seems to us. We find the idea of the order of perceptions diverging from the perceived order of their objects to be incoherent *when we introspectively reflect upon our experience*. As a result, those who reject the naïve view must think of us as alienated from our own experience in its temporal aspect. On their view, our experience seems to be a way it is not. We are mistaken about our own experience.[9]

Those who reject the naïve view typically try to avoid the unhappy idea that our experience systematically misleads us about its own nature by denying that we have *any* access (apparent or otherwise) to our experience itself. Such theorists claim that experience is wholly diaphanous to introspection, and that we have no access at all to its properties (including its temporal structure), but only to the (apparent) properties of the world. If this view could be sustained, then the relation of act- and object-time would be beyond our introspective ken, and there would indeed be no basis for thinking that there was such a thing as the naïve answer to the special question raised by time.[10] Two challenges confront this picture.

The first challenge is dialectical. As already much emphasized, time is special. Thus, whatever a claim's merits with respect to other aspects of experience, its application to the temporal case demands special consideration. It is no doubt right to resist a move from a claim about perceived redness or squareness to a claim about the redness or squareness of our perceptual experience. But our experiential encounter with time is quite unlike color or shape, since our experience is not just of time, but also manifestly in time. Consequently, just as we should not generalize from the claim that experience inherits the temporal form of its objects to a more general claim about experience, so we should not generalize from a claim about nontemporal aspects of experience to a claim about temporal aspects. This undermines the typical strategy adopted by those defending a general claim of diaphanousness. That strategy begins with examples such as seeing "the intense blue of the Pacific Ocean" (Tye, 1992, 160), claims that the relevant aspects of experience in such cases are diaphanous, and then generalizes from these cases to all aspects of experience. This will not do if time is special.

The second challenge is that it is part of our ordinary conception of the mental that experience has a temporal structure *of which we are aware*. This awareness may of course go via the event-structure that we are perceptually aware of—and so commit us to naïve matching—but it would be a mistake to think that this was a bar to awareness.[11] We can see this by considering two very simple cases. Next time you see the traffic lights change from amber to red, stop and consider: which experience came first, your experience of the red light, or your experience of the amber light? I predict that you will be able to answer knowledgably and with ease that your experience of the amber light occurred before your experience of the red light. Next time you hear someone knock twice at your door, consider: did your experience of the first knock itself last longer or shorter than your experience of the second knock? Again, I predict that you will be able to answer knowledgably and without difficulty.

It is, in other words, very natural to think that we can straightforwardly make judgments about the temporal features of our experience itself just in virtue of undergoing it. The theorist who denies this must claim that we never understand the above questions as directly asking us about our experience (or answer such questions as if they asked directly about our experience). Moreover, they must explain the difference between time and color or shape in this regard. For we both understand and *reject* questions such as, when you looked at the two patches, which of your experiences was itself redder? Or, when you saw the two shapes presented one after the other, which of your experiences was squarer than the other?

In this light, it is no surprise to find the attractions of the naïve view recognized in the literature. The most notable advocate of naïveté is Helmholtz, who, emphasizing time's specialness, insists that the *only* case in which

> our perceptions can truly correspond with outer reality, is that of the *time-succession* of phenomena. Simultaneity, succession, and the regular return of simultaneity or succession, can obtain as well in sensations as in outer events. Events, like our perceptions of them, take place in time, so that the time-relations of the latter can furnish a true copy of those of the former. (1925, 445)

Helmholtz is famously criticized by James (1890). Yet, although James's objection that "*a succession of feelings, in and of itself, is not a feeling of succession*" (1890, 628), is one of the most commonly quoted slogans in the literature, his immediate reaction is rarely noted.[12] This is what James writes:

> One experiences an almost instinctive impulse, in pursuing such reflections as these, to follow them to a sort of crude speculative conclusion, and to think that he has at last got the mystery of cognition where, to use a vulgar phrase, "the wool is short." What more natural, we say, than that the sequences and durations of things *should* become known? The succession of the outer forces stamps itself as a like succession upon the brain. The brain's successive changes are copied exactly by correspondingly successive pulses of the mental stream. The mental stream, feeling itself, must feel the time-relations of its own states. But as these are copies of the outward time-relations, so must it know them too. That

> is to say, these latter time-relations arouse their own cognition; or, in other words, the mere existence of time in those changes out of the mind which affect the mind is a sufficient cause why time is perceived by the mind. (1890, 628)[13]

Here James eloquently testifies to the naturalness of the naïve view, even if he ultimately regards it as "unfortunately too crude."[14] Contemporary orthodoxy follows James.[15] In the rest of this chapter, I defend Helmholtz.

7.5 Hopelessly Naïve?

Lee identifies a "confused tendency in our thinking about temporal experience" (2007, 343) that he labels the *cinematic view* of temporal perception. According to the cinematic view, "experience presents temporal phenomenology in virtue of its own temporal layout," a claim with the consequence that there is "a direct link between the temporal properties of perception, and its temporal content" (ibid.). Lee accuses such a view with "content/vehicle confusion," suggesting that "most would agree that the model is prima facie very dubious" (373).

Lee's cinematic view is not the same as the naïve view. According to the cinematic view, experiential temporal content is possessed in virtue of the intrinsic temporal properties of experience. Naïveté reverses the order of explanation: in the absence of illusion, the temporal structure of experience is (in part) determined by the temporal properties of the objects and events that one confronts. The intrinsic temporal properties of the stream of consciousness are partly taken up from the temporal structure of the world. Nonetheless, both views crucially agree that there is "a direct link between the temporal properties of perception, and its temporal content." And in this regard Lee nicely articulates the current climate of hostility when he suggests that this shared view is widely agreed to be "prima facie very dubious"—the very opposite of naïve.

Lee suggests that the cinematic view exhibits a content/vehicle confusion. Yet neither the cinematic view nor the naïve view confuses contents and vehicles. Rather, both explicitly propose a relation between two temporal structures: that of experience and that of the objects of experience. Nonetheless, what Lee evidently has is mind is the hugely influential critique of a naïve model of temporal experience found in the work of Dennett (especially, Dennett & Kinsbourne, 1992 and Dennett, 1991).[16] Dennett urges us to "distinguish time represented from time of representing" (1991, 161), and contends that the two come apart at short timescales. In Dennett's view, all that matters for determining the order of the apparent objects of experience is the temporal content of experience (ibid., 149ff.). Consequently, he thinks that there is no reason why contents should not be tokened in temporal orders quite distinct from the temporal orders of the events that they represent. On his view, it is, for example, quite possible for one's experience, as of a flash followed by a bang, to be structured in the opposite way to that in which the events are represented as occurring (ibid., chapter 6, passim). To think otherwise is just to confuse time represented with time of representing.

Dennett's suggestion that contents can be tokened in temporal orders quite distinct from the temporal orders of the events that they represent is logically coherent.[17] Nonetheless, if the naïve view is right that the temporal structure of experience is determined by the temporal structure of the apparent objects of experience, then contra Dennett, there *is* a principled reason why contents cannot be tokened in temporal orders distinct from the temporal orders of the events that they represent. Given this constraint, it is not possible for one's experience (as of a flash followed by a bang) to be structured in the opposite way to that in which the events are represented as occurring.

I shall shortly come to Dennett's central and much-discussed argument based on short-timescale "postdictive" phenomena. However, Dennett's critique of the "representing/represented confusion" as applied to the temporal case is almost universally applauded, despite the fact that his central argument is extremely controversial.[18] The reason is that Dennett offers a series of analogies and intuition pumps which have a great deal of suasive force in their own right.[19] As a result, it is worth briefly dwelling on these analogies and pumps before considering Dennett's central argument.

7.6 Analogies and Intuition Pumps

Consider Hurley, who, citing Dennett, urges that we should not "project temporal relations between vehicles of content into the content of temporal representations" (1998, 29). Hurley argues as follows.

> In general representations do not have to resemble what they represent. This is clear enough in some cases: no one thinks the representation of something green must itself be green, or that the representation of something round must itself be round. But it is easy to slip into this confusion for more complex, abstract or relational properties, such as simultaneity. (1998, 29–30; also Tye, 2003, 90, and 2006, 511)

Hurley is, of course, right when she avers that experiences representing green trees do not themselves have to be green. Nor, of course, is Emily Dickinson's reference to Spring—"This whole experiment of green"—itself green! Yet it is hard to see how this bears on the case in point. Temporal structure, unlike color, is a property essentially and manifestly common to experience and its objects. Consequently, there is no analogy between the representation of color in experience (or poetry) and the representation of simultaneity or relative duration in experience.[20]

Similarly, Treisman concurs with Dennett when he writes, "The time represented by an element of phenomenological experience is not the time at which that element is generated—as the naïve realist with respect to time would suppose—but the time to which it refers, just as beige is not the color of a conscious sensation but of my word-processor" (1992, 225; cf. Shepherd, 1992, 223). But to repeat, this last analogy is irrelevant: at least in their subjective aspect, experiences do not have color properties, whereas they do manifestly have temporal properties. The naïve view is entirely unthreatened.

What we see in these passages, and especially in Dennett's own work, are repeated and vivid appeals to the way properties including time are represented in other media—for example, novels (Dennett, 1991, 148), letters (ibid., 146–7), pictures (ibid., 131, 147) and films (ibid., 137, 152)—followed by the implicit suggestion that experiential representation should be expected to operate along similar lines. However, for such appeals to be probative, the ways in which such media represent must be analogous to the experiential representation of time. In many cases a simple point suffices to defeat the analogy. Novels, letters, and pictures are not themselves temporally structured. Thus, although their modes of temporal representation clearly allow for time of representation (whether writing or reading, painting or viewing) to come apart from time represented, it is hard to see what bearing this has on a case where the medium of representation itself has temporal structure.

For these analogies to be probative we need to find a medium that, like experience, has a temporal structure of its own. Cinema is the obvious choice, for film is a paradigmatically temporal art. However, when one considers the case of film, it is far from clear that the analogy tells in Dennett's favor. Indeed, the natural view of cinematic depiction precisely involves a direct link between the temporal structure of the film itself and the temporal structure depicted—hence Lee's name for the allegedly confused "cinematic view" he identifies! Walton, for example, contrasts photographs with films on the grounds that photographs do not represent movement or change by themselves moving or changing, whereas, in contrast, motion pictures can be *defined* as "pictures whose temporal properties do contribute to their representational content" (2008, 164; see also Currie, 1995, Yaffe, 2003). Moreover, it is not just that there is a link between the depicted temporal structure and order of depiction with respect to film. There is, arguably, at least within scenes, a direct *match* between the two structures.[21] Thus the analogy with depiction in film, far from supporting the idea that the temporal ordering of experience itself can come apart from the temporal ordering of events presented, plausibly suggests the opposite: the temporal structure of experience and the temporal structure of its objects must match (at least within unified stretches of experience).

7.7 Postdiction and Naïveté

I now turn to Dennett's central argument against the naïve view. Dennett cites a number of experimental findings he claims are incompatible with our naïve conception of experience in time, and instead motivate (what many take to be) a form of antirealism concerning temporal experience. Subsequent writers offer similar cases in order to reject naïveté and to defend their own theories of time consciousness.[22] My interest in this section is to show how we can account for the relevant experimental data while maintaining the naïve view (i.e., without abandoning the matching thesis). As a result, my focus will be on the data as opposed to Dennett's (or anyone else's) positive proposals.[23]

Dennett's cases—visual masking, apparent motion phenomena (what Dennett calls color "phi" though in fact is "beta") and the cutaneous rabbit—are instances of what Eagleman and Sejnowski (2000) call *postdictive* effects.[24] Postdictive effects are cases where perceptual experience of an initial target stimulus is modulated (sometimes dramatically) by a second stimulus, even though that second *modulator* stimulus is presented sometime after initial target offset. In the cutaneous rabbit illusion (Geldard & Sherrick, 1972), for example, a series of fifteen 2 ms pulses are delivered in rapid succession (gaps must be less than 200 ms with optimal effects occurring with 40–60 ms gaps): the first five at the wrist, the second five 10 cm toward the elbow, and the final five 20 cm toward the elbow. If you experience only the first five pulses, then, *ceteris paribus*, you accurately experience them all as located at the wrist. But in the set-up just described, the pulses "seem to be distributed, with more or less uniform spacing" from wrist up the arm (Geldard & Sherrick, 1972, 178). Thus, it appears, that whether the second pulse, say, is felt (accurately) to be at the wrist or (inaccurately) to be a little way further up the arm depends on the occurrence and location of subsequent taps.

Such cases, and their name is legion, raise an obvious question: what is felt immediately following the second pulse? More generally, in relation to postdictive effects, what is perceived immediately following initial target presentation (i.e., before a modulator potentially occurs)? An apparent dilemma emerges. If no subsequent pulses had occurred, the second pulse would have been felt to be just where it was. So it seems either the second pulse is in fact felt to be where it is even when a modulator does occur, in which case something must be said to explain why subjects do not report it to be there, or there must be a significant delay in conscious experience such that neural processing can take into account whether and where subsequent taps occur before the presented location of the second tap is fixed.

Grush's account—the "trajectory estimation model"—takes the first horn. His trick is to claim that whereas "*at the time of the second impulse* the subject perceives it to be at the wrist, at the time of the fifth impulse, the subject has no recollection of this prior interpretation, and rather has a perceptual state to the effect that there is currently a sequence of impulses, the second of which was just proximal to the wrist" (2007, 39, his emphasis). In other words, Grush proposes that the initial experience is very rapidly forgotten, and is then followed by a second, illusory experience of the target that is remembered. Grush suggests his picture is consistent with the multiple drafts model that Dennett and Kinsbourne (1992) and Dennett (1991) use to explain postdictive effects. But it seems clear that Grush's picture is, in fact, what they call an *Orwellian* account, since it posits conscious experiences that leave no lasting cognitive trace, being overwritten within some tens, at most hundreds, of milliseconds.[25] Orwellian interpretations clearly abandon naïveté. As Grush puts it, "at the time of the fifth impulse, the subject … has a perceptual state to the effect that there is currently a sequence of impulses, the second of which was just proximal to the wrist" (2007, 39).

Dainton (2008b) takes the second horn of the dilemma and defends what Dennett and Kinsbourne call a *Stalinesque* approach to postdiction. On Dainton's account, conscious experience lags a hundred or so milliseconds behind the stimulus presentation, in such a way that subsequent stimuli can affect the ongoing processing within this window. With such a lag there is only a need for a single, illusory presentation of the world in postdictive cases.[26] This Stalinesque response is quite compatible with the naïve view, which is entirely consistent with *some* delay between events and our experience of them. (Some delay is arguably required by time-lag considerations.) As a result, it is preferable to the Orwellian account.

Nonetheless, once one considers the full range of postdictive effects, the kind of delay such a response is committed to (upward of 300 ms) can start to look problematic. This is a line Dennett pursues on behalf of Orwellian accounts of postdiction, since he takes it to conflict with the "abundant evidence that responses under conscious control … occur with close to the minimum latencies (delays) that are physically possible" (1991, 122). It is not entirely clear what evidence Dennett has in mind, and it is a matter of some controversy whether demonstrative evidence exists in this relation. Nonetheless, in light of this concern, Dainton's response can at most receive a cautious welcome, and the naïve view remains under threat.

In what remains, I argue that a proper understanding of Dainton's own extensionalist view of time consciousness (and, for that matter, a proper understanding of what we have rejected in rejecting PSA) shows how we can avoid both Stalin and Orwell and provide a plausible account of postdiction that safeguards naïveté.

7.8 Extensionalism and Naïveté

According to Dainton's extensionalism, awareness is not "packaged into momentary acts" (2000, 166); rather, consciousness essentially "extends a short distance through time" (2008a, 631), that short distance being the specious present, which Dainton reckons to be on the order of half a second in length.[27] The extensionalist theory is intended as a theory that, at least in part, explains our awareness of succession and change. Yet, in the context of that debate, it is natural to object that, just as a succession of experiences does not in and of itself amount to an experience of succession, we cannot "trace the idea of duration and succession back to the fact of the duration … of the psychical act" either (Husserl, 1964, 31). If stretches of experience are inevitably built up out of shorter (perhaps instantaneous) stretches that are themselves incapable of presenting temporally unfolding objects, it does indeed remain obscure how combining such elements could ever constitute experience of succession.

In order to address this worry, the extensionalist must deny that experience is to be thought of as built up from any such units. When it comes to experience, it is significant stretches, not instants, that are explanatorily and metaphysically fundamental. In other words, the key claim required to make sense of temporal experience is not merely that experience is *extended* through time, but rather that there are certain durations of experience that are *explanatorily* or *metaphysically prior* to their temporal subparts. Though Dainton does not state this explicitly, this is how we must understand the extensionalist denial that "our consciousness is confined to an instant" (Dainton, 2008a, 626).[28]

The extensionalist, as I have interpreted him, need not thereby deny that there are truths about instants. They can instead think of such truths as holding in virtue of what is true over a surrounding, and explanatorily fundamental, period. The most basic facts about our experiential lives are facts about extended stretches of the stream of consciousness, and what is true at an instant is true only in virtue of that instant being an instant during such a period of experience. As a result, truths that hold at instants need not be of the form: S has an experience *e* of event ε at instant *t* (with the consequence that ε cannot be a succession on pain of rejecting naïveté). Instead, in virtue of having an experience *e* of an event ε *over* some period Δ*t*, S can be *experiencing* ε at *t*. Thus, imagine that, over a half-second period, a batsman experiences a ball's motion from one end of the wicket to the other. It will not be true that, at an *instant* during this period, the batsman has *an experience* of any of the ball's motion. Nonetheless, it may be true that he is *experiencing* the ball's motion at that instant in virtue of that instant being a temporal subpart of a longer experience that has the ball's motion as object. Similarly, over a very short period of time, the batsman does not have an experience of the ball traveling the tiny distance it covers in that time, on pain of pretending to super-human powers of discrimination. Rather, during that brief period the batsman sees the ball *continuing on its way* from crease to crease (or more precisely: traveling from one discriminably different position on that path to another).[29]

We can now return to postdiction with two key facts in mind. According to the extensionalist (as I have developed their view): (i) the metaphysically fundamental units of experience are extended in time; and (ii) these metaphysically fundamental units are of the order of half a second in length. Now, consider again the cutaneous rabbit experience. The orthodox view that there must be a delay in our conscious experience to explain the apparent spatial distribution of taps is driven by the following reasoning. Consider two trials of the experiment. On the first trial, only the five taps at the wrist are presented; subjects report feeling all five at the wrist. On the second trial, the same five taps are presented, followed by a second and third set, 10 and 20 cm up the arm, respectively. Apart from the first, sixth, and final tap, all others are mislocalized, being experienced as spread up the arm from their actual location.

It is extremely natural to think about the situation in the first trial as follows. The second tap is presented at time *t*; the subject then feels the tap at some later instant, *t* + δ*t*. On this picture we are led to ask: *what does the subject feel at t + δt in the second trial?* If we want to resist the answer being, *the tap at the wrist* (as the Orwellian account claims), then we seem forced to claim that δ*t* is a period of at least 240 ms (plus further processing time)—enough time for the tap to be relocalized in the light of information about the subsequent taps.[30] However, this natural way of thinking implicitly assumes that we can legitimately ask what is true of experience at some instant, *t* + δ*t*, without taking into account the nature of the subject's experience at subsequent times. That would be legitimate if experience were analyzable down to instants (or very brief durations). But that is precisely what the extensionalist denies. If extensionalism is correct, then in thinking about postdictive effects such as the cutaneous rabbit, we cannot assume that what is perceived at $t + \delta t$ must be the same across trials. For that instant is part of a different, metaphysically fundamental stretch of experience in each case.

Thinking about things from the metaphysically fundamental perspective, what is true is that, over an extended period of several hundred milliseconds, one is either presented with a series of taps at the wrist and nothing else, or alternatively with a series of taps at the wrist followed by taps further up the arm. These are the stimuli with respect to which the basic experiential facts are determined, and upon which facts about instants are derivative. As a result, there is no reason to assume that the experiential presence of subsequent taps at the wrist is irrelevant to answering the question as to whether the initial taps are mislocalized or not. Certainly, it is true that, if no subsequent taps had occurred, then the wrist taps would have been correctly localized. But this has no bearing on the case where the taps did occur. *Where was the tap felt to occur at* $t + \delta t$*?* is not a question that one can answer without settling facts about one's experience during the surrounding period of time. Thus, there is no reason to assume that a tap will be experienced in the same way when it forms part of a different series. Our extended experiences may be just of wrist taps (correctly localized), or of (largely) mislocalized taps moving up the arm.

Nothing in this account demands a delay. It is not ruled out, but nor is it necessary. As a result, the interpretation of this and other postdictive effects is not hostage to evidence of responses under conscious control being possible at very short latencies. Furthermore, the interpretation shows how we can respond to the puzzle of postdiction without relinquishing the naïve view of temporal experience. Certainly, the extensionalist account of postdiction just outlined is far from naïve. But there is no reason to expect the theoretical underpinnings of naïveté to be naïve.

7.9 Conclusion

Dennett's objection is not the only objection that can be raised against the naïve view. One obvious challenge comes from cases where subjects are inclined to talk of time as slowing down, in particular during situations of life-threatening danger.[31] Another challenge is presented by Watzl (2013), who argues that motion silencing effects (Suchow & Alvarez, 2011) constitute a counter-example to the naïve view.[32] Nonetheless, what I have shown here is that the naïve view is both highly intuitive, and capable of withstanding a central and influential line of criticism. I have also called for a fresh start to debates about time consciousness. If we reject PSA, we need to go back to the beginning and reconsider why we need a philosophical theory of time consciousness in the first place. What I have argued is that we need not so much a theory as an answer to the special question that temporal experience poses, namely the question of the relation between the temporal structure of the objects of experience and the temporal structure of experience itself. The naïve "theory" is the natural answer. Arguably it is also the right answer.[33]

Notes

1. This is a rough and ready formulation. Compare Dainton's: "to be experienced as unified, contents must be presented simultaneously to a single momentary awareness" (2010, Sec. 3).

2. Arguably, this reasoning is central to Kant's critical project. Throughout the *Analytic of Principles*, Kant asserts, "time cannot be perceived by itself, and what precedes and what follows cannot, therefore, by relation to it, be empirically determined in the object" (2003, B233). In Guyer's view, Kant is "more intelligibly" rendered as claiming "that particular temporal relations are not directly perceived" (1987, 167).

3. This approach is Kantian in spirit; it is also the natural reading of Husserl (1964). Prichard (1950, 47–8) notes, it seems to me decisively, that in audition we can simply make no sense of experience without temporally extended contents: sounds (and, I would add, silences) essentially have duration, and all auditory experience is experience of sound (or silence). Consequently, the constructive memory theorist has no resources with which to get this project started.

4. See Dainton (2000) and (2010) for an excellent introduction and overview.

5. See Phillips (2010). For specious present and memory theories that are committed to rejecting PSA, see Dainton (2000) and Kiverstein (2010), respectively.

6. Cassam cites Dray (1957, 160) as the source of this view and directs us also to Nozick (1981, 8–11) and Stroud (1984, 144).

7. This claim is emphasized by a number of writers. For example, Mellor draws attention to "the striking fact … that perceptions of temporal order need temporally ordered perceptions. No other property or relation has to be thus embodied in perceptions of it: perceptions of shape and color, for example, need not themselves be correspondingly shaped or colored" (1981, 8), and Carnap notes in the *Aufbau* that "the psychological objects have in common with the physical ones that they can be temporally determined. In other respects, a sharp distinction must be drawn between the two types. A psychological object does not have color or any other sensory quality and furthermore, no spatial determination" (1967, §18, 33). It may seem that if identity theories are correct, then time cannot be special in the way proposed. However, the claim here concerns what is common between the objects of experience and the manifest or *experiential* properties of experience. The identity theorist precisely proposes that experience has properties that are nonexperiential. See Phillips (2009, chapter 1) for further discussion and clarification.

8. The naïve answer recalls a principle Miller labels the "principle of presentational concurrence," the principle that "the duration of a *content* being presented is *concurrent* with the duration of the *act* of presenting it. That is, the time interval occupied by a content which is before the mind is the very same time interval which is occupied by the act of presenting that very content before the mind" (1984,

107). Miller's principle is naturally read as involving commitment to a strict match between time intervals as opposed to the merely structural match on which the present discussion focuses.

9. For more on this theme see Phillips (2009, chapter 3) and Phillips (2010).

10. Indeed, on the picture here presented it is no longer clear that time *is* special.

11. I endorse this claim, and so a form of temporal transparency, in Phillips (2010).

12. James's slogan can be interpreted in different ways. In a weak form it merely claims that not every succession of experiences is an experience of succession. As such the principle is clearly true, but no threat to the naïve view. In a strong form it claims that no succession of experiences ever constitutes an experience of succession. This claim should be rejected—for it amounts, in effect, to a version of PSA, and we should reject PSA (see Phillips, 2010).

13. James treats the naïve view as committed to claims about the timing of neural events (as well as to a claim about the "mental stream"). Naïveté, as I understand it, makes no such commitments (though it recognizes that certain views of the relation between the mental and the physical would generate such commitments).

14. Cf. Dainton (2010, §7.1), who comments that the "picture painted by Helmholtz is plausible and appealing," before noting that there are, "inevitably, complications," not least the objection discussed below.

15. A rare exception is Foster: "we have to take experience to extend over a period of real time in a way which exactly matches the phenomenal period it presents" (1991, 249).

16. For convenience I focus on Dennett (1991). This should not obscure the collaborative nature of the original work.

17. Roache is wrong to claim that "it would be contradictory to assert that the order of perceptions may differ from the perceived order" (1999, 237).

18. Of the twenty-eight original commentators on Dennett and Kinsbourne (1992), Rollins (1992) is alone in questioning the view that time of representing might come apart from time represented. Hardly any of the commentators agree with the proposed multiple drafts model. Block, who in other respects trenchantly criticizes Dennett and Kinsbourne, simply remarks, "[Dennett and Kinsbourne] correctly point out that the temporal order of outside events needn't be represented by the temporal order of inside events. This Kantian point (Kant distinguished apprehension of succession from succession of apprehension) is certainly correct" (1992, 206). Block here gives no indication of why he thinks Dennett and Kinsbourne are "certainly correct." Indeed, as with Tye (1993), he *rejects* their Stalinist/Orwellian arguments; he does not appeal to analogies as they and others do; and the appeal to Kant only establishes a conceptual distinction and not a genuine possibility. See also Clark (1992, 207), Farah (1992, 209), and Lloyd (1992, 215).

19. As Reingold writes: "[Dennett and Kinsbourne] not only expose brilliantly an important confusion between the temporal properties of the process of representing and the temporal content of the representations themselves, but they also provide powerful metaphors that may help one sliding back into this ingrained confusion" (1992, 218).

20. Poetry might be written down in colored ink, but there is nothing essentially colored about written or spoken representation; it is evidently not a case where color is used to represent color.

21. I defend this claim at length in Phillips (2009, chapter 2). In defending the claim it is crucial to distinguish between (among other things) the temporal structure *depicted* by the film and the temporal structure of the narrative *represented*. These can clearly come apart. One obvious example is the use of reversal effects. For instance, in Avary's *The Rules of Attraction*, a piece of film of a plane moving through the sky is played backward within the intended structure of the film to indicate a backward shift in narrative. What is strictly speaking depicted is a plane moving backward through the sky (this despite our knowledge that the scene actually filmed involved a plane moving forward through the sky). The depicted order has the plane first at point B, then at point A; the narrative and scene structure places the plane first at A, then at B. When considering the analogy with experience, we should focus on the relation between depicted structure and order of depiction. It is depiction that is distinctive of cinematic representation.

22. Grush 2007, for example, offers three cases as evidence that the structure of act- and object-time come apart: the cutaneous rabbit, apparent motion, and representational momentum. The first two of these cases are straight from Dennett. Grush's target is Dainton's extensionalism. He apparently takes it as obvious that the extensionalist will want to endorse the naïve view. It is not clear why.

23. It is a nice question how exactly we should understand Dennett and Kinsbourne's precise arguments and position. See Phillips (2009, chapter 5) for one suggested reading.

24. For more on how we should understand postdictive effects and the claim that so-called "iconic memory" is simply a postdictive effect, see Phillips (2011a).

25. Dennett and Kinsbourne argue that both Orwellian and Stalinesque accounts are wedded to a false assumption about experience. For discussion see Phillips (2009, chapter 5).

26. Grush suggests another problem with the naïve view (or rather with this alleged commitment of Dainton's extensionalism), viz. "its inability to say anything about representational momentum" (2007, 41), the illusion that, in certain circumstances, stimulus motion apparently continues beyond its actual termination. He does not say why, and it is puzzling why he thinks this should be so. The existence of temporal illusions itself in no way shows that naïveté (or extensionalism) is false. The naïve view claims a match between the structure of experience itself and its *apparent* objects. Furthermore, in claiming that the extensionalist cannot "say anything" about representational momentum, Grush implies that the extensionalist cannot take advantage of the kind of information-processing account he proposes. But as Dainton (2010) makes clear, the processing level is one thing, the phenomenal level is another. With this distinction in mind, the extensionalist might even endorse Grush's very own account at the processing level, while holding onto extensionalism at the phenomenal level.

27. Dainton attributes the view to Foster (1979, 1982, 1991), who is, as we saw above, a rare contemporary defender of the naïve view. Dainton (2002) contends that the act/object distinction is a false dogma that we should discard; thus, there really is no possibility of act-time coming apart from object-time, because the structures are identical. Though I cannot argue for it here, I think we should resist Dainton's rejection of the distinction.

28. Dainton himself introduces a special relation of diachronic co-consciousness at this juncture, as opposed to appealing to the metaphysical primacy of stretches of experience. There are different ways of understanding this idea. However, insofar as Dainton conceives of the relata of the unity relation as independently specifiable experiential units, I am skeptical that this maneuver goes far enough. The problem is that the nature of experience over short timescales may simply be unspecifiable except by appeal to some longer stretch of experience of which the relevant sub-stretch is a sub-part. If that is right, then even if there are reasons to talk of diachronic co-consciousness, it must not obscure the metaphysical primacy of stretches as developed here. For more on these issues see Phillips (2011b) and below. An important influence on my treatment is Soteriou (2007, esp. 552–4).

29. See Phillips (2011b) for much fuller discussion of this point.

30. If the 2 ms taps are spaced 60 ms apart, then the time between the second tap and the sixth (the first tap not at the wrist) is a period of 240 ms. If more taps are required for the effect to occur, then a longer period is necessary.

31. Dainton (2010, §7.1) cites a more mundane case of this kind as a further reason for giving up the naïve thesis as a general claim about temporal experience. Lee (2009) forcefully presses a form of this objection. For discussion and response see Phillips (2013). See also Arstila (2012) for a helpful discussion of our experience in these cases.

32. See Phillips (forthcoming) for a response.

33. This work grew out of my PhD which was primarily supervised by Mike Martin to whom I owe a large and long-standing intellectual debt. A rather different version of this material was presented at a workshop in Geneva in 2009. My thanks to the participants there for very helpful discussion. Shortly after it had gone to press in 2010, I also presented a version at a workshop in Harvard. I am very grateful to the audience there, and especially to my excellent commentators, Laurie Paul and Geoff Lee. I hope to address the issues they raised more fully in future work. Special thanks also to Barry Dainton for very helpful written comments and, as always, to Hanna Pickard.

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III Choppy Streams of Consciousness

“When I’m looking at the car first, it seems far away. But then, when I want to cross the road, suddenly the car is very near.” Thus reports patient LM, a sufferer of akinetopsia, or motion blindness (Zihl, Von Cramon, & Mai, 1983, 315). According to Zihl et al., LM “had difficulty, for example, in pouring tea or coffee into a cup because the fluid appeared to be frozen, like a glacier. In addition, she could not stop pouring at the right time since she was unable to perceive the movement in the cup (or a pot) when the fluid rose” (ibid.). LM, it seems, could perceive and recognize objects and people, but experienced their movements only as isolated, discontinuous, stroboscopic snapshots—quite unlike the ordinary experience of those with normal motion perception. For most of us, experience seems to be as William James (1890, 239) would have it: “It is nothing jointed; it flows.” Experience is smooth and continuous, like a river’s flow, and like the continuous processes that we observe in the world around us. Or so it seems.

The next two chapters challenge the metaphor of the flowing stream of consciousness to reveal that we have more common ground with LM than we might suppose. In chapter 9, Alex Holcombe introduces the do-it-yourself demonstration of discontinuity. Stand before a mirror and stare at your right eye, and now your left. You can see the change in your direction of gaze, but you’ll never see your eyes in motion, quite like LM’s description of an approaching car: far away and then, suddenly, very near. This is saccadic suppression, the quick edit of the visual world to omit the blurry jump from one fixation to the next. We execute several saccades a second. We don’t experience the blurry jump, nor do we experience a temporal gap, a blank or flash to fill the time required to complete the saccade. If the saccadic jumps were replaced by a blank field, they would be undeniably prominent. But the moments of lost time are lost to the stream of consciousness as well. A discontinuous psychological process gives rise to a seemingly seamless flow of the experienced world.

These little lapses of saccadic suppression suddenly open the possibility that the processes that construct subjective time are neither smooth nor continuous. The metaphor of cinema returns: what if perception really were stroboscopic, as it was for LM, but with a frame rate fast enough to enable us to live successfully in a continuously mobile world? In certain perceptual situations, particular illusions of motion might present themselves. One is the familiar "wagon wheel illusion"—in movies and television, forward-spinning spokes can appear to be turning slowly backward: One frame catches a particular spoke upright while the next frame catches the next spoke nearly upright. Instead of seeing two spokes in succession, we sometimes see one spoke moving backward. This depends on the frame rate and the speed of motion of the wheel. We all know this illusion, which depends entirely on the stroboscopic snapshots captured by the video or film camera. If our visual system worked like this, then the wagon wheel illusion should appear in real life as well, even in continuous lighting (sunlight, for example), which it does. Not always and not for everyone, but often enough to raise the possibility that ordinary perception proceeds as a quick succession of snapshots, with or without gaps between—or if not a succession of snapshots, then a continuous process that waxes and wanes in sensitivity, whose pulsing could produce stroboscopic effects like the wagon wheel illusion.

Niko Busch, Rufin VanRullen (chapter 8), and Alex Holcombe (chapter 9) discuss the evidence for a choppy stream of consciousness. The visual system is not a video camera, but does the cinema metaphor explain any part of the process of motion perception? There are alternative explanations, and ingenious experiments to probe them. At issue is James's assertion that consciousness is "nothing jointed." If the flow of time is in fact "jointed," then the phenomenology of time will come under new scrutiny. When we perceive motion, what really moves?

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8 Is Visual Perception Like a Continuous Flow or a Series of Snapshots?

Niko A. Busch and Rufin VanRullen

While there is virtually no debate over the fact that the world exists continuously and that movie cameras and many other technical devices operate in a discrete fashion, there is an old and still-ongoing debate regarding whether the world is represented in a continuous or a discrete fashion in the human mind. Moreover, the notions of what it means to say that the mind represents the world in a (dis)continuous fashion have changed over previous decades. Before we begin to discuss historical and contemporary accounts of the issue of continuous versus discrete perception, it will be useful to offer a definition of the central concepts of this debate.

When I look out of the window of my office, I see the traffic moving on the street. Right now, I see a taxi driving down Luisenstrasse.[1] I see the taxi as moving continuously down the street. Saying that an object moves continuously means that at each moment it occupies a certain position in space, and in order to move from A to B it needs to traverse through all positions between A and B. In simple terms, the object does not jump from one position to another. In the words of William James: "I can only define 'continuous' as that which is without breach, crack, or division" (James 1890, 237). Likewise, a perceptual or cognitive process is said to operate in a continuous fashion if this operation is persistently active during a time interval, undergoing continuous change in relation to the continuous changes in the environment, or if it could possibly begin at any arbitrary time.

Now imagine that I take a movie camera, say an old-fashioned Super 8 film camera, and shoot a movie of the taxi driving down the street. On film, the continuous motion of the taxi will be recorded in a discontinuous or discrete fashion. Saying that something is represented in a discrete fashion means that the continuous motion is represented by recording samples only at certain time instants (approximately every 42 ms for film). If these discrete sampling intervals were not precisely contiguous, information about the moving taxi outside the sampling intervals would be lost. In addition to the discrete onset of the snapshots, the acquisition of information by the camera also involves temporal integration: a single frame of the film represents not a single instant of time, but integrates and fuses information for as long as the shutter is open, such that two events happening at different times but within the same sampling interval will appear as simultaneous. In other words, "within a moment, time appears to stand still."[2] In our example, the apparent position of the taxi on a single frame of Super 8 film actually represents all positions the taxi occupied while that frame was exposed. While discrete sampling usually involves integration periods, these two processes are conceptually distinct. An integration period simply corresponds to temporal sluggishness of a device or a sensory system—a temporal interval over which the system blurs information together. It can occur regardless of how that device or system processes information, whether in a continuous or discrete fashion (Holcombe, 2009). Temporal integration of information underlies a host of experimental effects, in which stimuli in close temporal succession are fused, such as flicker fusion (Andrews et al., 1996), visual persistence (Di Lollo & Wilson, 1978), or visual masking (Breitmeyer, 2007). In addition to temporal integration, discreteness crucially implies a sequential succession of nonoverlapping integration periods, while continuous processing may be related to sliding or overlapping integration periods (Allport, 1968; Holcombe, 2009).

A concept related to discrete sampling is that of periodic or oscillatory processes. The notion of oscillatory neural mechanisms as the basis of psychophysical processes dates back to the pioneering works of psychophysics in the nineteenth century (cf. Fechner, 1860)—a time when the actual electrophysiological mechanisms of the nervous system were still largely unknown. Examples of periodic or oscillatory processes are the regular fluctuations of membrane potentials of cortical neurons. These oscillations go together with a fluctuation of the neurons' excitability (Bishop, 1932; Buzsáki & Draguhn, 2004; Fries et al., 2007). Thus, neurons are more likely to respond when external input arrives during the high-excitability phase of the internally generated oscillation. Discrete and periodic processes are similar in that they imply a sampling of information. In the case of a periodic or oscillatory process, the sampling is due to the excitability fluctuation, and thus the likelihood or the extent to which information is processed. An important difference between discrete perceptual moments (at least as described by most proponents) and periodic or oscillatory processing concerns temporal integration of perception: periodic sampling does not imply a priori that events sampled at different times during an oscillatory cycle are perceived *as* simultaneous. Accordingly, it is important to mind the distinction between claims about the discrete or periodic nature of the experience of time and the physiological or cognitive processes underlying this experience (see van de Grind, 2002; van Wassenhove, 2009), similar to the distinction made between the content (time represented) of a representation and its "vehicle" (time of representing; Dennett & Kinsbourne, 1992). While it is easy to see that there is no isomorphism between content and mechanism for stimulus properties such as color—the perception of a sunset does not involve orange-tinted neurons—there has been confusion between the content and mechanism of time, possibly because both experienced time and underlying neuronal processes do indeed have relevant temporal characteristics (whereas the color of neurons is obviously irrelevant to the experience of color). Nevertheless, a temporally discrete or periodic nature of sensory processing would not necessitate that we experience time as discrete moments.

8.1 A Brief History of Discrete Processing from the Nineteenth Century to the Present Day

The general notion of cognitive processes as a series of discrete events can be traced back at least to the British empiricists of the eighteenth century. David Hume noted that the stream of thoughts is "nothing but a bundle or collection of different perceptions, which succeed each other with an inconceivable rapidity. ... The mind is a kind of theatre, where several perceptions successively make their appearance" (Hume, 1826, 821).

Several authors have cited the Baltic-German scientist Karl Ernst von Baer as the first proponent of a theory of discrete mental-processing epochs who coined the notion of the "moment" (cf. Geissler, 1987; Fingelkurts & Fingelkurts, 2006; Pöppel, 2009). In his treatise (based on a lecture held in 1860), von Baer (1908) put forward the idea that an organism's sense of space and time is rooted in its metabolic, physiological, and anatomical conditions. Just as humans measure distances in terms of the length of feet or armspans, we seem to measure time (and short time intervals in particular) by salient physiological events occurring on a comparable timescale, such as heartbeats, breath, or eye blinks. For von Baer, the most important psychophysiological basis of the temporal progression of sensations and mental operations was the speed at which the sensory systems can create new sensations. Based on the empirical data available at the time, he estimated that humans can enjoy between six and ten "life moments" within one second, reasoning that the number would be significantly smaller for other species such as snails.[3] Thus, the organism's bodily processes are thought to provide a clock, while the speed and discrete nature of these processes result in the discreteness of mental operations, especially sensory processes.

William James refuted the idea of discrete perceptual moments as units of cognition. In his view, cognition proceeds continuously while the external world consists of discrete, discontinuous events. It is interesting to note that James's conception runs exactly counter to that of many twentieth-century scientists who endorsed the idea of discrete processing epochs.

> Consciousness, then, does not appear to itself chopped up in bits. Such words as "chain" or "train" do not describe it fitly as it presents itself in the first instance. It is nothing jointed; it flows. A "river" or a "stream" are the metaphors by which it is most naturally described. (James, 1890, 239)

> Things are discrete and discontinuous; they do pass before us in a train or chain, making often explosive appearances and rending each other in twain. But their comings and goings and contrast no more break the flow of the thought that thinks of them than they break the time and the space that lies between them. (James, 1890, 240)

However, with the advent of cinema and motion film only a few years later, the idea of a pseudo-continuous stream, which is actually made up from a series of discrete snapshots, appeared to be a viable metaphor for contemporary scholars. One example is the philosopher Henri Bergson, who devoted a section of his monograph "Creative Evolution" to the topic of "The Cinematographic Mechanism of Thought, and the Mechanistic Illusion." Being familiar with a technological artifact that represented the dynamic and fleeting visual world on a series of discrete frames led him to propose a view that was directly opposite to James's view of the streamlike nature of cognition and consciousness:

> Instead of attaching ourselves to the inner becoming of things, we place ourselves outside them in order to recompose their becoming artificially. We take snapshots, as it were, of the passing reality, and, as these are characteristic of the reality, we have only to string them on a becoming, abstract, uniform and invisible. … Perception, intellection, language so proceed in general. Whether we would think becoming, or express it, or even perceive it, we hardly do anything else than set going a kind of cinematograph inside us. (Bergson, 1911, 306)

Interest in the issue of discrete versus continuous processing was fueled by another scientific and technological advancement: the advent of cybernetics and the digital computer. Scientists soon noticed the similarity between the serial, pulsating operations of digital computing machines and the pulsating character of neuronal responses (i.e., action potentials), and discussed whether the digital computer can serve as a model for the brain and the human mind (see Gerard, 1951 and von Neumann, 1958 for a discussion). This similarity soon sparked the question of how information is represented in the brain. This is exemplified by McCulloch's question: "If you will, for the moment accept the distinction between analogical and digital, the question is whether information be continuously coded or discretely coded" (cited in Gerard, 1951; see Eliasmith, 2000 for a contemporary discussion).

The influence of the new field of cybernetics and the development of digital computers is illustrated in Stroud's remark: "The question arises: How much of man is, at any given time, working as a synchronized computer?" (Stroud, 1955, 201). At about the same time, several neurophysiologically oriented researchers began to investigate the link between brain oscillations and neuronal information processing, and the alpha rhythm in particular. The alpha rhythm was first described by Berger (1929) as a dominant oscillation in the ongoing electroencephalogram (EEG) with a frequency of roughly ten cycles per second. This rhythm is most pronounced in a state of relaxed wakefulness when subjects have their eyes closed, but can be observed even when eyes are open and subjects are engaged in an experimental task (see Palva & Palva, 2007 and Klimesch et al., 2007 for recent reviews). At that time, it was generally assumed that brain oscillations relate to regular fluctuations of neuronal excitability (Bishop, 1932), a view that is still largely accepted today (Buzsáki & Draguhn, 2004). Pitts and McCulloch (1947) suggested in their theoretical work on visual form recognition that the alpha rhythm implements a "scansion" mechanism, which reads out information from different cortical layers in a serial fashion: "If our model fits the facts, this alpha rhythm performs a temporal 'scanning' of the cortex which thereby gains, at the cost of time, the equivalent of another spatial dimension in its neural manifold" (133). A similar scanning mechanism was proposed by Wiener (1948): "The scanning apparatus should have a certain intrinsic period of operation which should be identifiable in the performance of the brain. … In fact, it has the order of frequency appropriate for the alpha rhythm of the brain, as shown in electroencephalograms. We may suspect that this alpha rhythm is associated with form perception, and that it partakes of the nature of a sweep rhythm, like the rhythm shown in the scanning process of a television apparatus" (165–66). Similar views were put forward by Walter (1950) and McReynolds (1953).

Stroud (1955) investigated the implications of such a scanning mechanism for perception: the temporal organization of perception as discrete processing epochs and the loss of temporal information within one such epoch or moment. He suggested that "physical time *t* is represented in the experience of man as psychological time *T*" (177), with *T* being a discrete variable. On the basis of his own experiments and various findings reported in the literature, he concluded that the moment as the "least possible timewise element of experience" has a duration of approximately 100 ms and that incoming sensory information is processed in consecutive and nonoverlapping samples or moments "directly analogous to the frames of motion pictures" (Stroud, 1967, 624). As an example, he referred to the finding that the perceived brightness of a visual stimulus increases with an exposure duration of up to 90 ms, indicating a time window of temporal integration with a duration of 90 ms. Note that, although Stroud distinguished between physical time and psychological time, it is not entirely clear whether "psychological time" refers to the experience of time or to the perceptual or neuronal processes underlying this experience, and at which of these dimensions temporal discreteness applies. Even though he frequently referred to the discrete nature of *experience*, the temporal aspects of this experience were actually not investigated in the studies cited in his paper. Rather, these experiments seemed to address the discreteness of the *processing* associated with this experience (see Efron, 1970 for a similar critique). In subsequent years, a number of studies presented evidence in favor of the discrete perceptual moment hypothesis. These were mostly concerned with perceived simultaneity, response time distributions, and correlations between EEG oscillations, perception, and behavior.

There is a certain minimal interstimulus interval for which two successive events are consistently perceived as simultaneous. This interval depends on stimulus conditions and has been estimated to last around 20–50 ms for visual stimuli (Kristofferson, 1967). White (1963) investigated a phenomenon called "temporal numerosity," whereby subjects underestimated the number of stimuli presented in a rapid sequence, supposedly because stimuli falling into the same perceptual moment cannot be distinguished. Similar experiments using dichoptic stimulation have demonstrated that such an integration of events falling into the same epoch occurs after binocular fusion, that is, at a later stage than V1, and therefore is not due to peripheral limitations (White et al., 1953; Andrews et al., 1996). According to the perceptual moment hypothesis, two successive events are perceived as simultaneous when they occur within a single discrete "epoch" of processing time. Thus, these studies appear to be compatible with the idea of discrete perceptual moments of 100 ms or less, within which stimuli would be grouped and subjectively interpreted as a single event. However, it has been demonstrated that in some cases, phenomenal simultaneity is better explained by visual persistence (Efron and Lee, 1971; Di Lollo & Wilson, 1978) or by a "travelling psychological moment" (Allport, 1968)—a continuously moving temporal integration window—rather than by non-overlapping discrete moments. Furthermore, the estimate of the time-window of integration appears to be strongly influenced by stimulus properties (Efron & Lee, 1971). This effect of stimulus properties has been criticized as inconsistent with the idea of a central scanning mechanism producing discrete moments of fixed duration (Patterson, 1990; Fraisse, 1984). The finding of variable integration times might be easier to reconcile with a more recent model of discrete processing. The time-quantum model by Geissler (1987; Geissler et al., 1990) proposes a much shorter type of intermittence as the smallest unit of psychological time. According to this model, the duration of an elementary time quantum is ≈5 ms and represents an absolute lower bound of temporal resolution. Importantly, concatenation of quanta may lead to longer, but still discrete processing intervals of various lengths (always multiples of the elementary quantum), although an upper bound for the length of an epoch is assumed.

Chronometric studies have demonstrated robust periodicities in reaction-time histograms at intervals of ≈100 ms (Venables, 1960) and 25–30 ms (White et al., 1953; Pöppel, 1970). Some studies find that the length of this periodic interval is task-dependent, with an average of ≈25 ms (Dehaene, 1993). Similar periodic distributions have been reported for saccadic reaction times with periodicities of 30–60 ms (Frost and Pöppel, 1976). Such periodicities could occur if some stimuli, arriving too late to be processed in one particular discrete epoch, were deferred to the next. Note that this would only become apparent in reaction-time histograms if the length or the onset of these discrete epochs were dependent on stimulus presentation.

Several studies have investigated the correlation of the alpha rhythm of the EEG and various aspects of perception and action (see Sanford, 1971, for a review). For example, Murphree (1954) reported that individual frequency of the alpha rhythm co-varies with individual simultaneity thresholds. Furthermore, several studies found a correlation between simple response times and the phase of the alpha cycle at the time the stimulus was presented (Lansing, 1957; Callaway & Yeager, 1960; Dustman & Beck, 1965). However, these studies have generally failed to show any effect larger than ≈10 ms, and some studies were not successful in finding any effect of the alpha rhythm on perception (Walsh, 1952). According to the theory of discrete psychological moments, this effect indicates that longest reaction times occur when a stimulus is presented as a new snapshot begins, while shortest response times are found when a snapshot is about to finish. However, these effects can also be explained by a cortical excitability cycle (Harter, 1967): stimuli presented at the excitable phase of the rhythm are preferentially processed. In line with this idea, several studies have found that the neuronal response to a stimulus is correlated with the phase of the alpha rhythm at stimulus onset (Callaway and Layne, 1964; Haig and Gordon, 1998; Barry et al., 2004; Jansen & Brandt, 1991), and even the perceptual threshold itself was found to oscillate (Latour, 1967).

Notably, a key prediction of the perceptual moment hypothesis has hardly been addressed at all: if the alpha rhythm represents the succession of perceptual moments, two stimuli falling into the same alpha cycle should be perceived as simultaneous. The only notable exception is the experiment by Varela et al. (1981), who found that presenting two flashes of light with always the same stimulus onset asynchrony, but at different phases of the ongoing alpha rhythm could induce dramatic changes in perception: when at one particular phase they were judged as simultaneous, at the opposite phase they were perceived as sequential. Importantly, this finding cannot be reconciled with the concept of a continuously shifting integration window. Furthermore, it extends beyond periodic excitability cycles since the alpha cycle did not influence the detectability of a stimulus, but rather affected the perceived simultaneity of two events. Although this finding lends strong support for the perceptual moment hypothesis, attempts to replicate the result have repeatedly failed (see VanRullen and Koch, 2003).

Recently the popularity of the idea of discrete processing epochs has been fuelled by a number of neural network models of visual perception (cf. Körner et al., 1999; VanRullen & Thorpe, 2002; Fries et al., 2007), which code information about stimulus features not only by the *strength* of the neuronal response (i.e., number of action potentials fired per second), but also by its *latency* (Rieke et al., 1997). The plausibility of a latency code is supported by the finding that latencies of the first spikes fired are informative about stimulus contrast (Gawne et al., 1996) as well as the match between a stimulus and a neuron's orientation selectivity (Celebrini et al., 1993). Since a neural network does not have information about the objective time when a stimulus is presented, network models implementing a latency code evaluate response latencies relative to an internally generated oscillatory reference signal. For example, in a model by Fries et al. (2007), the temporal reference frames are provided by networks of inhibitory interneurons generating synchronized rhythmic activity. These interneurons impose periodic cycles of excitability and inhibition onto nearby pyramidal cells, such that the network is receptive to excitatory input (i.e., due to stimulus presentation) only during certain moments of reduced inhibition. This mechanism allows coding of the strength of excitatory input by the latency of the network's response: cells receiving the strongest excitatory input (for example, due to high stimulus contrast or when the stimulus matches the neuron's preferred feature) will be able to respond first—that is, at a phase of the reference cycle when rhythmic inhibition is still relatively strong. By contrast, cells receiving weak input will tend to fire late relative to the reference cycle, at a moment when rhythmic inhibition is weak. Computational models have demonstrated that latency coding allows for a rapid classification of image content (VanRullen & Thorpe, 2002), which matches the speed and accuracy of object recognition in human observers (Thorpe et al., 1996; VanRullen & Thorpe, 2001). Of course, temporal coding of stimulus features is thought to operate on a short timescale only; latency differences that are longer than the duration of an epoch of the reference signal would indeed be coding temporal properties of the stimulus. In this respect, this coding principle resembles the idea of perceptual moments: within a moment, "time stands still." Therefore, neural network models that rely on latency coding and processing epochs have contributed to the renewed interest in the possible discreteness of perception and the perceptual moment hypothesis (see VanRullen & Koch, 2003). This recent work will be reviewed in the following sections.

8.2 Discreteness in Recent Studies

8.2.1 The Wagon Wheel Illusion in Continuous Light

Engineers know that any signal sampled by a discrete or periodic system is subject to potential "aliasing" artifacts: if the sampling resolution is lower than a critical limit (the Nyquist rate), the signal can be interpreted erroneously. This is true, for instance, when a signal is sampled in the temporal domain. When this signal is a periodic visual pattern in motion, aliasing produces a phenomenon called the "wagon wheel illusion": the pattern appears to move in the wrong direction. This is often observed in movies or on television, due to the discrete sampling of video cameras (generally around 24 frames per second). Interestingly, a similar perceptual effect has also been reported under continuous conditions of illumination, such as daylight (Schouten, 1967; Purves et al., 1996; VanRullen et al., 2005). In this case, however, because no artificial device is imposing a periodic sampling of the stimulus, the logical conclusion is that the illusion must be caused by aliasing within the visual system itself. Thus, this "continuous version of the wagon wheel illusion" (or c-WWI) has been interpreted as evidence supporting the view that the visual system samples motion information periodically (Purves et al., 1996; Andrews et al., 1996; Simpson et al., 2005; VanRullen et al., 2005).

There are many arguments in favor of this "discrete" interpretation of the c-WWI. Firstly, the illusion occurs in a very specific range of stimulus temporal frequencies, compatible with a discrete sampling rate of approximately 13 Hz (Purves et al., 1996; Simpson et al., 2005; VanRullen et al., 2005). Secondly, as predicted by the discrete sampling idea, this critical frequency remains unchanged when the spatial frequency of the stimulus (Simpson et al., 2005; VanRullen et al., 2005) or the type of motion employed (i.e., rotation versus translation motion, or first-order versus second-order motion) are manipulated (VanRullen et al., 2005). Thirdly, EEG correlates of the perceived illusion confirm these psychophysical findings and point to an oscillation in the same frequency range around 13Hz (VanRullen et al., 2006; Piantoni et al., 2010). Altogether, these data suggest that (at least part of) the motion perception system proceeds by sampling its inputs periodically, at a rate of 13 samples per second.

There are, of course, alternative interpretations of this phenomenon. Several authors have pointed out that the continuous wagon wheel illusion is not instantaneous, and does not last indefinitely; rather, it occurs as a bistable phenomenon which comes and goes with stochastic dynamics. Such a process implies a competition between neural mechanisms supporting the veridical and the erroneous motion directions (Blake & Logothetis, 2002). Within this context, the debate centers around the source of the erroneous signals: some authors have argued that they arise not from periodic sampling and aliasing, but from spurious activation in low-level motion detectors (Kline et al., 2004; Holcombe et al., 2005) or from motion adaptation processes that would momentarily prevail over the steady input (Holcombe & Seizova-Cajic, 2008; Kline & Eagleman, 2008). We find these accounts unsatisfactory, because they do not seem compatible with the following experimental observations: (i) the illusion is always maximal around the same temporal frequency, whereas the temporal frequency tuning of low-level motion detectors differs widely between first- and second-order motion (Hutchinson & Ledgeway, 2006); (ii) not only the magnitude of the illusion, but also its spatial extent and its optimal temporal frequency—which we take as a reflection of the system's periodic sampling rate—are all affected by attentional manipulations (VanRullen et al., 2005; VanRullen, 2006; Macdonald et al., 2013); in contrast, the amount of motion adaptation could be assumed to vary with attentional load (Chaudhuri, 1990; Rezec et al., 2004), but probably not the frequency tuning of low-level motion detectors; (iii) motion adaptation itself can be dissociated from the wagon wheel illusion using appropriate stimulus manipulations; for example, varying stimulus contrast or eccentricity can make the motion aftereffects (both static and dynamic versions) decrease while the c-WWI magnitude increases, and vice versa (VanRullen, 2007); (iv) finally, the brain regions responsible for the c-WWI effect, repeatedly identified in the right parietal lobe (VanRullen et al., 2006, 2008; Reddy et al., 2011), point to a higher-level mechanism than the mere adaptation of low-level motion detectors[4].

Another debate concerns the question whether the sampling mechanism acquires information simultaneously across the entire visual field, or whether sampling is a local phenomenon. When two separate motion stimuli are viewed simultaneously, the illusion of reversed motion rarely occurs for both objects together, ruling out global sampling of the entire visual field (Kline et al., 2004). The same result holds when two objects are presented at the same location and superimposed by transparency, arguing against purely location-based sampling (Kline et al., 2006). Instead, perceptual sampling appears to be object-based: when a rotating ring stimulus is split into two separate halves, and the two halves move in opposite directions (thus appearing to belong to separate objects), perceptual reversals occur in either half-ring at a time, but rarely in both halves at the same time. When the two halves physically move in the same direction (thus appearing to belong to the same object), they generally appear to reverse simultaneously; the illusion keeps the perceptual object united (VanRullen, 2006). Hence, it is the high-level organization of the scene that determines the extent of perceived motion reversals, rather than the local low-level properties of the motion stimulus. Attention can indeed be directed to features or objects as well as spatial locations (Kanwisher &Wojciulik, 2000). Thus, several studies support the conclusion that the c-WWI effect is limited to the—not necessarily spatial—focus of attention.

To summarize, our current view is that the reversed motion signals most likely originate as a form of aliasing due to periodic temporal sampling by attention-based motion-perception systems, at a rate of ≈13 Hz; the bistability of the illusion is due to the simultaneous encoding of the veridical motion direction by other (low-level, or "first-order") motion-perception systems. The debate, however, is as of yet far from settled.

8.2.2 Ongoing EEG Phase Predicts Perceptual Variability

The wagon wheel illusion under continuous light suggests that certain types of visual information (e.g., motion) are sampled discretely or "periodically" by the brain. If such sampling occurs, there must exist signatures of the sampling process at the neuronal level, for example in the form of an activity that waxes and wanes with every sample—in other words, in the form of neural oscillations, which are linked to perception or performance. Note that some of the neural network models mentioned above imply a similar interactive effect of stimulus input and rhythmic neural background activity on perception and the neuronal response. Recent studies by our group and others have tested this prediction by exploring the impact of the phase of ongoing prestimulus EEG oscillations on the subsequent perception of a visual stimulus (see VanRullen et al., 2011, for a detailed review).

In our first study (Busch et al., 2009), we presented brief (6 ms) and dim peripheral flashes of light, with the luminance of the flash adjusted individually, so that the exact same stimulus would be perceived on approximately half of the trials, but go completely unnoticed on the other half. We computed prestimulus phase-locking separately for the two trial groups corresponding to perceived and unperceived flashes, and found for each group a significant increase in phase-locking (compared to phase-locking computed on the same number of trials but drawn randomly, irrespective of perceptual outcome). This increase occurred just before stimulus onset, at a frequency of ≈7 Hz (see figure 8.1a), and the effect was maximal over frontocentral electrodes. In fact, by considering the phase of the 7 Hz band-pass-filtered EEG recorded at those electrodes just before stimulus onset in each trial, we could predict the subsequent response of the subject well above chance-level. Up to 16 percent of the trial-by-trial differences in perception were accounted for by comparing trials with the optimal phase angle versus those at the opposite angle (Busch et al., 2009). In a similar vein, Mathewson et al. (2009) reported that the phase of low-frequency oscillations (around 10 Hz) just before stimulus onset predicted trial-by-trial perception of masked stimuli. This relationship between the phase of spontaneous oscillations and visual perception indicates that visual information is not acquired to the same extent at all times. Rather, the results are in favor of a periodic sampling of visual information.

8.2.3 Ongoing EEG Phase Reflects Periodic Attentional Sampling

In a next study, we asked whether the influence of ongoing phase on perception was mediated by top-down attentional factors (Busch & VanRullen, 2010). The previous results had been obtained under conditions in which the target location was always known in advance; therefore, subjects may have paid covert attention to that location in order to improve their detection performance. Would ongoing oscillations still affect detection of a target appearing at an unattended location?

Before each trial began, a central cue indicated the location on the screen where the observer should expect to see the target. When the flash of light did occur at the attended

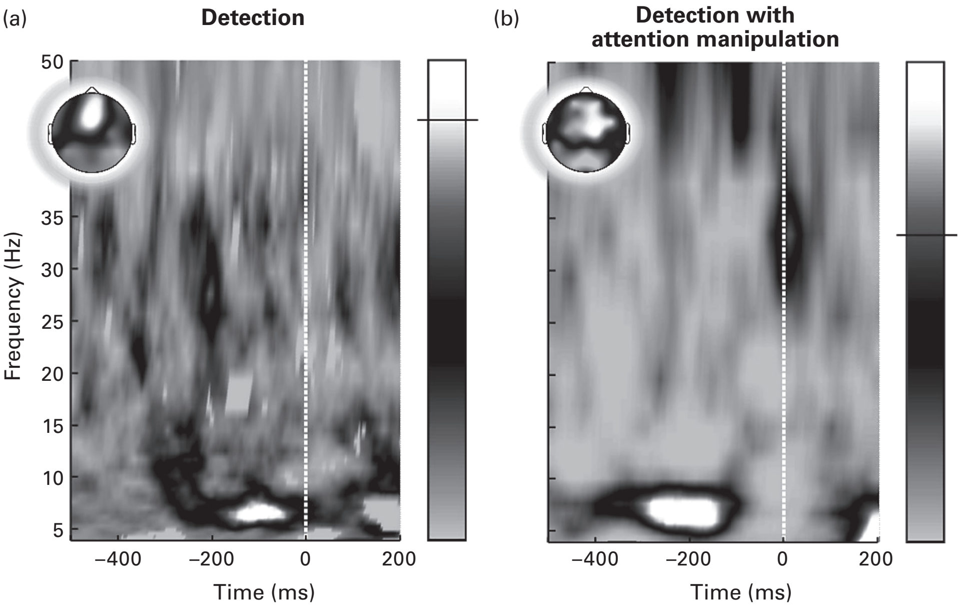

Figure 8.1
Two examples demonstrating the influence of prestimulus EEG phase on behavioral response variability. Each image illustrates the significance of a relation between the phase of ongoing EEG oscillations and a subsequent behavioral response recorded on the same trials, for various frequency bands (y-axis) and at different prestimulus times (x-axis). Time zero marks the (unpredictable) onset of the stimulus. The color bar represents *p*-values, with the significance threshold marked by a horizontal line ($p<<0.05$, corrected for multiple comparisons across time and frequency points using the FDR procedure). The insets illustrate the topography of the effect at the optimal time-frequency point. (a) The response specified whether or not the observer had perceived a peripheral flash of light. The influence of phase was measured by comparing the phase-locking computed for two groups of trials corresponding to perceived and unperceived stimuli to surrogate phase-locking values obtained under the null hypothesis (random permutation of behavioral responses). At ≈7 Hz and 100–200 ms before the stimulus appears, the phase of frontal EEG on each trial was strongly predictive of the perceptual outcome (Busch et al., 2009). (b) In a separate experiment, observers again reported their perception of a flash of light, but the focus of spatial attention was manipulated with a cueing procedure. A significant relation between ongoing EEG phase and trial-by-trial perception was recorded only when the target was flashed at the attended location. Here the image illustrates the significance of a circular-to-linear correlation between prestimulus phase (the circular variable) and post-stimulus global field power (GFP, a linear variable which we used as a marker of subjective perception; indeed, this GFP was virtually zero when the target was undetected). As in the previous case, the EEG phase at ≈7 Hz, recorded 100–400 ms prior to stimulus onset on frontal electrodes, was maximally predictive of target perception (Busch & VanRullen, 2010).

location, everything happened exactly as in the previous experiment—and indeed we confirmed our previous results in this condition, with a strong impact of ≈7 Hz prestimulus EEG phase on the probability of target perception (figure 8.1b). When the stimulus appeared at an unattended location, subjects had more difficulty in perceiving the stimulus (as indicated by the higher light intensity that proved necessary to achieve a 50 percent detection rate in this condition). This confirms that the observers were focusing on the cued side to the detriment of the rest of the screen. Critically, on those trials where the target appeared outside the focus of attention, the phase of the ongoing oscillation had no effect on detection of the stimulus. In other words, perception was related to ongoing EEG phase only via the action of attention. We thus hypothesized that attention samples visual information periodically, and that each ≈7 Hz ongoing EEG cycle is the reflection of a new attentional sample (Busch & VanRullen, 2010). Stimuli occurring around the optimal phase benefit from attention (i.e., are easier to detect), while others are processed merely as if they were out of the attentional focus. For some reason, likely related to its architecture and its neuronal substrates, the attention system could not apply the optimal strategy (optimal for such a detection task with unpredictable target onset) of steadily monitoring the expected location. These findings concur with conclusions from a previous psychophysical study which reported that attention samples information periodically at ≈7 Hz, even when only a single item needs to be attended to (VanRullen, 2007). In this context, the topographic localization of the phase effects over frontocentral electrodes may reveal the contribution of the frontal eye field (FEF), an area known, among other functions, for its involvement in visual attention (Crowne, 1983; Kodaka et al., 1997; Wardak et al., 2006).

8.3 Conclusion

In conclusion, the idea of discrete processing epochs has been repeatedly put forward by numerous scientists and philosophers for over a century, although their reasons for proposing such a processing mode have changed considerably. These changes were influenced not only by accumulating experimental evidence, but more importantly by technological advancements and a deeper understanding of the mechanisms of the mind and the brain. The invention of the cinematograph in the nineteenth century provided the metaphor of the “snapshot,” while twentieth-century theorists were strongly influenced by the invention of the digital computer and by computational neural network models. The empirical support for a strong form of discrete processing—non-overlapping moments during which temporal information is lost—is still inconclusive; some of the classical findings may be more compatible with a continuous processing mode involving a temporal integration window or visual persistence. However, evidence for periodic sampling mechanisms based on periodic fluctuations of neuronal excitability has accumulated, and neuronal network models have demonstrated the possible functions of such a mechanism for neural computations.

Notes

1. Other chapters in this book will have more to say about what it means to say “right now.”

2. *“Innerhalb eines Momentes ‘steht die Welt still,’”* (Brecher, 1932, 240)

3. *“Da nun unser geistiges Leben in dem Bewußtsein der Veränderungen in unserem Vorstellungsvermögen besteht, so haben wir in jeder Sekunde durchschnittlich etwa sechs Lebensmomente, höchstens zehn”* (von Baer, 1908, 156).

4. The neural mechanisms of the continuous wagon wheel illusion are the topic of a separate review (VanRullen et al., 2010).

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9 Are There Cracks in the Facade of Continuous Visual Experience?

Alex O. Holcombe

In a bowling alley, a professional player launches his ball down the lane. As the ball rolls toward the pins, our visual experience of it is smooth and seamless. The ball shifts in position continuously, and this seems to be represented with high fidelity by our brain. There are no subjective gaps, no stutter, and no noticeable blur.

One might assume that, in every instant, the brain simply processes the retinal input through various feature and shape detectors, with the results becoming available to awareness, millisecond by millisecond. This picture of a continuous system, with information continually ascending the system before being replaced by the information from the next instant, is still the predominant way in which psychologists and perceptionists think about the visual brain.

However, the results of experiments have steadily chipped away at this image. Together, these findings indicate that the smooth, seemingly high temporal resolution movie we experience during the roll of the bowling ball reflects a massive construction project by the brain. Many problems of ambiguous input are resolved, processing artifacts like blur are suppressed, and missing information is guessed at. Some of the more firmly established of these processes will be described at the end of this chapter. Unfortunately, there is no agreement on the extent to which these complexities should push us to revise our simple framework of millisecond-by-millisecond processing. Here, we will focus on phenomena that are more clearly at odds with the standard view. The bulk of this chapter is devoted to one particular way in which the processes that underlie our visual experience have been proposed to not resemble experience itself.

Visual experience over time feels seamless and undifferentiated. Following the bowling ball, we are aware of no frame rate, no intermittent updates as new information occasionally becomes available. Nevertheless, over the last few decades it has been suggested that behind the scenes, the visual system embodies processes that fluctuate up and down according to a regular rhythm. On this view, visual information is processed somewhat intermittently, or at least certain critical operations only occur on an occasional schedule.

While this proposal is surprising from the perspective of visual experience, perhaps it should not surprise those familiar with the habits of the brain.

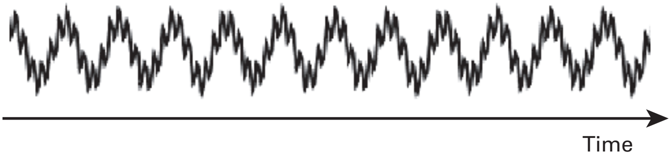

Figure 9.1
A schematic depicting the sum of an 8 cycles per second sinusoidal oscillation and a 50 cycles per second oscillation.

Oscillations or rhythmic fluctuations in activity and excitability occur in many biological systems. Although such rhythms likely exist for good reasons, they have the potential to disrupt the processing of sensory information. Visual information that arises during the down phase of a rhythm, when neurons are less excitable, might be entirely missed.

Figure 9.1 depicts a simple fluctuation, a theoretical example created by combining an eight cycles per second sinusoid with one that repeats fifty times per second. The faster wave is in the so-called gamma range of oscillation frequencies frequently found in the visual cortex and other areas of the brain (Engel et al., 1991; Fries, Nikolic, & Singer 2007). As far as I know, it has not been suggested that visual information arriving in gamma's up state is processed to a greater extent than information arriving in the downward deflection. However, it has been suggested that when many neurons oscillate together in this way, the information they represent can then become conscious (Crick & Koch, 1990). Although this hypothesis is less popular than it was twenty years ago, it exemplifies the fact that some oscillations have been proposed to play an important role in computation without any proposal that they regularly disrupt the representation of visual information. In the case of the fifty times per second oscillation, perhaps it is not disruptive because it is faster than the temporal scale of perception (Holcombe, 2009). The temporal smoothing that likely precedes perception would obliterate 50 Hz waves.

In contrast, waves like the slower one depicted in figure 9.1, at 8 cycles per second, are sometimes suggested to have a profound effect on the processing of incoming retinal information (vanRullen, Reddy, & Koch 2005). This chapter will consider the suggestion that at a particular rate, brief "snapshots" are taken of the visual scene, and in between these snapshots, visual information is ignored or at least given little weight. A less radical proposal is that intrinsic brain oscillations do not actually modulate the stream of incoming information, but that particular visual processes only occur once every cycle, even while other aspects occur continuously. This chapter will discuss two sources of evidence for these proposals.

To put things in perspective, it is useful to begin with a less controversial phenomenon, one that indubitably slices visual processing into temporal chunks and periods of nonresponsiveness. These are eye movements, specifically saccades—sudden jumps of the eyes.

9.1 Sampling the World via Eye Movements

Many sorts of animals use sensors that provide very intermittent information about the environment. In rats, the whiskers are actively brushed back and forth to identify objects, whereas bats emit high-pitched cries to locate insects and the elephant-nose fish (*Gnathonemus petersii*) periodically spouts electric pulses in order to find prey.

Humans also sense information intermittently. In vision, the eyes move at irregular but frequent intervals. While the center of our gaze provides very high acuity, vision to the side has much poorer spatial resolution. To build up an adequate representation of the scene front of us, our eyes must jump from one region to another. The rate of these saccades vary, but are made on average three times a second. The eyes move at such a high speed during a saccade that the brain represents the image as a blur. An important consequence is that we are essentially blind for a significant proportion of our waking lives. Yet we are not aware of this.

The visual brain actively inhibits visual processing during the rapid slide of the eyes. This is called “saccadic suppression” (Dodge, 1900). For a stark demonstration of the phenomenon, first look in a mirror at your left eye. Then, quickly shift your gaze (saccade) to your right eye. Saccading back and forth, you never see your eyes move. The existence of saccadic suppression lends some plausibility to the possibility of intermittent processing in other contexts. In the case of saccades, certainly, visual processing is interrupted (e.g., Krekelberg, 2010). Remarkably, this interruption causes no anomalies in our everyday experience of time. We do not notice the frequent blackouts of vision. The brain may simply ignore these intervals, but this is perhaps not sufficient to account for experience. To compensate for the lost time of a saccade, the brain may actively fill in the interval with the objects seen before and after (Yarrow et al., 2001).

The brain thus has the capability to accommodate rapid variation in the uptake of visual information. In addition to avoiding subjective temporal interruptions, the spatial disruptions caused by the jumping about of the eyes are also rendered inconspicuous. The brain actively anticipates the location of objects on the retina after a saccade, which helps preserve the feeling of a stable world every time an eye movement jerks the image in one direction or another (Wurtz, 2008). The mechanisms mediating each of these phenomena are activated intermittently, each time a sudden shift of the eyes is executed.

The relatively well-understood example of eye movements sets the stage for two possible periodic processes that are more controversial.

9.2 Periodic Processing in a Jittering Illusion

Imagine again the bowling ball rolling down the lane of a bowling alley. We seem to experience the ball traveling smoothly, shifting in position continuously and seamlessly. Few would suspect that our brain only occasionally resolves a conflict among cues to its position, and that it does so suddenly. However, this is precisely the conclusion that presents itself when one views a particular visual display.

The relevant display involves a red disc centered on a large green disc with the same luminance as the red. This red-green bull's-eye moves across a dark background. Rather than appearing as smooth motion, the red circle seems to jitter as it moves (Arnold & Johnston, 2003).

It is well known that equiluminant motion of a red figure against green is perceived as moving more slowly than motion involving a luminance difference, such as the larger green area against the dark background (Cavanagh, Tyler, and Favreau 1984). Several results support the idea that the jitter is caused by a conflict between the discrepant apparent speeds of the equiluminant figure and the larger luminance-defined figure it sits on (Arnold & Johnston, 2003, 2005). This conflict may be detected when a "motion-based forward model" of the spatial pattern "is compared against new input" (Amano et al., 2008). The motion signal corresponding to the small red figure is weak compared to that of the green figure, therefore the green figure is expected to move farther. Every so often, the system compares this predicted difference in position against the new retinal image, which indicates no difference in position. The percept may be based on the expected shift until the comparison of model and input is done, at which time the conflict is resolved by snapping the two figures into alignment, in accordance with the retinal image.

The jitter seems to occur at a consistent rate—when a truly physically jittering stimulus was compared to the perceived jitter in the illusion, a rate of 10 or 11 Hz was found to match best (Amano et al., 2008). This was true regardless of speed of the moving stimuli or distance between the discrepant figures. Apparently the ~10 Hz rate corresponds to that of an intrinsic process of the visual system, rather than being triggered when the cue conflict reaches a certain value. This is surprising, because from an ecological point of view, it would seem more adaptive to resolve any cue conflict continuously rather than periodically. For example, optimal cue combination over time may be embodied in a Kalman filter (Bryson & Ho, 1975) that yields an estimated position for the two objects that compromises between the two estimates. But this should change smoothly over time. Therefore, the periodic jitter may reflect the particular importance of oscillations for brain-style computation (Koepsell et al., 2010).

If the oscillations of the brain are indeed important for visual processing, one might expect more than one manifestation of them in perception, and there is in fact another prominent candidate. It too is an anomaly or illusion of motion perception. With this second anomaly, the associated theory has been more radical than that an intermittent process occasionally refines perception. The proposal this time is that the illusion indicates regular visual sampling of the retinal image, with information falling between the samples ignored.

9.3 Illusory Motion Reversals

While watching a movie or television program, almost everyone has seen it, although many have never noticed it. Car commercials on the television, and car chases in the cinema, often feature a fast-moving vehicle. In some cases, the wheels on the car appear to be rotating backward even as the car moves forward. This optical illusion is an artifact of the way a video camera captures the scene. The effect is clearest for wheels with spokes, or with a regular pattern on their hubcap, and occurs because video cameras capture the scene as a series of snapshots. For certain wheel speeds, between successive snapshots the spokes will travel far enough that in the resulting movie, the spokes appear to travel backward. Consider spokes at twelve o'clock and eleven o'clock that are identical and on a wheel rotating clockwise. If the snapshots of the film occur at certain rates (and the wheel is rotating at certain speeds), then the spoke originally at twelve o'clock will move nearly to one o'clock by the next frame, let's say it is in the position corresponding to 12:45. Of course, this also means that the spoke that was at eleven o'clock will be at the 11:45 position (nearly at twelve o'clock). The brain will naturally assume that the identical successive images of a spoke first at twelve o'clock and then at 11:45 are one and the same spoke, caused by the wheel rotating counterclockwise. This will occur for each spoke and its successor, yielding a clear percept of counterclockwise motion of the wheel. A good demonstration is available at http://www.michaelbach.de/ot/mot_wagonWheel.

Viewed under clear and constant illumination in the real world, one would not expect to perceive a wheel to appear to rotate contrary to its true direction. After all, the visual system is not thought to have much in common with a video camera. But with prolonged viewing, an ordinary wagon wheel is very occasionally perceived to rotate in the wrong direction. When this was reported by Dale Purves and others in 1996, they suggested that the visual system really does behave like a video camera, periodically sampling the scene to yield the illusory reversals. This notion that the visual system temporally samples the world at regular intervals was greeted with profound skepticism from many perception researchers. Some even doubted that the illusion really existed. The reaction of one prominent vision scientist to the report of the illusion was "it can't happen." The researcher will remain nameless, although his (or her) peremptory judgment soon received some support from an article reporting that the illusion could not be replicated (Pakarian & Yasamy, 2003). Although several subsequent investigations have replicated the illusion, the resistance to the initial report and its interpretation was not entirely unreasonable. Even in those laboratories that have documented the illusion (such as my own), apparently some people never experience the illusion. And regarding the illusion's proposed interpretation, it seems to fly in the face of the enormous body of mainstream motion psychophysics results, which never had yielded much reason to posit a temporal sampling account (a few reports outside of mainstream psychophysics had, such as Kristofferson, 1967).

The illusory motion reversal illusion does occur in most observers, and vision scientists have had to grow accustomed to this fact. Soon after the 1996 report (Schouten in 1967 may have discovered the phenomenon first), it was proposed that the phenomenon could be explained with conventional motion models (Kline, Holcombe, & Eagleman, 2004). No appeal to periodic intermittent sampling of the scene was needed.

The starting point for the temporal sampling theory had been the apparent similarity between the illusory motion reversals and the wagon-wheel illusion. The plausibility of the newer theory arises in part from the resemblance of the illusion to the motion aftereffect. After an extended interval of viewing a stimulus moving in a particular direction, unambiguously stationary stimuli are perceived to move in the opposite direction (for a demonstration, see http://www.michaelbach.de/ot/mot_adapt/index.html). Moreover, stimuli moving very slowly in the original direction, if they are moving slowly enough, are perceived to move in the opposite direction.

Kline, Holcombe, & Eagleman (2004) suggested that extensive adaptation to the veridical direction contributes to the incidence of illusory motion reversals. Holcombe & Seizova-Cajic (2008) found some support for this, as the stimulus that began the first percept was always perceived in the correct direction, and this first epoch of veridical perception usually lasted much longer than subsequent epochs of either reverse or forward motion. Moreover, it is certainly true that extended motion adaptation is enough to cause the experience of reverse motion in a stationary or slowly moving pattern. However, the motion aftereffect wouldn't be expected to cause perception of the reverse direction while the stimulus continues moving at the original speed. Previous studies of the motion aftereffect, including measures of its apparent speed, suggest that it is never as strong as the adapting stimulus. Some other factor seems needed to explain reversals, perhaps in combination with accumulated adaptation. Kline et al. (2004) suggested that detectors for the reverse direction are inappropriately activated to a small degree by the forward motion of the stimulus, and it is this activation in combination with extensive adaptation to the veridical direction that yields the reversal. Specifically, Kline et al. proposed that detectors might respond to the wrong direction due to a potential flaw in their construction. The flaw is embodied in the standard Reichardt motion detector model, which detects motion via detecting stimulation at two disparate locations. The detector is set up with a delay on the line coming from one location, so that the detector responds best if it is stimulated first in one location and subsequently in the other. However, a stimulus moving the opposite direction can stimulate this detector if separate objects happen to pass through the two critical locations at the right relative times. This can occur for example with the spokes of a wheel, wherein one element of the motion detector is stimulated by one spoke, and the other is stimulated with the appropriate delay by another spoke (see figure 1 of Kline et al.). It is as if the system linked one passing spoke with the next following behind it, so that the first spoke jumped backward and transformed into the following spoke. This potential flaw in motion detectors is well known, and standard motion models include specific measures to avoid it (van Santen & Sperling, 1985). According to Kline et al. (2004), these spurious responses can, in combination with a weakening of the detectors for the forward direction, occasionally lead to greater response of detectors signaling the opposite direction.

It is important to realize that these hypothetical spurious motion responses are not caused by temporally discrete sampling. There are no temporal intervals that are actually ignored, unlike in the Purves et al. (1996) theory. In the Kline et al. theory, one part of the motion detector continually responds to visual stimulation from farther in the past than does the other part. Information at all times is eventually processed by both parts of the detector. Furthermore, as motion detectors in the visual system are thought to exist at a number of spatial scales, with varying temporal delays, any spurious responses would not occur at the same time for all motion detectors.

In the years since the initial proposals of these theories of the motion reversals, the results of new experiments have weighed against the possibility that regular snapshots are taken of the visual field. According to the snapshot theory, samples from disparate parts of the visual field should occur at the same time, in synchrony. Therefore, if two identical moving stimuli are viewed together, any reversals should occur simultaneously. Simultaneous reversals are instead fairly rare in this situation (Kline, Holcombe, & Eagleman, 2004). Still, this result does not categorically exclude temporally discrete sampling. Snapshots might still occur and cause the illusion, but they would have to occur at different times for different parts of the visual field. This is a position now advocated by proponents of the temporally discrete processing theory (vanRullen et al., 2010).

9.4 What Reverses in the Motion-Reversal Illusion?

The mechanism that generates reversals, be it temporal sampling or an aberrant motion response, must exist in some class of mechanisms of the visual system; possibly mechanisms involved in motion, local orientation, and complex form, or perhaps only a certain class of motion detector. If the reversals are caused by temporal sampling, which visual analyzers sample?

In addition to its generality across different types of mechanisms, another aspect of the mechanism that generates reversals should be considered. The mechanism that generates reversals must operate on either the entire field of incoming visual stimulation, or some portion of it. The possibility that the visual system temporally samples the entire visual field in unison, as a videocamera does, is contradicted by the existence of independent reversals in spatially separated stimuli (Kline, Holcombe, & Eagleman, 2004). If temporally discrete processing causes the illusion, it seems it must be caused by mechanisms with a narrow spatial scope.

VanRullen (2006) extended this approach of examining whether concurrent moving stimuli reverse together. The results led him to conclude that motion reversals are a phenomenon "whose spatial extent is entirely determined by the global perceptual organization of the scene into objects" (4094). His observers viewed a rotating textured ring with a gap in the center. The gap was in the shape of a long vertical rectangle, dividing the ring into left and right halves. In one condition, both halves rotated in the same direction and at the same speed. When observers viewed this display, reversals overall occurred quite infrequently, as is usual in studies of illusory motion reversals. However, when they occurred, reversals tended to occur in both ring halves simultaneously. In fact, this was about twice as likely to occur (7% of total viewing time) than was a reversal in just one half-ring. In a second condition, the left and right halves of the rings rotated in opposite directions. Now, reversals occurred much more frequently (18% of viewing time) in only one ring then they did in both rings simultaneously (~1.5% of viewing time). VanRullen postulated that the crucial difference between these displays is that in the opposite-motion condition, the rings are represented by the visual system as two separate objects, whereas in the same-direction condition, they are grouped into a single object. If this is true and were the only difference between the stimuli, then the co-occurring reversals would imply that the scope of the motion-reversals mechanism encompasses entire objects. In the same-direction condition, the reversal-inducing mechanism processes the entire ring as a whole, causing reversals in the two ring halves to occur together. VanRullen therefore concluded that the reversal-generating mechanism is "object-based" and "restricted to the object of our attention" (2006). Motion reversals are an "object-based" effect "whose spatial extent is entirely determined by the global perceptual organization of the scene into objects" (4094). However, there is reason to question this conclusion.

In a scene of ambiguous moving stimuli, the visual system sometimes favors interpretations in which all the stimuli move in the same direction, even when these stimuli do not appear to be part of the same object. This is quickly apparent when one views a display with many two-frame apparent motion quartets. In the first frame of an apparent-motion quartet, two dots appear at opposite vertices of an imaginary square. In the second frame, the two dots have moved to the other two vertices of the square. If the two frames are set in alternation, for a time viewers experience horizontal motion, with each of two dots traversing back and forth along the top and bottom of the square. At other times, viewers experience vertical motion, with each of two dots traversing up and down along the left and right sides of the square. If several of these ambiguous stimuli are scattered about the screen, then rather than reversing direction independently, they usually do so in unison (Ramachandran & Anstis, 1986; for a demonstration, see Peter Schiller's webpage, http://web.mit.edu/bcs/schillerlab/research/A-Vision/A15-24.htm).

Unlike in vanRullen's stimulus, in the case of the dot quartets there is no reason to think that discrete temporal sampling could determine the perceived direction. Furthermore, few would suggest that dots scattered across the screen appear to be part of the same object. Nevertheless, the perceived motion direction of the stimuli are tightly linked. This link between the perceived motion direction of different stimuli may well be the principal factor that yielded vanRullen's result. When the two ring halves were moving in the same direction, the tendency for disparate stimuli to seem to move in the same direction should prompt reversals of the two halves to occur together. When the two ring halves physically move in opposite directions, this tendency would prompt reversals to occur more independently, because only when the two halves reverse at different times are they perceived to have the same motion direction. Admittedly, we do not know whether the tendency observed with quartets should also apply to other stimuli, such as rotating rings. The possibility that it does, however, yields a plausible alternative explanation to vanRullen's results. The issue of the spatial scope of the mechanism that generates reversals remains open.

Another attempt to determine the scope of mechanisms that generate reversals was made by Kline and Eagleman (2008). In their display, two orthogonal motions at different spatial scales were spatially superposed. One was the movement of the overall shape of the figure, the other was the movement of the local texture. Reversals of these two motions frequently occurred separately, leading Kline and Eagleman to conclude that vanRullen's conjecture that reversals occur in a mechanism that processes entire objects must be erroneous. Certainly this experiment appears to disconfirm the strong form of this hypothesis. However, the motions moved in different directions (isoeccentric vs. isoradial), and had different spatial frequencies. These factors may affect the propensity toward reversals, which might have contributed to the independence. Future experiments should be able to resolve the role of objecthood more definitively by manipulating it in a single experiment, without the motion-direction confound of vanRullen (2006). For example, using vanRullen's divided ring display with both ring halves rotating in the same direction, one might vary whether the central dividing strip appears to be in front or behind the depth plane of the ring. When it is behind, the rings will appear to be separate objects, whereas when in front, a single ring will be experienced. Will reversals in the two rings occur together much more frequently when the strip is in front? Such experiments should improve understanding of the nature of the unit analyzed by the motion-reversal mechanism.

9.5 Reversals That Make Morphing Motion

Prior to Kline and Eagleman (2008), all published investigations of motion reversals used stimuli made up of repeating patterns, such as a regular array of discs or a grating. If motion reversals are caused by periodic sampling, then with a repetitive pattern the motion percept could reflect matching of each figural element with the identical element immediately behind it. This would cause the motion percept to comprise a procession of all elements stepping backward. In the case of the wagon-wheel effect induced by a video camera, the periodic pattern of wheel spokes typically results in just this—each of the spokes is phenomenally linked to the following spoke. This linkage in phenomenology of elements in successive frames is known as "token matching."

When discussing the temporally discrete sampling theory of motion reversals, Kline and Eagleman (2008) write that "the temporal sampling mechanism ... requires periodicity. That is, the pattern must be composed of identical (or very similar) repeating elements for incorrect token matching to occur. If the perceptual snapshot hypothesis is responsible for [illusory motion reversals] then the illusion should not occur with stimuli such as a random texture or a periodic pattern with distinct elements" (1). To reach this conclusion, it appears they assumed that a requirement for motion across frames is that the motion must join identical or very similar elements. This is a strange assumption, because studies of apparent motion have consistently found that the strength of apparent motion depends little or not at all on similarity of the corresponding elements (Kolers, 1972; Burt & Sperling, 1981; Navon, 1976; a demonstration of how apparent motion can easily link objects of very different color and shape is available at the webpage of Peter Schiller: http://web.mit.edu/bcs/schillerlab/research/A-Vision/A15-33.htm). Rather than element similarity, standard motion models use "motion energy," which reflects the product of luminance contrast in successive positions (van Santen & Sperling 1985; Werkhoven, Sperling, & Chubb 1993). The model of motion reversals used by vanRullen et al. (2005) uses Fourier first-order (luminance) energy, so it also does not predict a dependence on similarity of elements. From the model's perspective, then, there is no surprise that reversals occur with non-periodic patterns such as a strip of black digits printed on a white background. The account proposed by Kline, Holcombe and Eagleman (2004), being based on the response of classic Reichardt detectors, also does not necessarily predict any role for similarity of elements.

The surprising result of Kline and Eagleman (2008), then, is not that similarity of elements was not required for illusory motion reversals. The surprise is that similarity of elements had any effect at all; and they did—reversals were much less frequent for the patterns with heterogeneous elements. This should push us to question previous assumptions about the nature of the analysis that yields the motion in the reverse direction. Since similarity of elements matters, perhaps the mechanism that yields reversals does not perform a motion energy analysis.

The specific proposal of vanRullen et al. (2005) was that reversals occur due to periodic sampling by "attention," followed by motion analysis. What kind of motion analysis normally follows the action of attention? Although vanRullen et al. (2005) assumed it was a conventional motion energy analysis, it may well be a distinct system (Cavanagh 1992; Lu & Sperling, 2001). One specific possibility is that it relies mainly on the movement of attention—if attention shifts with a visible object in a direction, then motion will be perceived in that direction (Cavanagh, 1992).

Attentional shifting or tracking with periodic stimuli such as an array of discs would mean that, to achieve a percept of reverse motion, attention would jump from one disc to the one arriving from behind. Thus joining them together, it might represent them as a single disc. With elements of different shapes, such as the series of digits used by Kline and Eagleman (2008), attention would step from one digit to another, which might lead each to appear to morph into another. Unfortunately, whether the percept looks like this has not been investigated, although it seems consistent with this author's percept. Can an alternative motion analysis of this sort explain why reversals were less common with dissimilar elements? Possibly, although there has been limited evidence for the importance of similarity even with motion that may be high-level and attentional (Green, 1986). The reason that motion reversals were less frequent with patterns of dissimilar elements remains unclear.

As described above, the existence of reversals with these aperiodic stimuli does not challenge the attentional temporal sampling theory. One stimulus of Kline and Eagleman (2008) has not been mentioned yet, however, and the authors put special emphasis on it in their paper. This stimulus was qualitatively different from the rest. In a wide rectangular aperture with soft edges (a sigmoidal contrast envelope to gradually decrease the contrast at the edge), they presented a random-dot pattern drifting at 17 degrees per second. From the perspective of Kline and Eagleman, with their emphasis on whether a stimulus allowed for token matching, their finding that this stimulus occasionally is perceived to reverse was very important. Because the stimulus never repeats, there are no translational jumps in the backward direction for which the corresponding locations before and after the jump present the same elements. Given that standard motion analysis does not require such matches, this property of the stimulus does not seem important.

The random-dot stimulus presents a problem for the temporal sampling theory for a different reason. For the other stimuli, performing conventional motion analysis on a temporally sampled version of the stimulus yields motion signals predominantly in the reverse direction for particular stimulus temporal frequency and sampling temporal-frequency combinations. However, this is not true of the random-dot stimulus. This result again points to the possibility that a different sort of motion analysis is responsible for the reverse direction.

At the upper reaches of the visual system, in the areas most influenced by attention, spatial resolution is coarse and capacity is limited, so each dot of a large pattern may not be represented individually. Instead, a random-dot pattern may be represented as a texture rather than as a collection of individual elements (for related ideas and evidence, see Parkes et al., 2001; Saiki & Holcombe, 2012. At this level, all the frames of the random-dot stimulus may be represented similarly, since they all have similar global statistics. In that case, for any two frames of a random-dot pattern, for the attentional system it may be equally plausible that the pattern has moved in any direction. This is entirely speculative, however, and there remains the problem of explaining why the reverse direction would ever become stronger than the forward direction. Although adaptation may weaken the motion systems' response to the forward direction, it is unclear whether this could cause the reverse response to be even stronger (unless one is willing to posit a substantial random noise component).

This section has addressed the results that Kline and Eagleman (2008) offered as evidence against a periodic temporal sampling theory, and argued that most of the evidence does not undermine the periodic temporal sampling theory. The random-dot stimulus does present significant difficulties, but does so not only for the sampling theory, but also for the other theories.

Earlier we discussed the flaw in standard motion detectors (Reichhardt detector subunits) that, if not avoided via some prefiltering of their inputs, can cause them to respond to motion in the wrong direction. This aberrant response, however, does not occur as consistently for a random-dot pattern. A moving random-dot pattern will include a particular spatial frequency that will stimulate the detector of the wrong direction; however, the combination of all the spatial frequencies that the pattern comprises will combine to yield no response (on average, at least, for a white-noise pattern; Snippe & Koenderink, 1994). Thus the lower incidence of reversals reported for the random-dot pattern is certainly consistent with this theory. The existence of any reversals at all, however, is a problem. Of course, there may be idiosyncrasies of biological motion filters that create the reverse response in a way not predicted by the Reichhardt motion-detector abstraction. Still, it is unsatisfying to appeal to some mysterious and unknown property of motion detectors, and it does not lead to new predictions. A concrete example of reverse neural responses has recently been revealed in a moth's visual system, and further study of it may lead to more specific hypotheses (Theobald et al. 2010).

A somewhat different sort of explanation for the motion reversals was ultimately offered by Kline and Eagleman in 2008. Their theory is that "the motion aftereffect … can be superimposed on a moving stimulus, creating a motion during-effect that can lead to illusory motion reversal." Although they did not elaborate on this statement, it raises the possibility that reversals are not a case of adaptation allowing an already existing, spurious reverse-direction response to come to the fore. Rather, it is theoretically possible that adaptation alone can yield the reverse percept without any assistance from spuriously responding motion detectors.

But the conditions that maximize the conventional motion aftereffect (very low temporal frequencies of adapter and test; see Bex et al., 1996; Pantle, 1974) are not the same as those that maximize motion reversals. VanRullen (2007) compared the incidence of reversals to the duration of the motion aftereffect with the same stimuli, and found some other dissociations as well. However, these conventional motion-aftereffect studies involve viewing a stationary test pattern after one adapts to a particular moving stimulus. But with motion reversals, the test pattern is essentially the original moving pattern. This resembles more the "flicker test" motion-aftereffect procedure, which uses a flickering pattern during the testing interval. The strength of motion adaptation as assessed by the flicker test can lead to adaptation that is strongest at temporal frequencies closer to the range that yields the highest incidence of reversals (Ashida & Osaka, 1995). Hence, the intriguing idea of reversals being a motion aftereffect superposed on the original stimulus remains viable.

9.6 Ten Hertz: Reversals' Favorite Frequency

A telling fact of motion reversals is that they occur most frequently at a particular-stimulus temporal frequency—10 Hz—rather than at a particular stimulus speed, spatial frequency, or set of combinations of speeds and spatial frequencies. Although this should be informative regarding the basic mechanism of motion reversals, understanding the implication of this result may be more difficult than has been supposed.

The peak at 10 Hz was documented by vanRullen, Reddy, and Koch (2006). The data of experiments by Simpson, Shahani, and Manahilov (2005) led those authors to a similar conclusion, but interpretation of their data was problematic because they lumped together reversals with other anomalous motion percepts as well as cases where no motion was perceived.

VanRullen et al. (2006; 2010) consider the 10 Hz peak to be good evidence for the theory that periodic temporal sampling results in the reversal illusion. Specifically, they concluded that the rate of the putative sampling process is 13.3 Hz, because “when the system’s sampling period is three-fourths of the motion period, the evidence for the erroneous motion direction will be maximal and outweigh the evidence for the actual direction” (2010, 525).

If a periodic pattern were to move three-fourths of a cycle between “snapshots,” then from the perspective of a mechanism that sees only the snapshots, the grating might appear to jump in the opposite direction by one-fourth of a cycle at each step. This one-quarter-step size is sometimes considered the “optimal” stimulus for the standard quadrature model of the human motion system (e.g., Baker, Baydala, & Zeitouni, 1989). When just two frames are presented, a one-quarter step is indeed optimal (Nakayama & Silverman, 1985) but for a multiframe stimulus, this is not generally the case (Watson, 1990). Therefore, the suggestion of vanRullen et al. that a 10 Hz peak for motion reversals points to a 13.3 Hz sampling period cannot be regarded as a by-product of a generic motion energy system. Instead, one must consider the details of a particular model.

In the modeling effort of vanRullen et al., they assumed that the sensitivity of the post-sampling motion detectors was the same as the motion system as a whole. As a measure of the sensitivity of the whole motion system, they used the proportion of times that people reported perceiving motion (forward or backward) as a function of temporal frequency. The shape of this curve was used for the relative sensitivity of the motion system to different stimuli. The proportion of responses measured is not likely to be a good measure of relative sensitivity, because proportions are not linearly related to internal response strength. For this reason, visual psychophysicists typically use the inverse of contrast at threshold to estimate sensitivity. Perhaps the predictions of the model would not be affected much by the refinement of this estimate, but more modeling is needed to be sure. The basic assumption that the spatiotemporal characteristics of the strength of the reverse-motion response resembles that of overall motion sensitivity should also be questioned.

As mentioned in the previous section’s discussion of Kline and Eagleman’s (2008) results, the nature of the motion system responsible for the reverse direction is uncertain. Under the theory that it receives input that occurs after attentional sampling, it may be high level, since attention has much larger effects at higher stages of the visual system. According to some researchers, attention-based motion perception is restricted to quite low temporal frequencies (Lu, Lesmes, & Sperling, 1999). In the framework of vanRullen et al. (2005), a consequence of this may be to push the predicted peak temporal frequency lower relative to the putative sampling frequency. In the original model, let’s say that a 10 Hz stimulus indicates a 13.3 Hz peak-sampling frequency. If the responsible motion detectors are more sensitive to lower temporal frequencies, then a 10 Hz maximal response may actually be the result of a higher peak-sampling frequency, since with the high sampling frequency, although the strongest motion energy may result from a temporal frequency higher than 10 Hz, the system is so insensitive to it that the 10 Hz stimulus is better. However, the finding that reversals are particularly associated with EEG signal change around 13 Hz lends some independent support to the 13 Hz estimate of sampling (vanRullen, Reddy, & Koch, 2005).

A particular rate of temporal sampling makes a specific prediction for the speed of reverse motion. A particular temporal frequency of stimulus motion, together with a sampling frequency, specifies the size of successive steps between samples and therefore a particular speed for the reverse motion. Unfortunately, to date there have been no reports of the speed perceived for motion reversals. In my experience when viewing rotating circular arrays of discs, reversals typically begin with a very flickery percept that may appear nearly stationary before reverse motion begins. This reverse motion appears to quickly accelerate to a peak speed before the percept returns to forward motion. One prediction of the sampling account is that the reversals should always be perceived to be slower than the motion in the forward direction. This follows from the basic notion that reversals occur when the pattern moves more than one half of a cycle between samples, causing displacement between successive samples to be shorter in the reverse direction than in the forward direction. In my experience, the perceived speed of the reverse motion is indeed always slower than the speed perceived in the forward direction. However, that the reverse motion tends to begin with flickery, possibly stationary or slow motion certainly complicates interpretation, as does the dependence of speed perception on contrast. At first, the variation in speed during the life of a reversal might seem compatible with vanRullen et al.'s suggestion of a variable sampling rate. But it seems difficult for this account to explain why reversals would consistently begin with flickering or near-stationary sensation. Nevertheless, there remains the possibility that the sampling notion could be partially validated or undermined by an experiment investigating perceived speed. According to the periodic sampling account, the speed perceived should never exceed half the speed perceived in the forward direction. This follows from the constraint that between samples, the pattern must travel more than half its period in the forward direction. Observer reports of speeds in excess of this would challenge the sampling account.

9.7 Ups and Downs over Time

Both illusory motion reversals and the motion-jitter illusion are potentially manifestations of intermittent, periodic processing of incoming visual information. However, the interpretation of illusory motion reversals seems less straightforward than interpretation of the jitter illusion.

Motion reversals could be caused by mechanisms other than sampling. This argument remained somewhat theoretical until the reports by Seizova-Cajic and colleagues of a strange illusion in the perception of one's own body (Seizova-Cajic et al., 2007; Holcombe & Seizova-Cajic, 2008). With eyes closed, participants had the muscle spindles in their biceps stimulated with a vibrator. The vibration activates the muscle spindles, which signals arm extension, and this is usually the resulting percept (Goodwin, McCloskey, & Matthews 1972). However, after prolonged stimulation one occasionally experiences reversals—flexion of the arm for several seconds. Because proprioception is a very different system than vision, the relevance to the reversal mechanism in the visual case is uncertain. Nevertheless, it does provide an existence proof that biological systems can exhibit motion reversals without any role for periodic temporal sampling.

The 10 Hz motion-jitter illusion discovered by Arnold and Johnston (2003) is more compelling evidence for a periodic visual process associated with perception. There are additionally other phenomena suggestive of periodic processes (Elliott & Muller, 1998; Geissler, Schebera, & Kompass, 1999), but these have not been studied much and their status is uncertain.

If one or more of these phenomena really are caused by periodic processes of the visual system, there remains the issue of how central they are to visual function. Are these phenomena cracks in the smooth edifice of experience that reveal the continual jerking and jittering of basic underlying machinery? The jitter seen in the displays of Arnold and Johnston (2003) may mean that perceptual position computation always follows a constant rhythm. The motion-reversal illusion is perhaps a sign that attention always processes things periodically (vanRullen, Carlson, & Cavanagh, 2007). Alternatively, these phenomena may reflect much more restricted processes.

Even without a role for periodic oscillations, the question of how the brain constructs the subjective time we experience is a difficult one. The problem has several aspects.

Let's begin with the continuous changes that occur in the world, and the seeming continuity of our experience. Consider again a bowling ball rolling down the lane toward ten erect pins. As we peer down the lane, the continuous motion of the ball seems to be represented accurately in our experience. A simplistic view is that the visual system analyzes the retinal image moment by moment, with subsequent temporal smoothing to eliminate the noise and achieve our seamless experience.

We now know that the problem is more difficult than suggested by this picture, and as a result some very complex processing is probably going on. First, different aspects of the visual input are processed by different populations of neurons, and these require different amounts of time to complete their processing (Holcombe 2009; Nishida & Johnston, 2010). The resulting temporal coordination problem becomes especially fraught when one considers that even information from other senses can decide our interpretation of the visual input (e.g., Lunghi, Binda, & Morrone, 2010). We do not know how the brain manages to successfully integrate cues that are processed at discrepant rates.

A second marvel of temporal experience is that our image of the moving bowling ball is crisp rather than a streak. Objects moving at the speed of bowling balls create extended strips of persisting activity in our visual cortices, which must be actively quashed (Burr, 1980). A further problem is that at any individual location, information is not present on the retina long enough for an accurate representation of the bowling ball's color and shape. Through so-called "mobile computation" (Cavanagh, Holcombe, & Chou, 2008), the visual system accumulates information from the successive positions the object occupies, and only then can the familiar crisp image be constructed (Nishida et al., 2007; Lu, Lesmes, & Sperling, 1999; Moore & Enns, 2004). A moving object's position is set in a way that may partially overcome the lag introduced by neural-processing delays.

When the rolling bowling ball reaches the ten pins, the scene seems to erupt with seemingly simultaneous collisions of the ball with the pins and the pins with each other. The sequence of multiple pin and ball motions is both fast and unpredictable, which foils some of the sophisticated processing mentioned previously. Here we get some inkling that the smooth experience of the bowling ball reflected complex processing that cannot accommodate arbitrarily complicated motions. The richoceting pins' trajectories are hard to follow, at least in part because attention cannot follow multiple discrepant changes in motion simultaneously (Tripathy, Narasimhan, & Barrett, 2007) or apprehend the relative time that each object occupies a particular position (Linares, Holcombe, & White, 2009). Indeed, because the temporal resolution of visual cognition is particularly coarse (Holcombe, 2009), our experience of temporally smooth motion perhaps relies heavily on deblurring and mobile computation.

Scientific understanding of most of the processes mentioned in the previous few paragraphs is still shallow. Even if the suggestions of discrete temporal sampling turn out to be erroneous, there is much more to know about the visual representation of a simple rolling ball.

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IV Fragments of Time

The wagon wheel illusion (as it appears in continuous lighting, away from the silver screen) seemed at first to support the idea that perception is a stream of cinematic snapshots. The EEG studies of Busch and VanRullen (chapter 8) point at least to oscillations in sensitivity in perception—to be perceived, it helps to catch the nearest alpha wave. This periodicity could create a wagon wheel illusion when the rhythms of the moving stimuli are just right. Holcombe's (chapter 9) discussion, however, reminds us that perceived motion is a joint production of many processes, each of which can be fooled in different circumstances. For example, low-level "delay line" detectors can misinterpret two objects as one object in motion, while higher-level motion sensors can fatigue, yielding the familiar visual sensation that a train just arrived at the platform is now moving backward. These effects may contribute to illusory motion reversal, although neither depend on periodic sampling. The many contributors to motion perception are not exclusive of one another, and there may be no single mechanism behind the wagon wheel illusion. The correct multiple choice answer here may be "all of the above."

The general implication is familiar. The single, sharply delineated percept of an object in motion is the product of many collaborators in the neurocracy. Committee work lies behind other perceptual achievements as well, with familiar multilevel and hierarchic stories told about detection of all the props and people of ordinary life. Each of these accounts has a curious distancing effect on phenomenology. In the neurocracy, nothing exactly corresponds to "seeing a coffee cup." Instead, in one cubicle a neurocrat prepares a report on edges while a colleague appends a list of their orientations. This is stapled to the executive summary on shape and sent to a wide distribution list. Somewhere in a meeting room a board of neurocrats will vote on the likely contents of the mug, while in another chamber strategies for coffee action will be debated—and so on. But when *I* see a coffee cup, the preferred description somehow unifies all these microprocesses. Explaining this unification is known as "the binding problem." There seem to be two poles of unity to be bound. On the object end, the many properties of the sensory array must be correctly bundled as *this* cup, here and now. On the subject end, all of these processes are somehow part of a single state of consciousness, unique and specially *mine*, here and now. Somehow many streams funnel into one.

"I see the cup." The grammar suggests the singleness of both subject and object, but does our experience concur? Kant referred to the contents of consciousness as a manifold, which seems apt. After all, neither "I" nor "cup" come close to exhaustively describing what is experienced in this or any other situation. Those "lower-level" edges and shapes don't disappear as the cup is recognized or grasped; all these features remain available, and their changes are necessarily monitored in order to orchestrate each grip, lift, and sip. The elusive "I" also seems to be a shifty and layered manifold. I can be absorbed into an action, but then back off to reflect on my place in the world. Like the coffee cup, I appear to myself as a loose swarm of properties, moving on and off stage according to need and interest in a continually shifting world. If all this must somehow be bound, then the binding can be loose, a casual bundle more than a monolithic brick. The neurocracy can stumble along without a central executive, and it may be that we experience just that.

Now I tap the mug with a pen. I see the pen strike the cup and I hear it as well. Objectively, there is just one event, and so it seems to us as we watch and listen. We may be content to allow the spatially distributed properties of the cup to remain scattered, but in the temporal dimension there really does seem to be one time point at which these two subjective sensory events occur. Indeed, synchronicity is often proposed as the manner of binding across the neurocracy. But it turns out that the two channels of sight and hearing proceed at different speeds (as do light and sound, of course, but this is less relevant at close quarters). As the chapters in this section describe, the constituent processes of vision and hearing (and all the other senses) run on different schedules. Just as there is no one place where "it all comes together," there is no one time where cotemporal events are simultaneously represented.

The authors of this section agree on this conclusion but arrive at it by different routes. In chapter 10, Konstantinos Moutoussis reviews the evidence for what we might call the pointillist view of time consciousness. The subjective *when* of experienced events could indeed diverge along different processing routes in the brain, leading to the experimental prediction that events in different modalities could be mis-synchronized by various involved islands of "microconsciousness." His chapter reviews many experiments that dissociate the time lines of motion and color. Bruno Mölder (chapter 11) turns to the logical next question: How does the subjective time line emerge? Following Daniel Dennett and Rick Grush, Mölder argues from familiar temporal illusions ("color phi," "cutaneous rabbit," and others) that the time when things seem to happen is a late addition to a cascade of processes that occur at other times.

As a consequence, the chapters in this section suggest that we must edit William James. The stream of consciousness is "jointed," with halts and surges, and possibly leaps and temporary freezes. More important, it is not one stream, but rather a watershed of division and confluence. There are many subjective times.

10 Perceptual Asynchrony in Vision

Konstantinos Moutoussis

10.1 Theoretical Issues

Studies of the visual system in both monkey and human have suggested a picture of functional specialization with respect to the processing of different visual attributes (Zeki, 1993). Such a specialization makes sense, since the computational procedures for the processing of, say, color are quite different from those necessary for the processing of, say, motion: the motion-specialized system needs to calculate the way in which an object changes position in space over time, whereas the job of the color-specialized system is to compare the light composition reflected from different objects and thus calculate their color, discarding any changes in the illumination. According to the doctrine of functional specialization, these different jobs are carried out by different, functionally specialized systems, occupying different territories of the visual brain. These different brain parts, in turn, are characterized by different types of neurons, connection patterns, conduction velocities, and so on (Zeki, 1993).

It is therefore reasonable to wonder whether it is possible for two such different systems to “finish” their different jobs at exactly the same time. The word “finish” is used here to refer to the emergence of the final conscious percept of the particular attribute being processed by the specialized system; the time it takes for this to be achieved (from the onset of the visual stimulus) will be referred to as *perception time*. The hypothesis put forward is that it is very likely that different visual attributes will have different perception times, and will thus not be perceived in synchrony. If they are not, one would have to imagine a third mechanism outside the two processing systems, one able to synchronize the percepts of the different visual attributes that arise from different functionally specialized systems. It is a suggestion that seems hard to swallow, since such a mechanism would have to receive the outcome of all specialized systems and be aware of the exact amount of processing-time differences between them in order to assign, say, a particular color to the particular motion that was synchronous with that color in real time. No such “integrator” has been yet discovered in the brain. On top of that, it would seem quite disadvantageous to delay a percept that can be made available at an earlier time in order to synchronize it with a percept which, although coming from a physically synchronous stimulus, will take longer to develop. It would be much simpler if each processing system was also a perceptual system, responsible for the perception of its corresponding attribute after a certain amount of time-consuming processing.

It is worth noting that perception time is considered to be a property of the corresponding processing-perceptual system as a whole, free from vague assumptions about particular brain areas and events. The reason for this is that we are still far from understanding where or how a conscious visual percept arises in the brain. The only things we can be certain of about conscious visual perception is that it actually exists and that it takes some time to happen. Perception is a property of the specialized system as a whole, and its (unknown) exact relationship with activity at any particular levels or brain areas (Moutoussis & Zeki, 2002; Moutoussis, 2009), or back-projections and feedback (Lamme & Roelfsema, 2000), oscillations and synchronizations (Singer, 1999), and so on, is irrelevant for the purpose of the present argument. A silent assumption is made, however, that there is a particular point in time at which perception takes place. Furthermore, we assume that it is this particular point in time to which the person assigns the occurrence of the perceptual event. Both these assumptions could be argued against from a philosophical point of view (see Johnston & Nishida, 2001).

The question of whether different visual attributes are perceived at exactly the same time or at different times after the appearance of a stimulus has been addressed experimentally by Moutoussis and Zeki (1997a, 1997b). The idea behind their experimental setup was that if the perception time for a particular visual attribute, say color, is *dt* time shorter than that necessary for the perception time for another visual attribute, say motion, then the color present on the computer screen at time *t* will be perceived synchronously with the motion present on the screen at time *t-dt*. If this motion is different from the motion present on the screen at time *t*, then the color present on the screen at time *t* will not be perceived to occur with the motion with which it physically occurred, but with a different one. Similarly, if the color changes at time *t+dt,* then the motion present on the screen at time *t* will also be perceived together with this new color, rather than with the color with which it physically coincided.

In other words, under such experimental conditions, color-motion pairs perceived to occur simultaneously are not simultaneously present in the real world. By changing both the color and the direction of motion of objects rapidly and continuously and asking subjects to report which color-motion pairs were perceived as coexisting, it was found that motion was paired to the color present on the computer screen roughly 100 ms later (Moutoussis & Zeki, 1997a, 1997b). If there were no perception-time difference between color and motion, then the perceptual experience of the subjects should follow the reality occurring on the screen. These results thus suggest that the color of an object is perceived 100 ms before its direction of motion, a phenomenon we have called *perceptual asynchrony* and that we have attributed to the different processing-times necessary for the two functionally specialized systems to "finish" their corresponding jobs. These systems are thus not only processing but also perceptual systems, creating specific visual percepts in their own time and independently from one another. In this way, functional specialization is extended from the processing to the perceptual level, and the experiments described above reveal the segregated nature of conscious visual perception.

It might be worth making a small point here regarding the temporal order of the experience of color and motion. Although it has not been explicitly discussed previously, if one were asked to make a literature-based guess, motion would probably be the attribute expected to be faster: the whole anatomy of the motion-specialized system reveals that it is specifically equipped with properties that make processing faster—properties like thicker myelination, faster conduction velocities, shorter response delays, and so on (Leventhal, Rodieck, & Dreher, 1981; Perry, Oehler, & Cowey, 1984; Raiguel et al., 1989; Maunsell et al., 1999). It might thus be surprising that color is actually found to be perceived before motion. A possible explanation is that all the advantages of the motion system mentioned above exist precisely because the processing of motion information necessary for reaching a perceptual endpoint is more complicated than that of color. The distinctive myelination of the motion system could be a consequence of evolutionary pressure to synchronize, as much as possible, percepts created by different processing systems in vision.

Whatever the reason for the particular order of the perception-time difference, it must be kept in mind that the issue of which of the two attributes is perceived first is only a secondary matter, and arguing about it could make one miss the main point—namely that there *is* asynchronous perception between the different visual attributes. Furthermore, predicting that motion is perceived before color would be rather naïve, since we are not yet in a position to directly relate neuronal and perceptual events. In area V2, for example, it has been shown that color-selective thin cytochrome oxydase (CO) stripes have longer activation latencies than motion-specialized thick CO stripes (Munk et al., 1995). This means that motion information is faster than color information at that level of processing, but does it also mean that one should expect motion to be perceived before color? Surely not, as no one has succeeded in equating neural activation in either type of CO stripe with conscious visual experience. We are still far from knowing where, when, and how perceptual experiences arise from neuronal events, and it would thus be inappropriate to translate any neuronal time delays to perceptual time delays. The strength of the psychophysical method described above lies in the fact that it measures perception-time *differences* without any need to refer to the where, when, and how of particular complicated brain mechanisms. The mind is being studied directly, and the perceptual asynchrony observed is related to the anatomical and physiological facts of the brain that support the idea of a functional specialization within the visual system.

The main point regarding the segregation of visual consciousness is that there is no single, integrated visual consciousness, but rather several different consciousnesses coexisting at the same time. This theory is usually referred to as the *microconsciousness theory* (Zeki &

Bartels, 1999) and has provided a new perspective on previous approaches. It can, for example, explain why damage restricted to one system will lead to an imperception of a particular visual attribute rather than to global blindness; conversely, it can explain why a system that is spared while all others are damaged can still function more or less adequately (Zeki, 1990, 1991, 1993). The realization that there is no single consciousness in vision, but rather several microconsciousnesses emerging from the existence of several functionally specialized systems, is the driving force behind this theory (Zeki & Bartels, 1999). It states that neuronal activation in any given system is sufficient to create a conscious experience of the corresponding attribute without the necessity of interacting with other systems or the need for the existence of a central "consciousness area." For this reason, visual consciousness seems to be distributed both in time and space, since spatially distributed specialized systems reach their corresponding perceptual endpoints at different times (Moutoussis & Zeki, 1997a, 1997b). Looking at it retrospectively, the idea that our impression of a single, unified consciousness may be the result of bringing together several separate, independent microconsciousnesses might also be partially suggested in the writings of Immanuel Kant:

> It is therefore absolutely necessary that in my cognition all consciousness belongs to one consciousness (that of myself). … The synthetic proposition that all the varied empirical consciousness must be combined in one single self-consciousness is the absolutely first and synthetic principle of our thought as such. (Kant, 1781, 117n38)

Although Kant thinks of the "unity of consciousness" in a very definitive way, referring to self-experience of the experiencing person, he also seems to imply (although ignorant of the concept of functional specialization) that the various attributes must themselves be synthesized first before being synthesized into the "pure consciousness." He also writes: "But because every appearance contains a manifold, so that different perceptions are in themselves encountered in the mind sporadically and individually, these perceptions need to be given a combination that in sense itself they cannot have. Hence there is in us an active power to synthesize this manifold," which he calls "imagination" (1781, 120). Kant supposed that this "synthetic, transcendental" consciousness is present a priori; that is, before any experience is acquired. But it may very well be the other way round, and the synthesis of several, separate perceptual experiences gives us the (elusive) impression of a single, conscious existence.

Prior to the psychophysical experiments mentioned above, the problem of temporal synchronization in visual perception was not considered in detail, if at all. Instead, attention was given to a similar problem that also arises from the functional specialization of the visual system, namely the problem of spatial integration, or which attributes belong together among several objects usually present in a visual scene. If different visual attributes are processed by different, functionally specialized systems, then how is it that in the end we have a single, unified perceptual experience of, say, a red bus moving to the left? How do we know that a particular color and a particular form or direction of motion belong to the same object? Since the specialized systems are topographically segregated in the brain, a possible solution could be the existence of an area of convergence of all specialized information, leading to a unified visual percept. On top of being quite simplistic, however, such a solution is also contrary to the anatomical reality of the visual brain, which suggests that no such area exists, but rather segregation persists throughout. For example, using orthograde tracers to trace the projections of areas V4 (color-specialized) and V5 (motion-specialized), it has been shown that these remain segregated in the ventral and lateral intraparietal areas (VIP and LIP) as well as in the superior temporal sulcus and subcortex (Shipp & Zeki, 1995).

There are other solutions to the problem that seem closer to anatomical reality, such as the existence of cross-communication between the different functionally specialized systems, as well as the possible role of less segregated feedback connections, from the higher to the lower visual areas (Shipp et al., 2009). But the fact remains that no clear satisfactory answer has yet been given. The contribution of the psychophysical demonstration of perceptual asynchrony is that it extends the problem of integration into the temporal domain as well. Different visual attributes belonging to the same object need not only to be brought together with respect to their similar spatial location and corresponding object, but also with respect to their temporal coexistence. One could perhaps imagine a solution for the spatial problem by referring all the specialized outcomes via feedback to area V1's detailed retinotopic map, but for a similar solution to the temporal problem, one would have to stretch the imagination much further.

An alternative, although somewhat extreme, solution to the binding problem is to adopt the position that what we refer to as binding does not really exist, and thus there is no problem to begin with: if each visual attribute is perceived independently and at its own time, perception is indeed characterized by segregation, not integration (Moutoussis & Zeki, 1997a, 1997b). The idea proposed here is that the visual brain is made up of several different, independent systems, and our perception is nothing more than the collection of the activity of all these perceptual systems. If one system is perceiving motion to the right and the other system is perceiving red color, we are perceiving both because *we are* both these two systems (and much more).

A similar solution is reasonable beyond vision: our visual system sees, our auditory system hears, our somatosensory system feels. What we *are* is all these independent systems together, not a single unified entity to which all the information converges—*coexistence* rather than *convergence* is perhaps the correct word to use. It is as if parallel selves are living inside us, and it might be exactly the temporal coexistence of these different mental events that gives us the illusory sense of unity in our being. Such a solution to the binding problem might sound slightly metaphysical, and it also seems to create philosophical questions characterized as "thorny" by some investigators (see Johnston & Nishida, 2001). The fact is that until the problem of consciousness and the more general mind-brain problem are solved, the answers to such questions will have to wait as well.

A slightly milder solution to the binding problem is offered by the microconsciousness theory, accepting on the one hand perception *without and before* integration, but on the other also accepting the existence of *postconscious* perceptual integration in terms of binding the conscious experiences generated in each system. According to this view, which Kant would probably favor, mutual integration between different processing systems is not necessary for the creation of a conscious percept, but it is the binding between the different microconsciousnesses that gives us an integrated image of the visual world (Zeki & Bartels, 1999).

10.2 Experimental Facts and Objections

The first experimental attempt to demonstrate a possible perceptual asynchrony in vision used a number of squares that changed color between red and green and direction of motion between up and down (Moutoussis & Zeki, 1997a). The results have shown a misbinding of these two visual attributes, suggesting that color and motion, which belong to the same object, are perceived independently and at different times. The possible need to "bind" color and motion as belonging to the same object had no influence on the perceptual asynchrony observed between them. It should be noted here that, due to the nature of the instructions given to the participants, a moderately high alternation rate (1–2 Hz) is necessary for a perceptual asynchrony to be revealed. Only then does the perception-time difference between the two attributes shift the temporal relation of the two percepts a significant proportion of the oscillation period, leading to a noticeable change in their pairing. It is for this reason that the phenomenon is diluted for very slow oscillations. For moderate rates, perception-time difference is found to be independent from the rate of oscillation (Moutoussis & Zeki, 1997a; Bedell et al., 2003; Holcombe & Cavanagh, 2008) Contrary to this finding, in a study in which participants judged which feature (color or motion) changed first and the peak relative timing for synchronous judgments was taken as the perception-time difference, it was found that the effect was diminished at slow alternation rates (Nishida & Johnston, 2002). However, subsequent studies have shown that timing judgments in certain situations may yield no asynchrony even when pairing judgments do (Bedell et al. 2003; Clifford, Arnold, & Pearson, 2003). This is not surprising, since a temporal order judgment can be made by simply identifying the feature that changed first, rather than identifying both features, as is required for reporting the pair.

In a variation of their original experiment, Moutoussis and Zeki separated color and motion so that they no longer belonged to the same but to two different objects in separate areas of the computer screen (1997b). Subjects were asked to judge which color on one half of the screen was perceived synchronously with a direction of motion on the other half of the screen. Results were identical to those observed when both the color and the motion belonged to the same object, and thus strengthened the idea that each attribute is being perceived by its own functionally specialized system, independently of the other. Since it is not yet possible to know where, when, and how in the brain a percept is being formed, there is no scientific way to measure absolute perception times directly—that is, to measure the exact time it takes for the appearance of a stimulus to be consciously perceived by the brain. The experimental setup described above is able to measure relative perception times of one attribute with respect to another; what can be measured directly, on the other hand, is the reaction time to a visual stimulus.

Several studies have used different methods to compare reaction times to color and motion stimuli, giving varying results (Barbur, Wolf, & Lennie, 1998; Nishida & Johnston, 2002). The problem with reaction time data, however, is that one cannot isolate the perceptual component of the delay, since data are confounded with both the preparation and execution of a motor response. It would be rather naïve to equate the second part of a theoretical stimulation-perception-decision-reaction model to color and motion reaction times in an effort to draw inferences regarding the perception time necessary for each attribute. First, it is not certain that the perception-decision-reaction sequence can be equated for the two functionally specialized systems—it is far from definite that they share common decision mechanisms or access the motor system in the same way. Secondly, it is not even true that the simplistic scheme of stimulation-perception-reaction always holds: it is possible that stimulation-reaction shortcuts might sometimes bypass the stage of conscious perception for a quicker response to, say, a moving stimulus. In general, it is difficult to attribute reaction-time variance to sensory processing with confidence.

It has been suggested that the perception of *the time* at which a percept is being experienced could be different from the time at which each functionally specialized system forms the neuronal representation of this percept (Nishida & Johnston, 2002). In other words, perceptual asynchrony could perhaps be introduced via the meta-analysis of salient temporal features, by a neural mechanism dedicated to coding the timing of events. If so, the subjective time course of visual experience is the product of analysis beyond the temporal processing of the content of the events themselves. On top of seeming a rather awkward idea, it suggests the existence of an independent system in the brain, responsible for the perception of the time of events, which is different from the mechanisms responsible for the perception of the events themselves. In such a scenario, a possible concern regarding the psychophysical results of Moutoussis and Zeki is that the asynchrony demonstrated using their method is not a matter of perception, per se, but rather a wrong judgment of the time of occurrence of perceptual events (Nishida & Johnston, 2002). The misjudgment observed would not necessarily reflect perception-time differences, but could rather reflect the properties of a third mechanism responsible for judging the temporal order of events.

It has been suggested that such a mechanism uses temporal markers to reference the time a specific event occurs in the world rather than the time the processing of the event completes in the brain (Nishida & Johnston, 2002). The way this could be achieved, however, remains a complete mystery. How can it be that the brain knows the timing of things happening elsewhere? Even if such a mechanism exists, it would be more useful in temporal order judgment (TOJ) tasks, where subjects are asked to report the order of events—for example, when a single color and a single direction of motion are being flashed with various time offsets between them. However, in such TOJ experiments, not only is the task different from the original one in the work of Moutoussis and Zeki, but subjects also must make a decision *after* the presentation of the stimuli based on the memory of single, transient perceptual events (see Viviani & Aymoz, 2001 or Gauch & Kerzel, 2008 for examples). On the contrary, in Moutoussis and Zeki (1997a, 1997b), decisions are not based on memory, since the stimulus is continuously present on the screen and the subject has to decide *online* which color is being perceived together with which direction of motion. The two methodologies are quite different, and it has been shown that "postdiction" mechanisms could be involved in temporal order judgments of single events, as for example in experiments investigating the flash-lag effect (Eagleman & Sejnowski, 2000). For these reasons, using TOJ tasks in single presentations or even using, as originally, continuous presentations but asking subjects to make a TOJ about the instances at which the color and the motion changes occur could potentially give quite misleading results regarding the perception time of a particular visual attribute.

Another objection with respect to the methodology of the original experiments (Moutoussis & Zeki, 1997a, 1997b) could be that the result does not reflect a true perception-time difference between color and motion, but rather a particular strategy used by the subjects in order to perform this rather difficult psychophysical task. Subjects could choose, for example, to always report the pairing perceived immediately after a color change rather than the pairing that was being perceived during most of the presentation time (as instructed). In order to disinfect the perceptual asynchrony results from any response bias or strategy, an ingenious study (Arnold, Clifford, & Wenderoth, 2001) has combined perceptual asynchrony with the well-known color-contigent motion-aftereffect (MAE). Continuous presentation of a rotating stimulus for a period of time will make a subsequent static stimulus appear to rotate in the opposite direction (Mather et al., 2008). This aftereffect can be contingent on color by associating a particular direction of motion to a particular color, and the opposite direction to a second color during the same adaptation period (Favreau, Emerson, & Corballis, 1972). The direction of the MAE will depend on the color of the static stimulus: if, say, during adaptation red was associated with rightward motion, a static red pattern will appear to rotate leftward.

In this way, the characteristics of the aftereffect will reflect the perceptual associations between color and motion during the adaptation period directly, without the need for the subject to report any of these associations. If the two different colors are correlated disproportionately with the two directions of motion, then a consistent color-contingent MAE should be observed. If the physical correlation is not disproportional, such a result (color-contingent MAE) would reveal a perceptual correlation that is different from the physical one, and thus suggest different perception times for motion and color. Arnold et al. (2001) have used the Moutoussis and Zeki original experimental setup for the adaptation period but with rotational motion. They found that, although subjects were not at all concerned with binding color to motion directly, their reports on the MAE were consistent with a perceptual misbinding between the two attributes, in the way described originally (Moutoussis & Zeki, 1997a). If the perception of color and motion was veridical, then the maximum MAE in this experiment would be obtained when the color and motion oscillations are in phase, with no MAE when the two oscillations are 90 degrees out of phase. The actual results did not confirm this hypothesis, but were instead in agreement with a perceptual lag of motion with respect to color. These results cannot be explained by a possible response bias that could also perhaps explain the original results. To account for the MAE results without perceptual asynchrony, one would have to stretch one's imagination quite far and argue for possibilities such as the existence of a hypothetical internal perceptual-linkage bias attributed to a change in the firing rate of neurons during the initial and final stages of the color stimulus appearance, or asymmetrical adaptation between the color and the motion system, and so on (Johnston & Nishida, 2001). However, it is not easy to give a reasonable account for such a bias, and questions such as why the binding should be stronger during the first part of the appearance of the new color rather than during the first part of the appearance of the new motion remain unclear.

If motion is not treated as an integrated percept on its own but rather as the perception of a change in the position of an object over time, the perceptual asynchrony observed could be attributed to the physical nature of the stimuli rather than to the functional organization of the visual brain. In the original experiments (Moutoussis & Zeki, 1997a, 1997b), the color changed between two values (red and green), and so did the motion percept (up and down). However, with respect to position, the directional change of a motion is a second-order change (a change in the way position changes over time—i.e., acceleration), whereas the color change is a first-order change, from one color to another. Perhaps the perceptual asynchrony result observed is thus simply because the brain is slower in calculating a second-order change than it is in calculating a first-order change (Nishida & Johnston, 2002). Technically speaking, one could argue that for a color change to take place, two monitor-frames are necessary to register a color change, whereas a motion change needs three frames. This gives a 14 ms time advantage to color, which is far less than the ~100 ms value observed experimentally. Furthermore, if memory is taken into account, the single next frame is enough to register whether a change has occurred or not for both color and motion.

But there are even more serious objections than this, coming from the fact that the first- vs. second-order explanation gives to the brain very machine-like properties, quite distant from the true characteristics of visual perception. As far as the perception of motion is concerned, it is questionable whether this sensation can be equated to a simple observation of objects changing position over time. There are instances when motion can be perceived without perceiving any object changing position, as in random-dot stimuli (Newsome, Britten, & Movshon, 1989), or even without any object changing position in reality, as in the MAE (Mather et al., 2008) or the Leviant illusion (Zeki, Watson, & Frackowiak, 1993). Stimulating area V5 can induce the perception of motion, again without any particular object being observed to change position (Salzman, Britten, & Newsome, 1990). Patients with an intact area V5 but missing area V1, which is the most informed visual area concerning the exact position of objects in the visual field, are still able to perceive motion (Ffytche, Guy, & Zeki, 1996).

Motion perception seems to be, as far as the brain is concerned, an independent entity, not the first derivative of position with respect to time, and should be therefore treated like any other type of percept, such as color and form (for a review, see Nakayama, 1985). Furthermore, the task in the original experiment was not to judge the temporal order of the color and motion *changes,* but to report on the color-motion pairs that were perceptually bound together. By manipulating the task and the stimuli so as to make the position change a first-order change (here/there) and the color a gradual change from red to green in a sinewave manner, one can reverse the asynchrony result (Nishida & Johnston, 2002). It must be noted, however, that such an experimental setup, having numerous color percepts and no motion perception involved at all, is very different from the original one. More relevant to the color-motion asynchrony hypothesis are experiments that show a perceptual time difference between color and form, the former being perceived faster (Moutoussis & Zeki, 1997b), where we are dealing with two first-order changes in every respect. What is also interesting is that in this series of experiments (Moutoussis & Zeki, 1997b), form was found to be perceived faster than motion, with the perception-time difference between color and motion being roughly equal to the sum of the perception-time differences between color and form and that between form and motion. A control experiment was also carried out in which participants had to pair upward/downward and leftward/rightward motions; no perceptual asynchrony within the motion system was found in this case (Moutoussis & Zeki, 1997b).

The well-known physiological effect of opponency, in which there is mutual inhibition between different neuronal populations with different encoding properties, has been suggested as a possible explanation for the existence of a perception-time difference between color and motion. Because of the way in which the motion system is wired, the two directions used (up and down) activate neuronal populations that inhibit each other maximally (Barlow & Levick, 1965; Snowden et al., 1991), and thus a delay in processing time could be observed within the system. The same could also be true for the red-green color pair used—the general idea being that, if perception time depends on the processing time of the system (as originally proposed by Moutoussis and Zeki), then disinhibiting one system might lead to a quicker processing, which in turn might lead to a quicker perception.

Along these lines, Arnold and Clifford have repeated the color-motion experiment of Moutoussis and Zeki (1997a) but with different pairs of directional motion (Arnold & Clifford, 2002). What they found is that the strength of the perception-time difference between color and motion varies with respect to the angular difference between the two directions:

the maximum perception-time difference was observed when the two directions were opposite; that is, when the inhibition between the two neuronal populations responsible for the processing of the motion signal was at its maximum. This observation further supports the original hypothesis put forward by Moutoussis and Zeki, namely that the observed misbinding between color and motion is due to a difference in perception time between the two attributes, which is in turn caused by differences in the processing time of the corresponding functionally specialized systems. In fact, stimulus manipulations with respect to depth and transparency suggest that the phenomenology of binding seems to parallel the physiological properties of area V5, further supporting the view that the former is a direct reflection of the time course of the underlying neural processing (Clifford, Spehar, & Pearson, 2004).

Another concern regarding the observed misbinding between color and motion is that it might not be the result of a perception-time difference between them, but rather a reflection of a "postdiction" mechanism in visual perception in general (Moradi & Shimojo, 2004). Such a mechanism has been suggested in order to explain the flash-lag illusion: when a stationary flash is presented to the same spatial location with a moving ring, at the time of the flash perception the ring is perceived at a different spatial location, which is actually the location it has around 80 ms after the flash (Eagleman & Sejnowski, 2000). The basic idea is that the brain "waits" around 80 ms in order to integrate various perceptual events taking place during this period and comes out with a integral percept, which it allocates temporally at the beginning of the particular "period." Each "period" is initiated by a transient, such as a flash, a direction reversal, or the like. In an experimental attempt to test whether this idea could explain the perceptual asynchrony data, random-dot stimuli with red and green dots were used: a particular group of dots suddenly turned gray and was set into motion, at the end of which they either returned to their original color or reversed color (Moradi & Shimojo, 2004). Most of the time, participants reported the color of the moving dots to be that *after* the motion was over. This result was taken as an indication that the brain integrated perceptual events over a long period of time and paired the motion together with a color that occurred later, in a "postdiction" manner. It must be noted, however, that the same result is also compatible with the original explanation given by Moutoussis and Zeki, who predicted that because color is perceived more quickly, it is perceived together with a particular type of motion that took place earlier in real time.

Additionally, although the postdiction theory gives a satisfactory alternative explanation for the results observed at a phase difference of 90 degrees, it cannot explain the results observed when the color and motion oscillations are in complete synchrony (i.e., at a phase difference of 0 degrees). Specifically, if the appearance of a new direction of motion "resets" the system and makes the pairing between motion and color stronger during the later stage of this motion, then this could potentially explain why this motion is not equally paired with the two colors, but more strongly with the second one at a phase difference of 90 degrees. The same explanation would also predict, however, a perfect binding between motion and its corresponding color at a phase difference of 0 degrees, contrary to what is actually observed. The perceptual asynchrony theory, on the other hand, not only explains equally well the result at a phase difference of 90 degrees, but also predicts the messy situation observed at a phase difference of 0 degrees.

A further blow to the postdiction explanation comes from a series of experiments showing that, if the presence of the opposite direction of motion is replaced by a different transient (total absence of the moving stimulus), results are very different from the original condition in both color-motion and motion-motion experiments (Arnold, 2005). More specifically, such a replacement minimized the perceptual asynchrony between color and motion and induced perceptual asynchrony in a motion-motion condition where upward-downward motion had to be perceptually paired with leftward-rightward motion (Arnold, 2005). It seems that the absence of the opponent direction of motion resulted in a faster processing for the motion system, thus reducing the differences between this and the color system and also introducing a perceptual advantage compared to a situation in which the opponent direction was present. Such a result is in agreement with the hypothesis of a perception-time difference originating from processing time differences between the different functionally specialized systems. It is not in accordance with the theory of postdiction, which predicts that any change in the motion status resets the system irrespective of the particular characteristics of this change.

Given the powerful effect of attention on visual perception in general, the possibility that the whole perceptual asynchrony phenomenon is a consequence of some kind of differential attention between color and motion has been also examined. Manipulations on endogenous attention by way of changing which feature dimension observers were instructed to attend to seems to have no effect, lending support to the possibility that voluntary switching between feature dimensions does not account for the better part of the perceptual asynchrony (Clifford et al., 2003; Arnold, 2005; Holcombe & Cavanagh, 2008). The effect, however, could be due to differences in exogenous, involuntary attention, which is set by the different intrinsic salience of the color and motion transients. Briefly presenting a ring around the targeted color-motion oscillation (present within a group of several other ones) can reduce or even eliminate the apparent latency difference between the two attributes (Holcombe & Cavanagh, 2008). The ring plays the role of an exogenous attentional cue, providing transients that indicate the time and place to attend. Without an external cue, the color transient is perhaps stronger than the motion one, and thus access to the new color happens more rapidly and leads to the observed perceptual asynchrony. But when the ring is presented, it acts like a strong exogenous attentional cue that might override the unbalanced intrinsic transients and give equally rapid access to both motion and color (Holcombe & Cavanagh, 2008).

This type of experiment, however, belongs to a very different methodology, in which the stimulus is presented briefly and the participant has to give a response based on the memory of a single rapid presentation. The presentation lasted for only half a period, and the results showed that subjects usually reported afterward the features predominantly cued by the ring when it was present; that is, color and motion mostly present during this time, independently of the relationship between the two. This is quite an expected result, because even if the two attributes are perceived with a slight time difference, they are reported as a pair, since there is nothing else there to remember and to (mis)bind with (but see also Linares & López-Moliner, 2006). Indeed, when participants in the same study were allowed to attend to the identical cued stimulus throughout the oscillation sequence, a perceptual asynchrony between color and motion was observed, as originally reported.

10.3 Summary and Conclusions

In the present chapter, I have tried to bring together experimental data and theoretical implications from various studies aiming to investigate the possibility of a perceptual time difference between the different visual attributes. The neurobiological reality of a functionally segregated visual system begs the question of how different characteristics of the visual scene, such as color and motion, are bound together in the temporal domain. Psychophysical experiments have shown that there is indeed a perceptual asynchrony between attributes that are processed by different, functionally specialized systems. In this way, the problem of space- and object-oriented integration and bonding is extended into the temporal domain. The idea of percepts that are independent in both space and time has in turn inspired the so-called *theory of microconsciousness*, which states that conscious visual perception is not single and unified but rather made out of several independent consciousnesses of different visual attributes. The perceptual asynchrony between the latter can be revealed by appropriate psychophysical tasks, designed to test the ability of subjects to correctly bind in time two different visual percepts they are conscious of. The perceptual asynchrony revealed, however, does not necessarily manifest itself in different types of tasks, like reaction-time measures, temporal-order judgments, or memory-based responses regarding single, brief stimulus presentations. Other theoretical explanations of the perceptual-asynchrony phenomenon, based on independent timekeeping circuits or perceptual mechanisms of postdiction or attention, have not given a satisfactory account of the observed experimental data. The latter can be best explained by differences in the processing speed of the underlying physiological mechanisms and are influenced by manipulations of these mechanisms, such as opponency and inhibition.

Thus, the perhaps not so objective conclusion of the present chapter is that there is indeed a perceptual asynchrony between the different functionally specialized systems of the visual brain. Different attributes of the visual scene seem to be perceived independently from one another and at different times. The picture emerging is that of modularity in the world of visual perception, with the possible existence of separate visual microconsciousnesses for color, motion, form, and so on. Careful consideration of both the scientific and philosophical implications of such a discovery, with respect to the architecture of perception and also of the mind in general, seems to be a fruitful and creative path to follow.

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11 Constructing Time: Dennett and Grush on Temporal Representation

Bruno Mölder

Incorporating the role of time is necessary for those theories that attempt to explain our conscious experience as well as for theories about the information processing that underpins experience. This chapter focuses on two models that have taken temporal properties, both at the level of experience and at the level of information processing, under special consideration. It is common to these models that they elaborate the constructivist view that temporal content results from constructive processing in the brain. The chapter attempts no more than outlining and explaining these models, as well as defending them against some common criticisms. The first part outlines Daniel Dennett's multiple drafts model of consciousness, which is motivated by certain assumptions concerning the neural processing of contents. The second part is dedicated to the approach proposed by Rick Grush, which presents an exact mathematical model based on the control theory and the emulation theory of representation. It shares the general approach of the multiple drafts model, but is more formal and precise, and thus has clearer empirical consequences.

In the case of temporal representation, one should distinguish between three kinds of temporal sequence, for a mismatch could arise between each sequence. These are

(a) the objective temporal properties of environmental events;
(b) the temporal properties of brain events;
(c) the temporal properties of events as experienced.

A divergence can occur between *a* and *b* as well as *a* and *c*. That is, we can register events taking place in an order that differs from the objective order in which they appear. There are some trivial examples of this, relating to the distance and speeds of light and sound. Thus, when an event *g* takes place before the event *h*, but *h* happens in close vicinity of the subject and *g* occurs much further away, then the subject's brain may register *h* happening before *g* (the same can hold for what the subject experiences).

There are also less trivial examples relating to perceptual illusions that involve a change in the temporal sequence of events. As Grush (2008, 153) has stressed, the very existence of temporal illusions demonstrates that temporal content is a result of constructive processing. In the case of an illusion, we perceive properties and relations that do not exist in the environment. When the illusion is temporal in its nature, this supports the idea that the perceived temporal relations are fixed by the interpretations of the cognitive system, not by the temporal relations between events in the environment (see Grush, 2005b, S210). Thus, when discussing these models below, their explanations for temporal illusions such as the cutaneous rabbit phenomenon and the illusions involving apparent motion are taken under special scrutiny.

Another important mismatch could occur between *b* and *c*. In some cases, some stimuli can be neurally processed in a different order than they are experienced. How this is possible, and how should we understand the relationship between brain events and consciousness, will be discussed when we will look more closely at the multiple drafts model.

We can now be more specific concerning the constructivist view. Stressing the constructive nature of processing involves two strands: first, this can be read as saying that the element of construction enters the picture when the brain works out its own interpretation of the temporal properties in the environment (the relationship between *a* and *b*). Second, it can be read as saying that experience, the conscious sequence of events, is a result of the constructive brain processes, in which case there is no one-to-one correspondence between the experienced sequence and the order of neural processing underpinning this experience (the relationship between *b* and *c*).

For example, Dennett and Kinsbourne (1992b, 183) summarize their approach in the following way: “The temporal order of subjective events is a product of the brain’s interpretational processes, not a direct reflection of events making up those processes.” Here, the events are neural events, not the events in the world that are represented. In view of this distinction, one might want to say that Dennett concentrates mainly on the second issue, whereas Grush deals mostly with the first issue. Indeed, in gesturing toward Kant, Grush (2005a, 205) claims that “temporal phenomenology is not simply a reflection of, or determined by, the temporal facts. ... [O]ur experience of time is not determined by the temporal features of the things themselves, but is at least in part a product of the brain’s own interpretation.”

However, the distinction is not so clear-cut, for if there is a mismatch between *b* and *c* due to the constructive role of the brain, then a mismatch between *a* and *b* is also expected, because the brain is not constrained to stick to the objective temporal order. Dennett’s claims therefore also have consequences for the first issue. And since Grush talks about the temporal content of perception (see, e.g., Grush, 2008) as well as “temporal phenomenology” (in the above quote), his discussion also concerns our experiences (*a* and *c*) and is relevant for the relationship between the temporal properties of subpersonal representations and the temporal properties represented in the content of experience (*b* and *c*).

Given these interweaving strands, it makes sense to formulate the constructivist view in a broader way, to encompass both strands. We could say the following: temporal content results from the constructive processing in the brain; it is neither a straight copy of the temporal properties of environmental events nor of the temporal properties of neural events involved in the processing.

Let us now turn to the models themselves.

11.1 The Multiple Drafts Model of Consciousness and the Time in the Brain

11.1.1 The Multiple Drafts Model: An Introduction

Time-related issues are central to Dennett's approach to consciousness. In what follows, I outline Dennett's so-called multiple drafts model of consciousness and explicate the role of time in this model. The locus classicus for the multiple drafts model is Dennett's book *Consciousness Explained* (Dennett, 1991).[1]

The multiple drafts model is a bundle of metaphors and suggestions rather than a formal model. It is presented as a replacement for other, presumably quite widespread sets of assumptions concerning the relation of consciousness and brain processes. However, since the discussion takes place at the level of general schemes that influence the way we think about consciousness, metaphoricity is a virtue, not a vice.

It could be said that the central idea of the alternative approach that Dennett seeks to demolish, dubbed "Cartesian materialism" by him, is that there is always a definite distinction between conscious and nonconscious brain processes, irrespective of the temporal and spatial resolution of the analysis. In principle, the distinguishing property could be either a spatial or a temporal one. However, in the way Dennett presents Cartesian materialism, the spatial property takes precedence over temporal properties. He construes the position as postulating a locus for consciousness in the brain, the "Cartesian theater" (Dennett, 1991, 107). This is the idea of a special location in the brain, such that when the information being processed in the brain reaches it, it thereby becomes conscious for the subject. This location can be envisaged as a center or just as a borderline; in both cases, there is a certain spatial property that is necessary for consciousness. This, in turn, determines the order in which the information becomes conscious. If certain bits of information cross the border earlier than others, one also becomes aware of those bits of information before the other bits.[2]

The multiple drafts model, by contrast, accounts for consciousness without presuming that there is a sharp boundary between conscious and nonconscious processing. The normal brain is incessantly processing information, so there is always a horde of different processes going on. To appropriate Dennett's writing analogy, we can compare these processes to the drafts of a text that are under revision. Imagine that there is not just one draft and a single writer, but that several drafts of the same text are being concurrently edited by different writers. In such a situation, there may be no principled basis for judging which draft constitutes a finished text.[3] The multiple drafts model incorporates this multiplicity into consciousness, as well as the resulting lack of a principled distinction.

The model consists of several key claims, introduced over the following pages. As already mentioned, underlying consciousness there are multiple parallel processes:

> All perceptual operations, and indeed all operations of thought and action, are accomplished by multitrack processes of interpretation and elaboration that occur over hundreds of milliseconds, during which time various additions, incorporations, emendations, and overwritings of content can occur, in various orders. (Dennett & Kinsbourne, 1992b, 185)

These processes involve operations on informational or representational content; sometimes Dennett calls such processes "context-fixations" (Dennett, 1991, 113).[4] A fixation of content influences other processes, and some content-fixations have larger effects on subsequent processing as well as the control of an agent's behavior than others. These effects are enhanced by "probes," that is, queries leading to reactions, whereby reports about the contents of one's consciousness can be elicited.

Dennett uses the notion of the domination of some content-fixations in controlling one's body to single out those processes that can be regarded as conscious: "Consciousness ... is the relatively greater influence of various contents on the processes that control the body of an agent composed of those processes and capable of telling us (and reminding itself) about some of them" (Dennett, 2009, 454; see also Kinsbourne, 1988).[5] Although it is a mark for consciousness, we can see it is deliberately fuzzy. An influence or dominance has neither precise temporal nor spatial location. Of course, it can be positioned in a larger scale, but this is too imprecise to be helpful in the present context.[6]

When there is no strict borderline of consciousness, no sense can be made of the idea, which for Dennett is a part of Cartesian materialism, that the product of nonconscious processing will be made accessible to consciousness at some point. There is no "double transduction," in the case of which the already processed contents will be grasped in a separate medium of consciousness (Dennett, 1998). Just as in the Cartesian picture, in which the image of consciousness as an inner theater is coupled with the image of an audience in the theater, the rejection of a separate location for consciousness goes hand in hand with the rejection of the special subject whose task is to entertain conscious contents. Instead, both the locus and the subject of consciousness are divided into multiple processes that take place in various parts of the brain.

11.1.2 Temporal Illusions and the Multiple Drafts Model

Dennett has used the multiple drafts model to make sense of several temporal illusions (Dennett, 1991; Dennett & Kinsbourne, 1992b). I will concentrate on two well-known illusions—the color phi phenomenon[7] (Kolers & von Grünau, 1976) and the cutaneous rabbit phenomenon (Geldard & Sherrick, 1972). The color phi phenomenon is the illusion of movement that occurs when the subject is presented with flashes of two objects of different colors in different positions (e.g., a blue spot and a red spot). It seems that the spot is moving from one location to another and changes its color midway through its movement. What is puzzling about this phenomenon is that the color seems to already change in the location that precedes the actual location where the spot with a different color is presented. Let us say that a blue spot is presented in location A, and a red spot is presented in location G, and that the spot appears to travel from A to G. In this case, it seems to the subject that the spot turns red in the location D, which is in the middle of A and G. This is puzzling, since the red color seems to be present before it is actually presented. To a naïve eye, it seems that the brain somehow processes the red spot before it is presented. However, when we rule out precognition, the experience of the red spot cannot be generated before the red spot is detected by the brain. Then the temporal order of experiences and the temporal order of brain events do not match. Why do not we experience first the blue spot, then the red spot and the intervening movement, if that is the order in which the brain processes the information (see Dennett & Kinsbourne, 1992b, 186)?

In the experiment that evokes the cutaneous rabbit phenomenon, taps are applied rhythmically at the different locations of a subject's arm, optimally at 40–60 ms intervals (see Geldard & Sherrick, 1972, who experimented with various conditions). First, there are five taps at the wrist; then five taps toward the elbow 10 cm from the original position; and finally, another set of five taps 10 cm from the previous location. The subject feels as if something moves regularly with smooth jumps up the arm. The jumps seem to be located uniformly along the arm, not only in the locations of the stimulation. Even the location of the second tap seems a bit shifted toward the elbow. When only the wrist is tapped, the movement is not felt. It almost seems as if the later taps have a backward effect on the felt location of the second wrist tap. If we exclude this option, the experienced location of the wrist taps should depend on the registration of the tap toward the elbow by the brain. If so, then we have a similar temporal order puzzle to the color phi case. Why do not we experience first taps on the wrist, then toward the elbow, and then the "hopping" movement from the wrist toward the elbow?

The multiple drafts model's account of these illusions involves two tenets aside from the basic principles of the model itself. The first point is the acknowledgment that when there is time pressure, neural processing optimizes and makes shortcuts: "When a lot happens in a short time, the brain may make simplifying assumptions" (Dennett, 1991, 142). The second rejects the one-to-one correspondence between temporal properties represented in the content and the time when the content is represented. Both of these points play a role in the explanation of the illusions.

The multiple drafts model's account of the color phi phenomenon is as follows (Dennett & Kinsbourne, 1992b, 195). Among the various parallel and competing processes, the "microjudgment" that overcomes alternative content-fixations is that the blue spot is moving and turns red. It is this conclusion that has an effect on the subject's report, and not other concurrently developed interpretations. Hence, the subject is conscious of this content, which turns out to depict an illusory event, and not other potential contents. Had the stimuli presented with different intervals or had the processing been interrupted, the subject's experience might have been different. But given the very short time in which the spots are flashed, the brain must solve the perceptual problem very quickly, and the partial fabrication follows. From this, we could also derive the explanation of the temporal order puzzle: the microjudgment that the blue spot is moving and turns red rules out the incompatible judgment that first there is the blue spot, then there is the red spot, and finally there is the movement.

The account of the cutaneous rabbit illusion follows the same theme (Dennett & Kinsbourne, 1992b, 195). The winning microjudgment is that there is a uniform distribution of the taps on the arm from the wrist toward the elbow. This conclusion is reached when the taps are already administered, and it overwrites other budding content-fixations. The conclusion again involves a simplification under time pressure, which leads to the illusory conscious experience. The puzzling feature of the phenomenon that the "hopping" experience appears with the tapping on the wrist can be explained by the fact that the corresponding microjudgment, which overpowers other interpretations, is actually finalized after the stimulation of the region near the elbow.[8] A solution to the temporal order worry can be drawn from this, along the same lines as in the color phi phenomenon. If the winning microjudgment is that there occurred a uniform movement along the arm starting from the wrist and directed toward the elbow, it rules out all microjudgments that include the ordering in which the taps toward the elbow precede the "hopping" movement.

Of course, these are sketches of explanations rather than full-blown accounts. It is also characteristic of them that they are functional explanations couched in intentional vocabulary, and are thus unavoidably metaphorical. Even so, they highlight important features of the approach. They are also instructive in what kinds of accounts they rule out. This becomes explicit later when we discuss the alternative explanations that, according to Dennett, stem from the adherence to Cartesian materialism. Here, I would like to point out that both explanations described above exemplify how consciously represented temporal properties need not match with the temporal properties of the neural processes that underpin these representations. It should be noted that the relationship between the represented temporal relations and the temporal properties of representational vehicles can be approached from two perspectives. From the epistemic point of view, the question is how we as observers could infer the experienced temporal content from the timing of the underlying neural processes. Another question is how the brain itself fixes the temporal relations between the events that it represents. The former question has a practical significance when devising and interpreting psychological experiments related to timing. In the present context, we are dealing mainly with the latter issue, but this also has consequences for the first issue.[9]

There are two ways to approach the relationship between represented temporal properties and the temporal properties of representations (see Dennett, 1991, 147–52; Kelly, 2005, 212). These could be termed the *temporal isomorphism* approach and the *temporal indicator* view. In the first view, there is an isomorphism between the respective temporal properties. When the representation of event *a* arises in the brain before the representation of event *b*, then, according to this view, *a* is represented as occurring before *b*. On the second approach, such isomorphism is not required. Representations carry temporal indicators, sometimes called "time stamps," that specify the temporal properties of the represented events. An example from a different field would be two stories, one of them written in 2009 and the other in 2010. It does not follow that the story written earlier would represent events that took place at an earlier time. On the contrary, a story written in 2009 can describe an event that took place in 2000, whereas the story written in 2010 can represent an event that happened in 1924.

Dennett is clear that the time when the representation is constructed does not carry over to its content. In broad terms, he subscribes to the temporal indicator view: "What matters for the brain is not necessarily when individual representing events happen in various parts of the brain … but their *temporal content*" (Dennett, 1991, 149; emphasis in original). However, his more specific proposal about how temporal content is fixed in the brain aspires to a higher biological plausibility than the idea of content carrying time stamps. The notion of a time stamp that suggests the idea of some unitary and static property disintegrates, to be replaced by an active construction of temporal information.

Dennett (1991, 152) presents his proposal, which he calls "content-sensitive settling," on the basis of the movie-editing analogy. Namely, when editing a movie, one can add soundtrack to images, even if neither sound nor picture contains any explicit temporal markers. This matching is possible when one relies on the correspondences between sound clips and scenes in a movie. Dennett notes that finding such correspondences requires following the content of both clips to a certain extent, but it does not require understanding the meaning of what is said in the soundtrack. When we apply this analogy to the brain, we get a picture in which the temporal information is inferred by multiple small processes in an order that need not be determined by the input. In accordance with the temporal indicator approach, Dennett's proposal does not include the requirement that the order in which the temporal information is read from various sources should correspond to the temporal order represented by the content. In Dennett's model, those processes that construct temporal contents themselves need not "understand" the full content of the information they handle. Accordingly, temporal information can be settled in quite an early stage of processing, and this suffices. Fixing the temporal content for a second time would not be economical. As in general, in the temporal case there is no need for a "double transduction," that is, the final presentation of the same information to the conscious mind in the "correct" temporal order (Dennett, 1991, 153).

11.1.3 Temporal Illusions and Cartesian Materialism

The multiple drafts model has been constructed to avoid the tempting preconceptions that lead to Cartesian materialism. In what follows, I describe some accounts of the illusions that embody such presumptions and discuss Dennett's reasons for rejecting them in favor of the multiple drafts model.

As noted, the main Cartesian preconception is that consciousness has a clear-cut boundary. It follows from this that all processes related to consciousness divide neatly into two classes—those that are already in consciousness and those that have not yet crossed the boundary of consciousness. Dennett argues that this clear distinction would evaporate at short timescales. To show this, he presents two alternative models that are both Cartesian in nature and argues that there are no grounds for distinguishing between them.

Both models involve revision of content, but they differ on whether this revision takes place before or after the boundary of consciousness. In one case, the experience of which one is conscious would already be revised; in the other case, the memory of one's experience will undergo a change. Dennett (1991, 116–7) dubs the first model "Stalinesque," alluding to the fabrication of evidence in the show trials of Stalin's Soviet Union, and the second model "Orwellian," in reference to the revisions of historical records depicted in George Orwell's *1984*.

Let us first look at the Stalinesque explanation for the illusions. The Stalinesque model explains the color phi phenomenon by postulating a revision of the original nonconscious representation of two spots (Dennett, 1991, 120). The revision adds an intervenient movement and a change in color. All editing takes place before the subject becomes conscious of the stimuli. What one becomes conscious of is a fabricated representation, which is completed entirely nonconsciously. This model involves a short delay of consciousness of the stimuli. It predicts that the representation must be kept from becoming conscious until the red spot has appeared, for otherwise nothing would have elicited the revisions. However, as Dennett (1991, 122) points out, a lack of lag time cannot be used to rule out the Stalinesque account, for in order to explain the control tasks in which the subject's performance does not display the delay, the supporter of this model can posit nonconscious reactions.

Dennett has not explicitly presented the Stalinesque account of the cutaneous rabbit illusion, but its form can be inferred from the description in Dennett (1991, 143). Also in this case, a representation is edited below the level of consciousness. An experience of the regular movement along the subject's arm is fabricated. As in the multiple drafts account, this representation (of which the subject becomes conscious) is created after the relevant taps are applied on the arm. However, the crucial difference is that in the multiple drafts model, the content of the representation is fixed with the microjudgment, whereas in the Stalinesque account, the initial unconscious representation of the separate taps is followed by the construction of a full illusory movement representation, which then becomes the content of a subject's conscious experience.

It is characteristic of the Stalinesque model that the consciousness of the experience is delayed until all the editing is finished. Only then will the completed "product" be made accessible to consciousness. This relies on the Cartesian assumption that the result of the processing has to be presented all over again to consciousness. By contrast, according to the multiple drafts model, the continuing construction of representations that compete for consciousness begins already with the stimulation, and their becoming conscious does not involve an additional presentation. It should be noted that Dennett (1991, 151) acknowledges the need for some kind of "temporal control window" during which the representation can be constructed and revised in a timely way to control the behavior properly. However, allowing such a window does not commit him to the Stalinesque notion that the representation must be entirely complete before it would transform into an experience.

Let us now examine the Orwellian account. The Orwellian model of the color phi illusion involves a contamination of the memory (Dennett, 1991, 121). The subject immediately experiences first the blue and then the red spot. Noting the conflict both in color and the location of the spots, the brain adds the memory of the changing color and the movement. It replaces the memory trace of the initial experience. The report of the subject is then based on the false memory; there is no access to the original experience. In the cutaneous rabbit illusion, the Orwellian story should be similar to the Stalinesque account, with the exception that instead of the change in experience, the memory traces would be faked—that is, the subject experiences every single tap, and then the memories of these taps are swapped with the memory of the experience of the passage of taps along one's arm.

Dennett argues that there is no data that could distinguish between the Stalinesque and Orwellian models. It may seem that the difference between the revision of memory and the revision of experience must be easily detectable. However, the claim is not that we cannot distinguish experiences from memories. It is rather that to deem one state an experience instead of a memory, and vice versa, requires interpretation, for which there is no principled basis on a small timescale. It is open for one to argue that such commonsense notions do not even apply to events happening during hundreds of milliseconds.

When we talk about consciousness instead of memory and experience, then Dennett's claim is that the notion of a consciousness-related difference between the predictions of these two models is a chimera. The models disagree on whether the revision happens before (Stalinesque) or after (Orwellian) the boundary of consciousness, but this is a difference only in theory, not in the "objective" brain processes or in the "subjective" awareness (Dennett, 1991, 124–5). The Stalinesque and Orwellian accounts were deliberately devised so that they cannot be distinguished from the *subjective* point of view, for in the time one has access to one's experience, the fabrications have already occurred. After all, the resulting experiences (the moving, color-changing spot and the feeling of a hopping rabbit) that both models seek to explain are the same. The putative neural and functional differences between the models actually depend on the notion that there is an exact moment when nonconscious processes become conscious. From the *neural* perspective, the difference boils down to the location and the time of the inception of consciousness. From the *functional* perspective, the disagreement is over the issue of whether the behavioral effects are due to nonexperiential reactions or experiences that one fails to recall (Dennett, 1991, 125). This differentiation again depends on where we mark the boundary of consciousness, which in turn presumes that such a boundary can be marked with the required precision. When outlining this difference in terms of nonconscious discrimination of contents and forgotten conscious discrimination of contents, Dennett and Kinsbourne (1992b, 193) thus draw a conclusion about the Stalinesque and Orwellian models: “They agree about just where and how in the brain these discriminations occur; they just disagree about whether to interpret those processes as happening inside or outside the charmed circle of consciousness.”

If the generation of consciousness has no sharp beginning in time, then every attempt to divide brain processes at the small timescale of investigation into those that are not yet conscious and those that are already conscious would indeed depend on the interpretation of the theorists. It is not prescribed by those processes themselves, and thus is not anything that could be drawn out from an increasingly closer examination of them.

A kind of consensus seems to exist, in which Dennett’s claim that we cannot decide whether the Stalinesque or Orwellian account is correct yields support for the multiple drafts model (e.g., Block, 1993, 192; Schneider, 2007, 315; Todd, 2009, 500). Even if this were the case, it does not follow that if we can somehow decide between these accounts, the multiple drafts model would thereby be proven wrong. The point about indistinguishability is rather an illustration of the idea that fixing the beginning of awareness of certain content among the multiple processes in the brain can only be an *arbitrary* decision, not a principled one (Dennett, 1991, 126; Dennett & Kinsbourne,1992a, 236). This is not to say that it cannot be done for some purpose or other.

11.1.4 Criticism of the Multiple Drafts Model

I conclude the presentation of the multiple drafts model with discussion of some of its recurrent criticism. It is intriguing to note that several main points are related to the question of whether consciousness can be sharply timed.

Some critics assume that the denial of the sharp boundary between conscious and nonconscious processing is due to verificationist assumptions (Van Gulick, 1992, 229; Block, 1993, 189; Seager, 1999). Namely, it is assumed that Dennett concludes, from the epistemic point that we cannot collect data to distinguish between the Stalinesque and Orwellian models, that there is no such difference between the models, and hence no “fact of the matter” concerning whether one was conscious of the stimulus or not.

However, although Dennett himself mentions verificationism in this regard (e.g., Dennett, 1991, 126), verificationist prejudices are not the reason for the denial of the lack of the distinction (see also Dennett, 1993, 56). The issue is not an epistemic one. There is objectively no sharp distinction between conscious and nonconscious content, when consciousness is understood along the lines of the multiple drafts model in terms of the gained dominance of effects. The reason is simply that the construction of conscious content takes place gradually, and hence there is no single moment when the consciousness of a particular content begins:

> Once discrimination and control get distributed around to many sub-agencies, operating on different schedules, all the accomplishments of consciousness occur, one way or another, at one time or another, but no grounds remain for deeming one version of these events the “actual conscious experience.” (Dennett & Kinsbourne, 1992a, 236)

Dennett and Kinsbourne (1992a, 236–7) invite us to consider the case when the beginning of conscious processing would be marked by a property that has a specific location in time (they call it "the property *K*"). They argue that when we take the property *K* as a functional or neural property, it needs to be established that it is linked to consciousness. Hence, it has to be identified by correlating it with the awareness of the subject; but the subject's reactions would not be as fine-grained as one would require if the property *K* were precisely locatable, so it is impossible to single out any such property.

It also would not help to respond that the property *K* could exist even when we cannot detect it, for it is a relational property, a property that relates brain processing and consciousness. For a relational property to have an exact moment of instantiation, both its relata also have to be datable with the same precision. But according to Dennett and Kinsbourne (1992a, 235; 1992b, 200) neural processes can be timed more finely than conscious events. Hence, such a property *K* cannot exist.

If consciousness is understood in the temporally extended manner instead, there would not be any difficulty in matching subjective evidence with those content-fixations in the brain, which have dominant effects. The vagueness in both cases is comparable.

Another objection to the multiple drafts model points out that its notion of consciousness is inadequate. The charge is that Dennett takes the subjective report for a sign that some content is conscious, and this overlooks more primitive kinds of awareness. In particular, Ned Block (1992, 1993) has argued that this model does not accommodate "phenomenal consciousness," which differs from the ability to make subjective judgments. When the existence of phenomenal consciousness is acknowledged, then one can distinguish the Orwellian and Stalinesque models from the subjective perspective. According to the Orwellian hypothesis, one is briefly phenomenally conscious of both spots, even though one cannot report about them. We could also distinguish these hypotheses from the neural perspective, when we could find out which brain processes are phenomenally conscious. Then one could just investigate whether there are the respective correlates for phenomenal consciousness, as predicted by the Orwellian story (see Block, 1992, 206; Block, 1993, 189–190; Flanagan, 1992, 82). Also, given that neural correlates can be precisely timed, the occurrence of the short-lived phenomenal experiences can also be precisely timed.

Dennett, indeed, does not acknowledge phenomenal consciousness as a separate kind of consciousness. Perhaps the reason is that he takes consciousness to be sustained by fixations of content. That is, every phenomenal appearance involves a reaction to it. In this sense, there is no "seeming" without "taking" it, to use Dennett's favorite vocabulary (Dennett, 1991, 133–4). Every experience is partly tainted by one's reaction to it. Thus, when something phenomenally "seems" to one, this would already be a matter of judgment in Dennett's sense, which results from a multitude of content-fixating processes.[10] As concerns the point that the brain events responsible for phenomenal consciousness could be precisely located in space-time, then this presumes that at the small timescale it is possible to find a fine-grained pairing of the events of phenomenal consciousness and brain processes. The reply to this line of reasoning is that it brings along the similar identification troubles (see Dennett & Kinsbourne, 1992a, 240).

Let us finally return to the question of why there cannot be data that allow us to choose between the Stalinesque and Orwellian stories. This is an issue that has puzzled many (see, e.g., Block, 1992, 1993; Todd, 2006, 2009).[11] Kathleen Akins (1996, 37) has outlined one potential way of distinguishing between the Stalinesque and Orwellian models in the case of the color phi experiments. This is to intercept the information processing just after both spots are being flashed and let subjects report their experiences. The Orwellian model would be true if it turns out that the subject experienced both the blue and the red spot. The Stalinesque model would predict that in that very moment, the conscious experience is not yet created, and hence the subject could not have an experience of either spot. Why can there not be data corresponding to these predictions? On the one hand, as already indicated, the assumption that an experiment of this kind would give us unambiguous results depends on a misguided conception of consciousness. Akins (1996, 37) points out that if Dennett is right, such a test cannot be run, for it presumes a mistaken assumption, which is also common to the Stalinesque and Orwellian models: "[B]oth postulate the existence of an ordered set of representations that does not exist. Thus one could never 'stop the clock' at the required juncture in processing, for that juncture does not exist either."

On the other hand, when one runs such an experiment, "stops the clock" and gets certain results, then it is always open for Dennett to respond that this experiment interfered with the very process of content-fixation. Asking the subjects immediately after spots are presented, but before the brain has had a chance to construct the illusion, constitutes just another probe, which influences which discriminations of content gain prominence. This result cannot be used for distinguishing between the Orwellian and Stalinesque accounts of an illusion, since the intervention did not allow the illusion to be generated in the way it would have developed without the probe: "If one probes 'too early,' one may gather data on how early a particular discrimination is achieved in the stream, but at the cost of disrupting the normal progression of the stream" (Dennett, 1991, 136).

This provokes some more general reflections concerning the empirical confirmation of the multiple drafts model itself. The claims of the model fall into three classes. In the first, there are claims specific enough to generate detailed predictions. The claims that belong to the second kind are too general to be confirmable experimentally. Finally, there are a priori claims, which result from the way the particular central notions are conceived. Their truth value does not depend on empirical particularities.

One claim that is relevant to the topic of time, and for which Dennett (1991, 465–6) sketches possible inventive empirical conditions that could confirm it, is the claim that "subjective sequence is a product of interpretation, not directly a function of actual sequence" (Dennett, 1991, 465). However, the claim that the sequence of stimuli does not match one-to-one with the sequence represented in the content of experience is not exclusive to the multiple drafts model. Indeed, it can be embraced by anyone who acknowledges temporal illusions. The claims in the second class that are too general include, for example, the point that consciousness is underpinned by multiple and parallel processes. This idea is simply too general to be confirmable by particular experiments, and it does not separate the multiple drafts model from other approaches that take consciousness as a global property of neural processing.

The claims of the third class—the a priori claims—might be easily confused with empirical claims, but in fact they ensue from the meaning of the terms. For example, since Dennett conceives consciousness in terms of dominance of content-fixations, the fact that whether some content is conscious becomes a matter of the subsequent effects of that content. As the manifestation of effects always takes some amount of time, it follows by a matter of logic that an awareness of content cannot be limited to a single instant: "One cannot—logically cannot—be famous for just 15 minutes; that would not be fame. And a content cannot be conscious for 15 ms and utterly forgotten afterwards; that would not be consciousness" (Dennett, 2009, 453). It is important to realize that this is an a priori point. *Given* this notion of consciousness, it would be pointless to try to falsify this claim by trying to establish empirically that one can be conscious of a single content for 15 ms only.

11.2 The Trajectory Estimation Model and the Construction of Temporal Representations

The remaining part of this chapter discusses Rick Grush's model of temporal representation, which is rooted both in philosophy and in control theory. As Grush himself has noted (see Grush, 2005a, 195), it is compatible with the multiple drafts model, but has the advantage of being expressed in formal control-theoretic terms. It is explicitly an account of the representations of temporal relations, which also takes the implementation considerations seriously. That is, the account is constrained by the assumption that the information-processing structure must be such that it can be implemented in the human brain. But it does not follow from the focus on the temporal *representation* that this account has no relevance for the conscious experience of time. On the contrary, as Grush (2005a, 160) claims, his aim is to explain "what it is that our *brains do* (at the subpersonal level) such that *we experience* (at the personal level) certain aspects of time in the way that we do."

In the background of the specific theory of temporal representation, there is a more general emulation theory of representation (Grush, 2004). The basic idea is that the representation in the brain is effected by the use of "emulators"; that is, internal models of the processes that are being represented. Such models simulate the output reaction to the incoming sensory inputs, and they can be used to predict the resulting behavior and correct the future estimates when the prediction differs from the actual output; they can also be used to simulate outputs that are not executed.

When applied to the representation of time, Grush's theory, the "trajectory estimation" model, claims that the emulators constructed in the brain produce estimates of the trajectory of the process over a certain interval of time (see Grush, 2005a, 2006, 2007; for formal details, see Grush, 2005b). These estimates are generated in view of the statistical information about the typical behavior of the emulated domain and incoming sensory data concerning the evolving process (Grush, 2008, 153). The production of estimates involves both the element of prediction of the future states of the process and correction of the past estimates given the incoming information.

In what follows, I outline some features of such emulators. Let $\hat{e}$ signify an estimate of the state of some represented process. This estimate is itself a representation of the process e (Grush distinguishes a representation from its target by the circumflex above the letter). The estimate is produced at a certain time and is an estimation of the process at a certain time. As these times can differ, the estimate needs two time indices. Thus $\hat{e}_{a/d}$ marks an estimate, which represents the state of the process at time a, but is constructed at time d (see Grush, 2008, 151 for such a notation). This already shows that Grush makes room for the idea that time is not represented by itself. Instead, what is being estimated at every instant is a period longer than the very instant, an interval $[t - l, t + k]$, where l and k mark respectively the beginning and the end of the temporally extended period. Using this notation, we can say that at every time t, an estimate $\hat{e}_{[t - l, t + k]/t}$ is constructed. In the next production cycle, which takes place at $t + n$, a new estimate $\hat{e}_{[t - l + n, t + k + n]/t + n}$ is generated.

Grush has repeatedly stressed that the emulator can correct its estimates (e.g., Grush, 2005a, 187; 2005b, S212). Thus, there can be two estimates of the state of the process during the interval of, say, t_1–t_5; one is produced at t_3 ($\hat{e}_{[t1, t5]/t3}$) and the later one at t_4 ($\hat{e}_{[t1, t5]/t4}$). When the estimate is revised on the basis of feedback, these two estimates of what goes on during the same interval would differ. In this case, the revision also concerns the estimations of what happened in those moments that are already in the past with respect to the revising time. This feature of the emulators is put to use in accounting for the temporal illusions, as we shall shortly discuss.

As concerns the extent of the interval, Grush (2005a, 196–8) presents some considerations about why the central nervous system needs to represent the events in the body and environment during noninstantaneous periods. Since it takes up to 200 ms for sensory input to arrive to the central nervous system, the estimates of this input by the centrally located emulator must be amenable to correction for this period. At the other end, the timeframe of the predictions that the system must make is determined by the time it takes to execute motor commands. Without such predictions, the motor commands would be late.[12] Thus, the interval is determined by the need for the central nervous system to stay flexible in revising its estimates in view of the information about the past it receives after a short delay, and to be prepared for what will happen in the immediate future.

The interval is not just a feature of the subpersonal information processing; it has a role in constituting one's experiences as well. Grush also describes the two ends of the interval in terms related to experience. The past end is "the region within which the nature of what is/was experienced can be overwritten without the change being phenomenally registered *as a change*, but rather as what was experienced all along," and the future end consists of "predictions that are so tightly woven into one's current experience that … they are not experienced as separate predictions at all, but become silently absorbed into the perceptual event along with incoming sensory information, in a way that erases all record of their status as anticipations" (Grush, 2005a, 197–8; emphasis in original.) The idea is thus that in the normal course of perception, not all results of the revisions of the estimates are experienced—the contents of awareness comprise intervals within which events seem present, and no changes, even if there are changes in underlying representations, are consciously detected.

In the following pages, I discuss how the trajectory estimation model accounts for temporal illusions. As in the case of the multiple drafts model, I discuss the cutaneous rabbit illusion and a phenomenon related to the color phi illusion. This allows us to see the model at work, and it helps to highlight the constructivist claim that perception is a constructive process, one that modifies the objective temporal features of events and adds elements that are not present in the environment.

The cutaneous rabbit illusion involves an estimation of the course of the taps, which is corrected on the basis of the probability considerations. According to Grush (2006, 445), the second tap, which is applied on the wrist, is initially located correctly by the emulator, but as the taps are applied at other locations, this estimate is overruled on the basis of the probability assessment of the representational system. As Grush (2005b, S213) suggests, a continuous course of movement has a higher probability of occurring than irregular motion. Accordingly, taps at three different places are regarded as having a lower statistical frequency than taps forming a regular pattern. The estimation of the trajectory of the taps is thus corrected, including the location of the second tap.

Grush does not discuss the color phi illusion, but he treats a related phenomenon that involves apparent motion but does not include a change in color. In this case, the subject perceives one moving spot, when in fact two separate spots in different, but nearby, locations are flashed quickly one after another. Also in this case, the representational system proceeds from a probability inference. It gives a higher probability to the option of there being a single moving object than to the event of two separate objects flashing very briefly and close to each other. Thus, when the second spot is flashed, the emulator updates its estimate by concluding that the spot has moved from the original location to the location of the second flash, and in doing so, the emulator makes an incorrect judgment that there was an intermediate location the spot had to traverse (Grush, 2005b, S213).

Are Grush's explanations for the temporal illusions compatible with the multiple drafts model? There is a certain difference in how the multiple drafts model and the trajectory estimation model conceive the updating of representations. In Dennett's model, the updating can be piecemeal; that is, each content can be revised at any time. There are no special restrictions to the effect that certain contents have to be revised together. In Grush's account, in contrast, the updating occurs in packages: the estimates of the representational system are constantly being updated in emulation cycles. That is, each emulation cycle can revise the contents involved in the previous emulation cycle, but there is no revising between cycles. This difference notwithstanding, what is similar to both models is the idea that representations are revised by the cognitive system.

But most crucially, the trajectory estimation model can harmonize with the multiple drafts model only if its explanations are neither Orwellian nor Stalinesque. As in the case of the multiple drafts approach, there is no distinctive mark that would inaugurate certain estimates as being conscious. While both the Orwellian and Stalinesque models presume a clear divide between conscious and nonconscious processes, already in this regard it would not be proper to deem Grush's model either Orwellian or Stalinesque. Indeed, Grush hardly mentions the word "consciousness" in his papers. However, it is obvious that he aims to account for our experiences and must thus imply that at least some products of estimation make up not only the representation of the environmental processes, but also appear phenomenally in one's experience. Given this, some discussion of the Orwellian and Stalinesque options is also required in the case of Grush's model.

As noted above, the Stalinesque model has to cope with a delay. The experience undergoes a correction before one becomes conscious of it, and this requires some time. In the model, a delay of consciousness must be incorporated but, as also noted, it need not manifest itself. Namely, the outwardly measurable delay can, in principle, be compensated for by postulating reactions before the awareness. The measurable delay is thus not a necessary component of the Stalinesque model. However, its presence can indicate underlying Stalinesque assumptions. For example, a delay is part of the smoothing model of Rao, Eagleman, and Sejnowski (2001), from which Grush (2005a, 2005b) distinguishes his own approach. In contrast to postulating a delay, the emulator in Grush's trajectory estimation model produces estimates before the stimulus appears, concurrently with it and when it is no longer present. Although the estimate may be revised during some period after the presentation of the stimulus, this is not a Stalinesque process, since we are not dealing here with delaying the access to consciousness.[13] This is rather akin to the temporal control window, which is also acknowledged by Dennett.

Grush's model is also not an Orwellian one.[14] In the Orwellian model, an initial stimulus is experienced but there is no later memory of that experience, since it is replaced by the memory trace of a different experience. It is indeed the case that in Grush's model, the emulator outputs different estimates, and the later, updated estimates may involve revisions of the earlier estimates. There is one passage in Grush's work that may strike one as Orwellian. Here Grush explains where and when the taps are registered in the cutaneous rabbit illusion:

> Even though *at the time of the second impulse* the subject perceives it to be at the wrist, at the time of the fifth impulse, the subject has no recollection of this prior interpretation, and rather has a perceptual

> state to the effect that there is currently a sequence of impulses, the second of which was just proximal to the wrist. (Grush, 2007, 39; emphasis in original)

However, this explanation is conditional on there being corresponding probes at the time of the second and the fifth tapping. Grush (2007, 39) is explicit on the point that what one experiences depends on the timing of the probe. Thus, depending on the time of the probe, the subject could report different experiences. In fact, Grush's explanation above involves implicit counterfactuals: had the subject been probed at the time of the second tap, then she would have located the tap at the wrist, and had the subject been probed at the time of the fifth tap, then she would have located the same tap near the wrist. This explanation does not make the Orwellian claim that when not probed, the subject was briefly conscious of the tap at the wrist, and then later this experience becomes inaccessible, since its memory trace is overwritten by a revised experience. In addition, note that there is no requirement in the model that one must be conscious of every single estimate. If estimates are revised within the temporal control window, then it cannot be said that the content of one's conscious experience undergoes a change.

Grush's account is more detailed than the multiple drafts model, and it makes specific predictions, which are open to empirical confirmation or falsification. What follows is a presentation of one such prediction of the model, which can be empirically tested. This proposal is from Valtteri Arstila (personal communication). In case of the apparent motion illusion, it follows from the model that the representation, which depicts that there was a movement, is not produced before the second flash has occurred. What happens when the construction of this representation is interrupted by an experimental invasion? Let us make the assumption that the estimate under discussion determines one's experience. Then the prediction of the trajectory estimation model is that when the emulation is intercepted at the point where information about the second flash is incorporated, the subject would have no experience of movement. This is a straightforward prediction, the confirmation of which would yield experimental support to Grush's model. However, when the subject reports an experience of movement but has no experience of the second flash, then this would constitute data not predicted by Grush's model.[15]

Note how in Grush's approach we can choose a specific moment of interception, which did not make sense in the case of the multiple drafts model. Even if there were several emulators that work in parallel, there is still the assumption that some estimates of the emulator are produced at an earlier time than the others. This allows pinpointing the exact time when the estimation of the state should occur. This assumption does not commit Grush to the Cartesian theater, since he requires neither that the conscious experience is constructed serially nor that there is a definite boundary for consciousness. Within a small time window, the changes in the representations underlying the experience are not detectable consciously.

In conclusion, let us highlight some commonalities between the two models discussed in this chapter. It is common to both accounts that the temporal relations we perceive in the environment are not merely copied from the relations between the events. Instead, they are the product of the constructive processing in the brain, whereby some illusory relations are also fabricated. Another strand in the constructivist view, the idea that the brain can process events in a different order from the order in which they appear in the content of experience, was also present in both models. The constant updating and revising of representations is also common to these accounts, with the proviso of the above-mentioned difference in elaborating the updating process. Neither model presumes that every revision of the subpersonal representations must constitute a change in the content of experience. The possibility of empirical confirmation of these accounts was also discussed, and in this respect the trajectory estimation model fared better than the multiple drafts model, since its claims allow the generation of specific predictions.[16]

Notes

1. The time-related parts of the book are based on Dennett and Kinsbourne (1992b), so part of the credit for the approach should go also to Marcel Kinsbourne. See also Kinsbourne (1988).

2. If instead of a physical location, one takes the center of consciousness to be functional, that would still be a version of Cartesian materialism, as the order of entering to the functional center then determines the order in which contents become conscious contents.

3. Dennett's analogy (see Dennett, 1991, 125–6) relies on a different feature of drafting, namely, on the effects of a paper on its audience. If there are multiple drafts and several readers, those effects become distributed and cannot be attributed to the published version. This point is important in relation to Dennett's explanation of consciousness in terms of effects on a subject's behavior.

4. I will bypass the questions concerning the relation of the contents of neural representations in the brain to the intentional contents of propositional attitudes and perceptual contents. For different approaches to this issue, see, e.g., Akins (1996) and Elton (2003).

5. Dennett has suggested that fame is a more apt metaphor for his account of consciousness than drafts (see Dennett, 2005). Fame is directly comparable to influence, since it conveys the aspect of contents "competing" with each other. Fame also depends on how people react in the long run, just as the domination of content-fixations depends on their later effects. Of course, the so-called "fame in the brain" approach only replaces the metaphor, but does not constitute a change in the account.

6. In the present context, we are dealing with a short timescale of hundreds of milliseconds. According to Dennett, at this scale there are no principled criteria for exact timing of conscious events: "There can be only arbitrary grounds for taking some point in that interval of several hundred milliseconds and declaring it to be the onset of consciousness. Consciousness does not *have to have* an onset measurable to the millisecond; it is much better to think of consciousness as distributed in both space and time" (Dennett, 1998, 103; emphasis in original).

7. Steinman, Pizlo, and Pizlo (2000) argue that a more correct name for this illusion is beta motion and that it should be distinguished from the phi phenomenon. Beta motion is a kind of apparent motion that is virtually indistinguishable from the real motion (see Bachmann, Breitmeyer & Öğmen,

2007, 96–9, for an overview). The phi phenomenon is an illusion of "pure" movement that does not involve moving objects. But since, in the philosophical literature, the particular illusion that Dennett described has been discussed under the name "color phi," I will keep with the established usage.

8. It would not be correct to describe this account by saying that it involves replacing the original experience with a false experience. In such a short timescale, one cannot yet individuate experiences. We are dealing rather with the ongoing construction of an experience.

9. A lesson from the multiple drafts model for the practical issue is that one cannot assume that the temporal properties of neural representations pass on to the represented temporal properties (see also Dennett & Kinsbourne, 1992b, 200). This is not to say that the time when brain processes occur does not matter at all. Dennett (1991, 149–51) notes two such points of importance. First, the onset time of brain processes can contribute to fixing content in the early stages of the processing. Second, the representations must be constructed at appropriate times—if the relevant representation is constructed after too long a delay, it cannot be employed by the organism for a timely control of its behavior.

10. If probes are necessary for consciousness, then this would yield additional support to this point.

11. Todd (2006, 2009) has argued that the Orwellian and Stalinesque accounts of metacontrast generate different predictions and thus yield functional differences, which can be tested. However, the test that he describes, and which—as he argues—supports the Stalinesque rather than the Orwellian model, differs from Dennett's cases in several crucial respects. First, it involves the comparison of the model's predictions across different (report/no report) conditions. Dennett's thought experiment deliberately formulated the rival explanations in such a way that one could not decide them within a test condition. Second, for Dennett, the supposition that there is no neural difference between the Orwellian and Stalinesque accounts was part of the scenario (note the "we can suppose" clause in Dennett, 1991, 125). However, in the metacontrast case discussed by Todd (2009, 511), there is a neural difference in processing that can be used to corroborate the Stalinesque approach.

Note that the neural difference need not support the Stalinesque mode. Namely, the defender of the multiple drafts model can argue that the difference in the functional roles of the discrimination of the white disc in different conditions (for particulars of the experiment, see Todd, 2009) is not due to the consciousness of the white disc in the second condition. Instead, one could explain the functional role in neural terms, but point out that in the second condition, the information processing in the brain reached a different area in the visual cortex, which influenced the subject's reports. This would be in line with the claim of Dennett and Kinsbourne (1992a, 238; emphasis in original) "that conscious experiences have no role in the functional organization of the brain *in virtue of meeting some criterion of consciousness*."

Ultimately, Todd chooses between the models on methodological grounds based on such considerations as "inference to the best explanation," "parsimony," "explanatory scope and predictive power," and "evolutionary assumptions" (Todd, 2006), as well as "internal consistency" (Todd, 2009). I presume that Dennett would not disagree with this. To my knowledge, he has never claimed that one cannot find theoretical reasons from philosophy of science to choose between these accounts.

12. Grush (2005b, S214) argues that the representational momentum effect (the illusory continuation of the motion of a stimulus) can be viewed as a support to the claim that the estimations of the visual system also involve predictions.

13. As Grush (2005b, S216) notes, "openness to revision for, say, 100 ms, should not be confused with delaying all interpretation until 100 ms has passed."

14. Wilberg (2006) claims that the Rao et al. (2001) account is Stalinesque and that Grush's model is Orwellian, but he argues that their commitments are actually not supported by the evidence, which does not allow us to choose between the competing Stalinesque and Orwellian accounts. As concerns Grush, Wilberg construes the trajectory estimation model's explanation to the color phi illusion so that it involves the assumption that the subject is initially conscious of the first static flash, and that this perception becomes later revised by another estimate. As I explain, I do not think that Grush is committed to such an assumption concerning consciousness.

15. In this case, one should also exclude the following explanation of the second result, which would make it compatible with the model. The experience of movement even when the second stimulus was not processed could be explained by the prediction of the emulator. The prediction that the spot has moved may be provoked by the fact that before the second flash occurs, there are two inconsistent states in the environment that have entered the emulator. There is information about the first flash, and then there is information that the place where the spot was flashed before is now empty. There is thus a puzzle that the emulator needs to solve, and one way to do it is to predict that the spot has moved. I presume that this option can be controlled by varying the direction of movement. That is, if one experiences movement in the direction that is not a statistically plausible direction for the emulator, then perhaps this explanation can be excluded.

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V Subjective Times and Lived Time

From lived time in the first two sections, this volume has turned toward laboratory time—that is, the perception of changes in artificial and sometimes unnatural environments—to reveal the ongoing construction of temporal perception and judgment. In style and nomenclature, phenomenology feels remote from the language of psychological experiment. But as John Wearden, Alan O'Donoghue, Ruth Ogden, and Catharine Montgomery point out in chapter 14, the button presses and verbal reports of laboratory volunteers are no less subjective than the musings of Proust. Laboratory behaviors are conscious productions, not automatic reflexes, and are thus "primary phenomenology," or more or less unreflective statements of the way things seem. Nonetheless, the situation of the experimental subject in a psychological experiment is usually not one that occurs in real life.

The three chapters ahead report on findings that enlarge the purview of research on subjective time. In chapter 12, Ernst Pöppel and Yan Bao review evidence for temporal "windows" at two timescales. The short window of 20 to 60 ms was discussed above by Busch, VanRullen, and Holcombe in part III, but Pöppel and Bao review a different set of experiments to support a flash frame during which temporal order and duration cannot be accurately reported. Within this window, temporal information appears to be integrated to construct momentary phenomenal events.

Pöppel and Bao also describe a longer window of integration of around two to three seconds. This window affords a plausible measure of the specious present (or, if you prefer, the horizon of protention and retention). Within this window, durations are accurately reproduced, sequences seem to be stored as groups, and action is parsed into meaningful "chunks" in execution and planning.

Three seconds also bracket myriad mundane cause-and-effect scenarios. Attention and timing conspire to convert a sequence of events and discontinuous perceptual takes into a storyline of objects and their dynamic interactions. Scientists may be scrupulous in their attributions of causality in the lab, but in ordinary situations cause and effect pop out with little regard for critical thought—a fact exploited by the stage magician. For the magician, every audience affords a new experiment in subjective time perception. In chapter 13, conjuror and cognitive philosopher Thomas Fraps reviews a history of magical thinking—that is, scholarship by magicians about the misdirection of temporal and spatial attention. He then peers inside a trick to describe in practice the manipulations of where and when that makes sleight-of-hand work.

At short timescales, as we have seen, the subjective timeline is rather jumbled and fragmented. The weight of evidence implies several different mechanisms for relating events and their subjective time of occurrence. At slightly longer frames, lasting a few seconds, subjective time is more orderly, though as Pöppel, Bao, and Fraps describe, still a construct prone to distortion. At still longer frames, other aspects of subjective time appear. We make judgments about the passage of time, noting that on some occasions time seems to pass more quickly, while at others time seems to slow down. In chapter 14, Wearden, O'Donoghue, Ogden, and Montgomery take a systematic look at the passage of time in ordinary life and the laboratory. Does time fly when attention is engaged in other activities, fun included? What makes experience vary in its subjective pace? One might hope that the awareness of the passage of time is modulated by other subjective states in an orderly and predictable way. But here, too, subjective time moves in mysterious ways.

12 Temporal Windows as a Bridge from Objective to Subjective Time

Ernst Pöppel and Yan Bao

12.1 Questions about Time in General and Subjective Time in Particular

What is the present? Is it the border with no temporal extension between past and future? Or is the present a temporal interval with some duration that can be measured? If the present has only one meaning, both answers cannot be true. But has the "present" just one meaning? This is only one question if one deals with subjective time and how it relates to objective time. And there are many more; time in general and subjective time in particular appear like an unexplored landscape. Here are more questions—to question the self-evident:

Why do we separate time in three domains: past, present, future? What does it mean to say, something has passed, or something will be? Can we say that what has passed is real (it cannot be erased any more), and what will be is only potential (it may never come)? If so, would it not make sense to talk only of two domains of time, present and past, as future does not exist? However, if the present is simply a border with no extension, would the conclusion not be, that there is only one domain of time, the past? Or would it on the other hand not be sensible to assume only one domain of time as the present, because one can also argue that the past is no more and the future will only be? But if the present is just a border without extension between past and future, would it not follow that time does not exist? This may sound like an intellectual exercise, but it indicates that the question of how to link subjective time to objective time is not at all trivial (Ruhnau, 1994).

Why do we sometimes experience the same objective duration as having very different subjective durations? Why does time seem to run faster when we are getting old, such that one is surprised that again a year has passed? What happens when we are bored, and the passage of time is apparently slowed down? Why does a phase of boredom appear retrospectively as a rather short interval? Do we possess an internal measurement system to tell us how much time has passed, or do we rely mainly or only on the clock? Why must physically defined events have a minimal objective duration to be perceived at all? Is there a relationship between numbers and time, in particular between cardinal or ordinal numbers and the experience of sequence?

What are the mechanisms of our neurocognitive machinery that allow us to experience something as simultaneous or as nonsimultaneous? If events are nonsimultaneous, do we know then also in which sequence they occurred, and we can give them appropriate time tags? What is the relationship between the sequence of thoughts and the thought of a sequence—that is, is the sequence of thoughts a necessary and sufficient condition for the development of the notion of sequentiality? What happens in our neurocognitive machinery that allows us to move from one thought to the next rather than be stuck with only a perseverating thought (which actually happens sometimes)? Why do we sometimes travel backward in time to our past to remember episodes of previous experiences? How can we project our plans and desires into the future, which may give us satisfaction but sometimes also anxiety in the present? Why do we enjoy a musical piece played at a certain tempo, but not at others; that is, is there a relationship between subjective time and aesthetic experiences? Why are we irritated if somebody talks too slow or too fast? Can one find out how long it takes to make a decision? How is it possible that we have the impression of a direction of time? And do we have in fact an experience of the direction of time, or is it an abstract notion? How are we embedded in the geophysical cycles dictated by the diurnal or annual rhythms of nature?

Why are we so sure that time passes with a constant pace? How do we know that time actually flows—could it not be that time changes in discrete steps? Is a moment a temporal interval that smoothly moves through time, or does the moment jump from instant to instant? How have theoretical notions of time been developed, such as in physics or philosophy, and what is their relationship to subjective time, if any? Why is it that we are apparently desperate to find one theoretical concept of time; why not many? Do we actually have one topic if we think about subjective time, or are we confronted with many topics? Could it be that the notion of time as a homogeneous background of events in the physical, biological, and psychological world simply masks the diversity of loci in the landscape of subjective time?

Is it possible to provide some conceptual frame within which some of these questions can be brought closer to an answer? The concept of “temporal windows” might be useful to provide at least an organizational structure or logistical infrastructure to locate some of these questions in the landscape of subjective time. But before doing so, what could be the reason, at least one reason, for being confronted with so many questions, which may or may not be related to each other?

12.2 Misguided Questions by Misusing Rational Conjecture

It is always useful to look back into history. Modern science can be said to have started in 1620 with *Novum Organum* (“New Instrument”) by Francis Bacon. It should impress us today that this early text in science starts with a description of mistakes we can make when we want to solve a problem, which after all is the business of science. Bacon describes four different sources of mistakes, which we unfortunately tend to forget we may all fall into.

Using modern language, Bacon argues that we (first) are victims of evolution, i.e., that genetic and epigenetic programs define constraints that necessarily limit insight. Our evolutionary heritage provides frames of reasoning or limits of understanding that nobody can transcend (Pöppel, 1985). Not knowing these limits easily leads to erroneous mental trajectories. The second source of mistakes arises from our individual natures. We may suffer from the constraints of imprinting; everybody has his or her own prejudices deeply rooted in the neuronal mechanisms that are basic to our personal knowledge systems (Pöppel & Bao, 2011). The third mistake Bacon refers to is of particular importance for the discussion of time: we are corrupted by language, since thoughts cannot be easily transformed into verbal expressions, if they can be represented at all within this other medium. And finally (the fourth mistake), we are guided or even controlled by theories, which may be explicit or implicit.

What are the implications here for thinking about subjective time? We are possibly caught in a language trap. On the basis of our evolutionary heritage we all share the power of abstraction, but this has, in spite of many advantages, an unfortunate consequence. Abstractions are usually represented in words, for apparently we cannot do otherwise; we invent nouns to extract knowledge from processes. Abstraction is obviously a type of complexity reduction to make a problem simpler. But why is this done? Evolutionary heritage dictates the necessity for speed, and abstraction is one way to speed up reactive behavior. It would, however, be a categorical error to confuse speed in action and reaction with the power of thinking. The selection pressure for quick processing of information invites a neglect of the richness of facts. This pressure allows the invention of simple, clear, easy to understand, easy to refer to, easy to communicate concepts.

Thus, because we are a victim of our biological past and as a consequence a victim of ourselves, we end up with theoretical notions that have left reality behind. The simple reference to “time” may mask the richness of phenomena behind this abstract term. Of course, we depend on communication, and this requires verbal references usually tagged with language. But if we do not understand within the communicative frame or reference system that we may be a victim of ourselves by creating notions that are too simple, we are misguided by our cognitive apparatus.

The unfortunate language trap has, in fact, a long history. It may have started with one of the most important texts on subjective time, namely the *Confessions* of Augustine. In the eleventh book of the *Confessions* we read the famous quotation on time: “*Quid est ergo tempus? Si nemo ex me quaerat, scio; si quaerenti explicare velim, nescio* (What, then, is time? If nobody asks me, I know it; if I have to explain it to somebody, I don’t know it.”) This rather simple statement is characterized by a categorical error, since knowledge is used here in two different reference systems; the first reference is to implicit knowledge, the second to explicit knowledge (Pöppel & Bao, 2011). It is only because no distinction has been made between different knowledge systems that this paradoxical statement can be made, and it has survived since antiquity. This categorical error in fact applies not only to questions referring to time. Any question starting with “what is…” and asking for a definition of an abstract term can lead to paradoxical answers.

The belief that we can solve all scientific problems within the context of explicit knowledge, which is usually expressed via verbal representations, is typical for philosophical rationalism. Perhaps the most important representative in modern times has been René Descartes, who in his *Discours de la méthode* (1637) defined four rules of thinking (but also described analytical geometry, which allows mathematical descriptions of functional relationships, such as expressing learning efficiency as a function of time, when time in the curve is actually treated as a continuous parameter).

What are the four rules defined by Descartes, and how do they relate to the problems of subjective or objective time? The first rule is to express a problem clearly and distinctly and without prejudice. Research on subjective time has suffered particularly from this challenge, as the many questions outlined above indicate. The second and third rules of thinking refer to specific tactics, such as how to deal on a practical level with problems: Descartes recommends identifying partial sets of the problem and pursuing an analysis, starting with simple questions and then going on to the more difficult ones.

The challenge to overcome here is how to separate partial sets of the general problem of subjective time, and how to proceed from the easy to the difficult. Without prior knowledge of what could be easy or what could be difficult, it seems impossible to disentangle the different trajectories of a potential analysis. Similarly, without some implicit knowledge of how to reduce one big problem into several subproblems to solve, the task at first seems to be close to impossible. The Cartesian rules may appear at first sight self-evident and convincing, and they express a strong belief in rational conjecture, but at the same time they are poisoned by circularity: one has to know already what one wants to know. Finally, Descartes' fourth rule of thinking indicates that an analysis of subjective time following his rationalistic advice is impossible, since it demands completeness—that all aspects of the problem have to be considered, with nothing forgotten. There is no yardstick available that guarantees completeness. A classification or taxonomy of temporal experiences simply does not exist, in spite of some attempts to solve this problem (Pöppel, 1978).

12.3 Historical Background for Research on Subjective Time

What are some conceptual issues in the history of modern psychology and neuroscience on how we deal with subjective time and how it relates to objective time? It was Karl Ernst von Baer (1864) who came up with the concept of a "moment," which is supposed to be the longest time interval to be objectively measured without apparent duration. Von Baer suggested that different organisms presumably have different moments if measured by external means, with clocks that represent objective time. This concept of a moment has important consequences for an understanding of psychological processes; it implies that we subjectively step out of the continuous flow of time, as has been suggested by Isaac Newton in his "Philosophiae Naturalis Principia Mathematica" published in 1687 when he writes that absolute, true and mathematical time flows by itself and from its own nature equably and without relation to anything external. In spite of this early insight, we tend to forget its implications for a deeper understanding of cognition, and we usually treat time as a continuous variable, looking at it as some kind of container within which cognitive processing is implemented.

A first empirical answer to the question of how long a moment is for humans was probably given by Ernst Mach (1865). He was interested in the discrimination of different temporal durations and attempted to define a simple psychophysical law to study differential sensitivity of temporal perception in the auditory modality. In his experiments, he observed that there is no experience of duration for intervals of 40 ms or shorter. On the basis of this observation, one can interpret a "time point" with no apparent duration as a representation of a moment for humans as conceived by von Baer (1860/1864), although Ernst Mach might not have been aware of the speech delivered a few years ago by Karl-Ernst von Baer and published several years later.

Today, one and a half centuries after the first experimental attempts to understand subjective time, perhaps every laboratory in psychology and cognitive neuroscience uses reaction times to look into the complexity and dynamics of cognitive processing. Chronometric analyses have become important indicators for mental activities. This experimental paradigm goes back to Karl Donders (1868), who used simple and choice reaction times to get a better understanding of psychological processes like decision making. It is worth noting that the use of reaction times as experimental indicators for cognitive operations rests on a hypothesis that usually remains implicit—that such operations are indeed of sequential nature. This hypothesis hides the potential alternative that cognitive operations, at least some of them, may actually be of parallel nature (Pöppel & Bao, 2011). The experimental setup may select one activity from these parallel operations and shift it into a frame of sequentiality; by doing so, the experimenter may be seduced into concluding that other activities that have not been selected are in fact nonexistent. With respect to subjective time, one can argue that the sequence of thoughts only superficially appears sequential; at any moment, parallel processes on an implicit level may be actively preparing the next mental content, which indeed seems to be the case.

Whereas Karl-Ernst von Baer, Ernst Mach, and Karl Donders were looking at rather short temporal intervals as fundamental to cognitive processing, Karl von Vierordt (1868) was interested in the question of how humans can reproduce the duration of temporal intervals that last for several seconds. He observed that short temporal intervals are reproduced longer than the stimulus, and longer intervals are reproduced shorter than the stimulus. This observation implies that between long and short intervals there must be an interval that is reproduced correctly; this interval is usually referred to as the "indifference point." The question is whether such an indifference point is an experimental artifact, or whether it reflects an underlying neuronal process that determines temporal perception (Pöppel, 1971).

Interestingly, both answers are correct. If in an experiment temporal intervals to be reproduced are chosen between one second and a few seconds, one observes an indifference point at approximately three seconds. Furthermore, reproductions up to this indifference point show a small variance, whereas reproductions beyond this point show a sudden increase of variance. The indifference point at this stimulus duration may reflect a neuronal process of high temporal stability being perhaps responsible for presemantic temporal integration (Pöppel, 2009).

It can, however, also be demonstrated that in other temporal regions indifference points are observed that do not reflect a temporally stable integration process, but that are created by the specific experimental conditions. As has been suggested in adaptation level theory developed by Helson (1964), human observers mentally construct a reference point if they are exposed in an experimental setting to stimuli of different intensity or different duration. These reference points may correspond to the geometric mean of all stimuli presented during an experimental situation. The ecological reason for the construction of such reference points may be that stimuli with higher probability should be processed with better differential sensitivity, which is hypothesized to happen closer to the reference point. Such a mechanism of temporal adaptation would imply the existence of a special temporal memory, which is continuously calibrated by stimuli of different durations. Such a mnemonic system might be the basis for temporal impressions of longer or shorter events, and thus might represent an internal measurement system to process the duration of subjective time.

It is intriguing to note that the important theoretical notions about subjective time and how subjective time might relate to objective time were already formulated some 150 years ago. One important aspect with respect to modern research is the hypothesis that we must think about time on the subjective level as a discrete process. Separate "temporal windows" of finite duration follow each other for temporal intervals that, for instance, define a moment or a point in time. But one question remains open, namely whether these moments have to be conceived of as "traveling moments" representing a continuous flow of subjective time, or whether with reference to objective time such moments are initiated sequentially. One of the founding fathers of modern psychology, William James (1890), believed that a "subjective present" flows continuously and is apparently unrelated to objective time. As will be shown, this classical concept cannot hold true.

12.4 A Temporal Window for Complexity Reduction

To gain some access to subjective time and how it is implemented, we must examine the challenges the brain has to deal with in information processing to overcome the complexity and temporal uncertainty of stimuli in the physical world. One source of complexity comes from stimulus transduction, which is principally different in the sensory modalities like audition or vision, taking less than 1 ms in the auditory system and more than 20 ms in the visual system (Pöppel et al., 1990). Thus, auditory and visual information arrive at different times in central structures. Matters become more complicated by the fact that the transduction time in the visual modality is flux-dependent, since surfaces with less flux require more transduction time at the receptor surface. Thus, to see an object with areas of different brightness or to see somebody talking, different temporal availabilities of local activities within the visual modality and similarly different local activities across the two modalities engaged in stimulus processing must be overcome.

For intersensory integration, aside from these biophysical problems, physical problems also have to be considered. The distance of objects to be perceived is obviously never predetermined. Thus, the speed of sound (not of light) becomes a critical factor. At a distance of approximately 10 to 12 meters, transduction time in the retina under optimal optical conditions corresponds to the time the sound takes to arrive at the recipient. Up to this "horizon of simultaneity," auditory information is earlier than visual information; beyond this horizon, visual information arrives earlier. Again, there must be some kind of mechanism that overcomes the temporal uncertainty of information represented in the two sensory modalities. How can this high degree of complexity and temporal uncertainty be explained?

It has been argued that the brain has developed specific mechanisms to reduce complexity and temporal uncertainty (Pöppel, 1997, 2009). One essential support for this hypothesis comes from the fact that the same temporal value of information processing is observed in the visual, auditory, or tactile modalities, on the level of single-cell or neuronal group activities, and on the level of cognition in measurements of reaction times or of temporal order thresholds. It is suggested (Pöppel, 1985; Ruhnau and Pöppel, 1991) that temporal noise can be brought under control if the nervous system uses stimulus-triggered neuronal oscillations. One period of such a "relaxation oscillation" is supposed to represent the logistical basis for a system state within which temporally and spatially distributed information can be integrated. These states are "atemporal" because the before-and-after relationship of stimuli processed within such states is not defined or definable. Experimental evidence for these hypothetical states is observed in the time domain of 30 to 60 ms (Pöppel, 1968, 1970, 1997, 2009). Interestingly, the concept of elementary integration units has also become fruitful for physical theories on time (Ruhnau, 1994), stressing the interdisciplinary nature of research on objective and subjective time.

What is the empirical evidence for "time windows" within the indicated range of some tens of milliseconds? There are indeed many experimental suggestions, old and new and using different paradigms, that such a mechanism must be at work (Pöppel, 1978). The reference to "different paradigms" is important: if it can be shown that even with different experimental setups similar numerical values are always obtained, this fact strongly supports the validity of these observations as a basis for deriving a general principle. One might refer to this mode of a scientific conclusion using induction as a mental operation as the "Darwinian principle," in reference to Charles Darwin's use of many independent observations to draw conclusions in his seminal work *The Origin of Species* (1859).

An important example supporting the conceptual notion of a temporal window in this time domain comes from observations with patients undergoing general anesthesia (Madler and Pöppel, 1987; Schwender et al., 1994). During wakefulness, one observes an oscillatory activity with periods of 30 to 40 ms in the auditory evoked potential (Galambos, Makeig, & Talmachoff, 1981). During anesthesia, this oscillatory activity within the neuronal assemblies disappears, which under normal circumstances presumably reflects potential system states. The auditory information is still transduced on the receptive surface, as can be concluded from the presence of brain stem potentials, but further processing states are blocked. As a result, patients in such a state process no sensory information that might be used for a conscious representation. Such patients report that other than during sleep no time seems to have passed between the beginning of the anesthesia and the reawakening after anesthesia. This oscillatory process, which is apparently implemented in the corticothalamic pathway, provides a formal framework for the reduction of temporal uncertainty. It can be argued that this process is the neuronal basis for the creation of "primordial events," or the building blocks of conscious activity (Pöppel, 1985).

It is important to note that this temporal window in its duration is not determined by what is processed (i.e., the content), but that it is implemented prior to any content. Thus, it represents an automatic presemantic process to be used for different kinds of information. This issue will come up again later when referring to a temporal window in the range of a few seconds, and it is of importance for an understanding of cognitive processing. One has to distinguish between logistical or "how-functions" that represent the necessary neuronal infrastructure, and content or "what-functions" that become the basis of conscious representation (Pöppel, 1989, 2010; Pöppel & Bao, 2011).

Strong experimental evidence for a temporal window or an elementary processing unit also comes from research on temporal order threshold (Hirsh & Sherrick, 1961). In such experiments subjects are asked to indicate in which temporal order stimuli have been presented, such as which ear was stimulated first when both ears are stimulated by acoustic signals with a short temporal delay. It has been shown that temporal order threshold has approximately the same value, of some tens of milliseconds, as for the visual, auditory, and tactile modalities. The correspondence of these values in spite of qualitatively different transduction processes in the sensory modalities favors the hypothesis of a common central mechanism for these systems. As the indication of a temporal order requires that events have to be defined in the first place to then be brought into a sequence, one can conclude that this mechanism is also necessary for the identification of "primordial events," which are the building blocks of conscious activity.

A different domain of research, the study of eye movements, also supports the notion of temporally segmented information processing with successive steps of approximately 30 to 40 ms. If a subject initiates pursuit eye movements when a visual target starts to move, the latency of these movements shows a multimodal distribution of responses with temporal intervals between the modes of 30 to 40 ms (Pöppel & Logothetis, 1986); unimodal response histograms are usually the consequence of too broad a bin width in measuring the latency; with a bin width of 20 ms or even more, selective response modes with a temporal separation of 30 to 40 ms are necessarily masked. Such multimodalities in response histograms can also be seen when saccadic eye movements are measured, although their latency is much longer than that observed for pursuit eye movements (Frost & Pöppel, 1976).

Multimodal response histograms have also been observed for choice reaction time (Pöppel, 1968, 1970; Harter & White, 1968; Ilmberger, 1986; Jokeit, 1990). Thus, latency distributions of two types of eye movements and response histograms for choice reaction time show identical characteristics. Apparently, an underlying decision process to initiate a movement shares the same temporal characteristics, in spite of the fact that the execution of the movement is implemented in different systems. In all cases—and this is important for the concept of a temporal window—the same temporal distance of response modes is observed. The underlying temporal machinery processes information in successive units of approximately 30 to 40 ms; these elementary processing units should not be understood as "physical constants," but as operating ranges with some individual variability.

There is further evidence for a temporal window in this operating range. Recordings of single cells show that the visual channel is characterized by oscillatory responses at an early stage of information processing (Podvigin et al., 1992, 2004), indicating that in the afferent pathways, before the cortex is reached, a temporal segmentation is taking place that allows the creation of temporal windows. Single neurons in the lateral geniculate nucleus of the cat that receive input from the retina, and before they send this information to the visual cortex, show stimulus-triggered oscillations in the same frequency domain. These results again support the notion of a general principle of temporally segmented information processing, since all organisms have to deal with the same challenges.

In most studies, as indicated above, a value close to 30 ms—or to be more conservative, between 20 and 60 ms—has been observed. Additional support for this unique temporal window comes from memory studies. For instance, when using a reaction-time paradigm, Sternberg (1975) observed that the scanning process, which is exhaustive, has an approximate speed of 30 ms per item. Taken together, there is overwhelming evidence for the robustness of this time window, which serves as a logistical basis for cognitive processing. These observations further answer the question of how subjective time is related to objective time on the level of short-term processing: the observed multimodalities indicate that temporal processing is embedded within objective time and disprove the possibility of a "traveling moment," which was pointed out some time ago (Pöppel, 1970); stimuli processed at the sensory surface always have to initiate a temporal window within which information is integrated.

12.5 A Temporal Window for Creating the Subjective Present

On a higher level of processing, the primordial events as they are made available by the temporal window discussed above are linked together. Observations made with different experimental paradigms provide evidence of the operative importance of such an integration mechanism and point to a temporal window of just a few seconds (Pöppel, 1997, 2009).

Although these observations have been made in different contexts, a common underlying principle is detected in spite of obvious observational diversities. Searching for common principles in different realms of activities again is guided by the Darwinian principle that if a phenomenon shows up in qualitatively different experiments or situations, a general principle has to be suspected. In what follows, an answer shall be given to the question of what the "subjective present" could mean.

The subjective present as a basic temporal phenomenon of subjective time has interested psychologists for more than a century (James, 1890; Stern, 1897). We are now in a situation to indicate how long such a subjective present may actually last. A numerical answer can be derived from a number of experiments or observations that all converge to a value of approximately 2 to 3 seconds. Support comes from different domains, such as temporal perception itself, speech, movement control, vision, and audition, as well as memory. All these observations suggest that conscious activities are temporally segmented into intervals of a few seconds, and that this segmentation is based on an automatic (presemantic) integration process providing a temporal platform for conscious activity. It should be stressed again that the temporal platform does not have the characteristics of a physical constant, but that an operating range of approximately 2 to 3 seconds has been identified; as is typical for biological phenomena, one has to expect some subjective variability.

What is the experimental evidence? If subjects are asked to reproduce the duration of either an auditory or a visual stimulus, one observes veridical reproductions with small variance up to 2 to 3 seconds, and large errors of reproduction, with a strong tendency for a shorter reproduction, with longer intervals (e.g., Pöppel, 1971). It appears as if short intervals can be experienced as a whole, while longer intervals temporally disintegrate; during short intervals of a few seconds, it is possible to focus the attention continuously on the stimulus.

The value of this rather simple experimental paradigm of temporal reproduction has been proven to be quite useful in research with autistic children (Szelag et al., 2004). If such children are asked to reproduce the duration of either visual or auditory stimuli, they show a tendency to reproduce even different intervals in ranges that are always close to 2 to 3 seconds. It appears as if they are no longer capable of modulating internal time on the basis of the duration of external stimuli. This experimental task allows a view into the eigen-operations of the brain by indicating temporal integration as a basic operation of the mental machinery in humans.

The link of the temporal window of a few seconds to attention has been demonstrated in research using the paradigm of inhibition of return (Bao et al., 2013). A return with full power of attention to a region in visual space that has been attended to before is only possible after a few seconds' delay. Interestingly, this return takes the same time of approximately 3 seconds for perifoveal and more peripheral positions in the visual field, although the inhibitory effects are much stronger in the periphery; the different inhibitory control of attention in the visual field supports the notion of its functional subdivision, and has also been suggested for other functions (Frost & Pöppel, 1976; Pöppel, von Cramon, & Backmund, 1975). This functional subdivision also shows up in another temporal parameter that relates to the shorter time window referred to above (Bao & Pöppel, 2007): the additional delay effect of inhibition of return for more peripheral targets compared to perifoveal ones happens to be approximately 30 ms.

Temporal integration can also be studied by subjective accentuation of metronome beats. One of the founding fathers of experimental psychology, Wundt (1911), pointed out that temporal grouping of successive stimuli has a temporal limit of approximately 2.5 seconds. In such a metronome task, the subject imposes a subjective structure onto identical physical events. If auditory stimuli like click sounds follow each other with an interstimulus interval of, for instance, one second, it is easy to impose a subjective structure by giving a subjective accent to every second of the stimuli. If, however, the temporal interval between the stimuli becomes too long (for instance, 5 seconds), one is no longer able to impose such an apparent temporal structure. The two sequential stimuli can no longer be united into one percept; that is, temporal binding for temporally adjacent stimuli is no longer possible because they fall into successive integration windows. In experiments with brain-injured patients, it has been demonstrated that the temporal integration process as studied with this metronome paradigm is selectively impaired after injuries in frontal areas of the left hemisphere (Szelag et al., 1997). Patients with injuries in these areas adopt a new strategy of integration by consciously counting successive events; the “pop-up” impression of belongingness of successive tones is apparently lost in these patients, and thus they reconstruct togetherness by an abstract strategy.

A qualitatively different paradigm providing further insight into the integration process comes from studies on the temporal reversal of ambiguous figures (Gomez et al., 1995; Ilg et al., 2008). If stimuli can be perceived with two perspectives (like the Necker cube, or a vase that can also be seen as two faces looking at each other) there is an automatic shift of perceptual content after an average of approximately 3 seconds. Such a perceptual shift also occurs with ambiguous auditory material, such as the phoneme sequence KU-BA-KU, where one hears either KUBA or BAKU; one can subjectively not avoid that after approximately 3 seconds the alternative percept takes possession of conscious content (Pöppel, 2009). The spontaneous alteration rate in the two sensory modalities, vision and audition, suggests that usually, after an exhaust period of 2 to 3 seconds, attentional mechanisms are elicited that open the sensory channels for new information. If the sensory stimulus remains the same, the alternative interpretation will gain control. Metaphorically speaking, every 2 to 3 seconds, an endogenously generated question arises regarding “what is new.” With stimuli such as ambiguous material, the temporal eigen-operations of the brain are unmasked.

In addition to behavioral studies, there is electrophysiological evidence supporting the operative range of a time window of 2 to 3 seconds. Data in a study by Sams and colleagues (1993), who investigated the amplitude of the mismatch negativity as a function of the interstimulus interval (ISI), also support the above considerations. The mismatch negativity, a component of the auditory event-related potential, is elicited by a physical deviant stimulus such as frequency or intensity of a tone in an otherwise homogeneous stimulus sequence. If during the experiment the ISI is systematically altered, the largest amplitude of the mismatch negativity is observed with an ISI of 3 seconds; that is, shorter and longer ISIs result in smaller amplitudes of the mismatch negativity. As negativity indicates increased neuronal activity, this result suggests that the auditory channel is characterized by a higher neuronal activity at regular intervals. This modulation is endogenously determined, being a property of the neurocognitive machinery itself, and it implies that approximately every 3 seconds the sensory channel is more sensitive than at other times for new information coming from the external or internal environment.

Temporal integration for intervals of 2 to 3 seconds is also seen in sensorimotor control. If a subject is asked to synchronize a regular sequence of auditory stimuli with finger taps, stimuli are anticipated with very small variance by some tens of milliseconds (Mates et al., 1994; Miyake et al., 2004). This kind of sensorimotor synchronization is, however, only possible within the operating range of a few seconds. If the next stimulus lies too far in the future (say, 5 seconds) it is not possible to program an anticipatory movement that is precisely linked to stimulus occurrence. In such a case, movements become irregular and subjects prefer to react to the stimulus instead of anticipating it.

Observations on the duration of intentional movements coming from ethological studies give similar numerical values (Schleidt, Eibl-Eibesfeldt, & Pöppel, 1987). Members of different cultures, including those from very old ethnic groups (for instance, Yanomami Indians in South America) show very similar temporal patterns for homologous movements, the preferential duration being 2 to 3 seconds. The same time constant is observed in the duration of embraces during the 2008 Olympics in Beijing (Nagy, 2011); after a victory, the winners embraced their coaches on average three seconds. Interestingly, winners from America showed slightly shorter embraces than Asians or Europeans. On the basis of these human studies, Gerstner and Fazio (1995) have observed in several species of higher mammals that they also tend to segment their motor behavior in the same temporal range as humans. This observation suggests that we are dealing with a universal principle of temporal integration that transcends human cognition and behavioral control.

Supporting evidence for a specific temporal integration mechanism also comes from studies on memory and speech. In a classic study (Peterson & Peterson, 1959), it was shown that the working platform for short-term retention is just a few seconds; only if rehearsal is allowed are we capable of storing information for longer intervals. Experiments on the temporal structure of spontaneous speech (Vollrath, Kazenwadel, & Krüger, 1992) also show that spoken language is embedded in temporal windows of up to 3 seconds' duration, giving speech its rhythmic structure. It is certainly not an accident that in most languages the duration of a spoken verse in poetry is embedded in the time window of the subjective present (Turner & Pöppel, 1983). Apparently, poets of all times and language environments have had an implicit knowledge of how to express a poetic thought in time.

Since the experimental and behavioral observations referred to above employ qualitatively different paradigms referring to perceptual processes in audition, vision, cognitive evaluations, movement control, speech, mnemonic representation, perceptual accentuation, and temporal integration, it is proposed that temporal integration in the range of 2 to 3 seconds is a general principle of the neurocognitive machinery. This universal integration process is automatic and presemantic; that is, it is not determined by what is processed, but defines a temporal window within which conscious activities can be implemented. Because of the omnipresence of this phenomenon, it can be used as a pragmatic definition of the subjective present, which is characterized by the phenomenal impression of "nowness."

But is there another reason other than creating a subjective present that such a temporal window has been developed in evolution? One of the greatest challenges for the neuronal systems is to maintain the identity of a mental representation over time; an additional challenge is to maintain such an identity only for a limited time to allow new input to be processed after additional time. Thus, both maintenance of identity of a mental representation and openness after some time for another mental representation are requirements for our cognitive machinery. On a conceptual level, it is the complementarity of maintenance *and* of dynamics that characterizes conscious activity (Pöppel, 2010; Pöppel & Bao, 2011). "Complementarity as a generative principle" characterizes many domains of cognition (Pöppel 2006), as in visual processing, where both bottom-up and top-down mechanisms have to be united to recognize something in its identity. Another example of complementarity as a generative principle is given in the taxonomy of functions (Pöppel, 1989), which distinguishes between logistical functions (like the "temporal windows") and content functions (like percepts). The representation of content functions is a necessary condition for conscious activity, but it is not a sufficient condition; without logistical support there would be no consciousness. Thus, the temporal window of a few seconds can be conceived of as the operative basis both for the maintenance of identity and the creation of new identities in percepts or other mental contents.

12.6 Temporal Challenges for Personal Identity

With these temporal windows (i.e., a 30 to 60 ms interval of integration and a temporal stage of approximately 2 to 3 seconds), a neuronal basis may be given for the experience of perceptual and conceptual identity. For the creation of personal identity, an external point of view toward mental activities that goes beyond the logistical basis of neuronal operations is essential; but without such a logistical basis, the operations on the higher and more abstract level would be impossible. This basic neuronal machinery in the time domain is presumably also necessary to allow the creation of personal identity. But other neuronal and mental operations are necessary, and here new experimental evidence gives some insight into a question that concerns everybody: how can we refer to our self with the effortless assumption that we are always the same person we believe ourselves to be?

Before turning to results from studies on episodic memory, we would like to refer to a specific challenge with respect to the creation of the personal self—the diurnal fluctuations of all somatic and psychological functions. Research in chronobiology, in particular on circadian rhythms, has indicated that every function shows a specific diurnal cycle (Merrow, Spoelstra, and Roenneberg 2005; Peres et al., 2011; Pöppel and Giedke, 1970; Roenneberg, Wirz-Justice, & Merrow, 2003) based on an endogenously controlled mechanism, the circadian clock (Aschoff, 1965). Different functions, however, do not fluctuate in parallel but show different maxima and minima at different times of day. The so-called phase-map of functions changes continuously, and only after 24 hours do we again observe a similar constellation of functions within this phase map. Thus, we change our biological and psychological identity continuously throughout the day, and we return to the same position in the phase-map only every 24 hours. We are "self-identical" only in steps of 24 hours. The enigma is, why we do not experience this? How is it possible that it is self-evident that we are the same person throughout the day, although this is objectively not the case? In fact, there are some cases involving deep depression where the experience of self-identity is not maintained throughout a circadian cycle, which indicates that an active mechanism is responsible for the creation and maintenance of self-identity; otherwise, it could not break down.

An answer may be given by results from studies on episodic memory that indicate how we explicitly, and presumably also implicitly, can refer to our self and by doing so overcome psychobiological fluctuations (Han & Pöppel, 2009; Pöppel, 2010; Pöppel & Bao, 2011). This research began with a rather simple question: How many images in our mind can we actually activate when we time-travel to our personal past? Several hundred subjects have participated in this introspective exercise, including men and women of different age groups, different professions, and members of different cultures. These time-traveling experiences to one's own past have indicated that everyone can activate only a few hundred images, although we may recognize many more images. This discrepancy indicates that very different neuronal mechanisms are involved in recognizing and remembering.

It is, however, another result that is important for our question about how personal identity is established over time. Independently of each other, subjects report that in the images of their personal past they "see" themselves as an agent (Pöppel, 2010). Most subjects report stationary images not like a photograph, and being themselves present not looking at themselves like into a mirror, but observing themselves in an activity, usually of high emotional impact. This mode of pictorial representation is of course physically impossible if images of the past are simply reflected in our memory system. Apparently, the memory system changes the images we have experienced, such that we are projected as an agent into the image of our personal past. Thus we become our own "Doppelgänger": we double our self, and by doing so we can refer to our self. This observation suggests that the creation of personal identity is made possible by projecting our self into our own pictorial past. With such self-reference we can refer to ourselves in our identity. This self-reference is an effortless process, and it is assumed that it happens continuously on an implicit level, but that it can be made explicit if under conscious control we time-travel to our own past. Thus, the tragedy of memory loss is not so much the loss of memory itself, but the loss of a potential self-reference. We know no longer who we are because we have lost ourselves in the personal mirror of our episodic memory.

12.7 Subjective Time: Complementarity as a Generative Principle

Time windows as described above provide a logistical basis for subjective time. The integration windows in the two different time domains are hierarchically organized, but their neuronal implementation appears to be independent. They provide temporal platforms within objective time as conceived in classical physics (Pöppel, 2006) to be used as a basis for cognitive processing. The time windows themselves are not expressions of subjective time, but they deliver a frame for subjective time, at least for some temporal phenomena. The time window of approximately 30 ms provides a logistical basis for the definition of "primordial events," and on that basis the mechanisms for the detection of sequences. Only if sequences are defined is it possible to attach time tags to mental representations of events. The temporal window of 2 to 3 seconds can be used as a pragmatic definition of the present. Thus, on this level of discourse, the present is not a border without temporal extension between past and future, but it has a duration that can be objectively measured.

The two time windows can presumably also be used to measure subjective duration, since they can be considered to represent internal clocks that monitor information processing. If within a time window of 2 to 3 seconds only a few events are registered using the time window of approximately 30 ms, retrospectively this interval will appear to be short, since "cognitive content" is known to determine subjective duration (Pöppel, 1978). If, on the contrary, a lot of information is processed within such a window, retrospectively this interval appears to have had a longer duration. With such a mechanism, it also appears possible to explain the subjective phenomenon of boredom: a lack of interesting information may draw the attentional focus on the flow of time itself with the impression that subjective time is slowly dragging along. If this is a valid hypothesis, one can conclude that we are adapted to an optimal amount of content within the time window of 2 to 3 seconds, and that the impression of boredom signals that we are outside this optimal range.

This pragmatic definition of a present implies that it does not make sense to treat subjective time independently of physical time; both subjective and objective time are necessarily entangled. We would not have access to a concept of physical time if we did not have temporal experiences, but we would also not be able to describe the phenomena of subjective time without reference to objective time (Ruhnau and Pöppel, 1991). This apparent circularity is an expression of complementarity as a generative principle which can be seen in quite a few instantiations of cognitive processing.

As argued in the description of a taxonomy of functions (Pöppel, 1989), one has to distinguish between content functions and logistical functions. To create mental content, logistics like temporal processing as expressed in temporal windows are necessary; without such logistics, consciousness would remain empty, as demonstrated for instance in experiments on anesthesia (Madler & Pöppel, 1987). But the operation of time windows without having access to content would be equally meaningless. Content and logistical functions complement each other.

This concept of complementarity as a generative principle might be useful in answering further questions related to subjective time and to better understand several unusual observations. A rather unique effect was observed in patients with brain injuries in subcortical regions (Rubia et al., 1997). These patients were required to simply count in steps of seconds. Under normal circumstances, this is no challenge for anybody. However, these patients showed an unusual pattern of counting: some of them counted twice as fast as corresponding to the expected pace of counting "seconds," others counted half as fast. A small injury in subcortical regions apparently disconnected strategically important structures that normally have to interact to allow counting in seconds. The selection of either double or half the speed of normal counting indicates that two oscillatory processes of high and low frequency provide a logistic frame for interaction to create a stable temporal process between these frequencies. Thus, to have learned what it means to count in seconds may be based on two complementary activities or two temporal attractors, both being necessary for a rather simple task.

It has become a truism that the two cerebral hemispheres are characterized by different functional competences, and this distinction refers to temporal processing as well. In experiments on the effect of alcohol on reaction time, an interesting dissociation of function was observed (Pöppel & Steinbach, 1986). Auditory or visual stimuli were either presented to the left or the right hemisphere by presenting stimuli either in the right or left visual field, or to the right or left ear. Under control conditions it was observed that auditory stimuli processed in the left hemisphere elicit shorter reaction times compared to stimulation of the right hemisphere; on the contrary, visual stimuli processed in the right hemisphere elicit shorter reaction times compared to stimulation of the left hemisphere. Thus, both hemispheres show a selective advantage for temporal processing of auditory stimuli in the left and visual stimuli in the right hemisphere. Under the influence of alcohol, this selective advantage disappeared, and reaction times to visual or auditory stimuli were the same in either hemisphere. This result also implies that there was no, or only a minute, effect of alcohol on auditory processing in the right and visual processing in the left hemisphere. The complementary activity in temporal information for stimuli coming from the left or coming from the right, providing an advantage to either hemisphere for a specific sensory modality, was eliminated under the effect of alcohol.

As indicated above, the two time windows, although independent, are related to each other in a hierarchical fashion, one being responsible for detecting events, the other for integrating such events in a subjective present. Both time windows represent neuronal processes that operate on a presemantic level: that is, they are not defined by what is processed, but they are used to provide a temporal frame for what is processed. They refer to information processing on rather short temporal intervals, but subjective time extends of course into much longer temporal intervals. How is the impression of subjective continuity of time possible, in spite of the fact that the temporal machinery creates time windows in the domain of milliseconds or seconds? Indeed, the apparent continuity of time may be an illusion, because time has to be processed in discrete steps due to the associated physical and biophysical challenges. What might be the basis for this illusion, which in fact is quite practical, since it gives the impression that subjective time corresponds to objective time? One answer is given by the fact that the time windows remain in the background on conscious representation; they themselves are not the content, but serve to represent content. Thus, the content of successive time windows is linked on a semantic level, and the continuity of semantics creates the impression of a uniform passage of time.

This leads to another complementarity, which can be illustrated by an activity many people are familiar with. Driving an automobile is an example of a goal-directed activity with high complexity in which several behavioral elements must be integrated and brought into sequential order. A hierarchical model has been proposed (Tanida & Pöppel, 2006) that can be adapted to any other goal-directed activity, such as writing a paper or cooking a meal. All these activities, like driving, are conceived of as being controlled by anticipatory programs. In the model, five different levels of temporal control are distinguished, each one representing a time window. The highest level is the strategic level, with a representation of the driving activity from the beginning to reaching the final goal. On a temporally segmented tactical level, the sequence of necessary milestones to reach the goal are represented. It follows an even shorter time window on the operative level, via actions like keeping a lane or knowing how to use the brakes. The short-term integration level of 2 to 3 seconds allows, for instance, immediate anticipatory control. Finally, on the level with the shortest temporal interval of some tens of milliseconds, the necessary sensory information is provided to create mental content.

The hierarchy of time windows is characterized by the complementarity of short time windows, which are presemantically defined, and longer-term time windows that represent learned actions on the operative level, or that define consciously controlled milestones or goals. Thus, time windows that are based on automatic integration processes of the human brain beyond voluntary control, and time windows defined by anticipated goals under voluntary control, have to complement each other for successful behavior. As for any goal-directed activity, the time windows are related to each other in a bidirectional way. A defined goal on the strategic level defines activities on the lowest level by selecting only that information through attentional control that is relevant to reach the goal. Similarly, the strategic goal can only be reached if the time windows on the two presemantic levels function properly by delivering the necessary information to the conscious level. Time windows on a consciously controlled level and on an automatic level are expressions of the complementarity in temporal control as a basis for successful behavior.

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13 Time and Magic—Manipulating Subjective Temporality

Thomas Fraps

We presume that everyone will agree to the recognition of magic as an art. As a matter of fact, magic embodies both art and science.

—Nevil Maskelyne and David Devant, *Our Magic*

The interest of scientists in examining the psychological, perceptual, and cognitive methods developed by magicians can be traced back over a hundred years (Binet, 1894; Jastrow, 1897; Triplett, 1900), predating a now-classic essay on the theory of magic written by two of the most influential magicians of that era (Maskelyne & Devant, 1911), who already acknowledged a possible connection between the art of magic and science.

Recently there has been renewed and increased interest in the scientific examination of the methods employed by magicians to achieve their apparently impossible feats and illusions (e.g., Parris et al., 2009; Kuhn, Amlani, & Rensink, 2008a; Macknik et al., 2008). This interest of cognitive scientists stems from the fact that conjuring illusions are created not only by expert sleight of hand, special gimmicks, and secret mechanical devices, but primarily by the magician's ability to control attention and awareness as well as manipulate higher cognitive functions, such as reasoning and decision making, in order to hide the actual method of the trick (Fraps, 1998; Fraps, 2006; Lamont & Wiseman, 1999; Kuhn, Amlani, & Rensink 2008a, Gregory, 1982). The application of these psychological principles during the performance of a magic trick is generally subsumed under the term *misdirection,* which is a pervasive topic in the theoretical conjuring literature (e.g., Fitzkee, 1945; Galloway, 1969; Tamariz, 1988; Sharpe, 1988; Minch & Elmsley, 1991; Minch & Wonder, 1996; Lamont & Wiseman, 1999; Ganson, 2001; Ortiz, 2006).

While there are certain clearly defined rules and principles of misdirection, a consensus among magicians or a specific definition currently does not exist (Lamont et al., 2010). This is mainly because of the multifaceted and dynamic nature of misdirection, which is not performed by one specific method. There are many different layers of misdirection, often applied simultaneously, with the exact mixture of the various strategies being highly dependent on the performer and context, such as size of the audience, style of magic, or overall setting of the performance (e.g., stage or close-up, live or on video). For example, a seemingly random, but in fact carefully planned, arrangement of props can set the frame for a precisely timed choreography using body language (hand or arm movements) and direction of gaze to nonverbally guide attention via social cues (Lamont & Wiseman, 1999; Kuhn et al., 2008b) and via language to influence top-down perceptual mechanisms as well as higher cognitive functions. The effective application of misdirection can only be learned through years of actual performing experience ("in vivo") and is very dynamic in nature, since it depends on interaction with an audience (Minch & Wonder, 1996, 18).

Furthermore, the exact form of applied misdirection has to be adapted for each trick individually, integrating all layers into a cohesive performance that appears natural. For example, Minch and Elmsley (1991, 15) note: "You should misdirect not only from something that would otherwise be detected, but also from awkwardness, from anything that might raise suspicion." Most importantly, the use of misdirection itself should never be detected or recognized as such: "Magicians seek to direct attention without resorting to crude distractions, as the audience should not be aware that their attention is being directed" (Lamont et al., 2010, 17). Thus successful misdirection should not only hide the method(s) of a trick but also itself, so that the very process becomes invisible to the observer.

The first experimental studies examining misdirection in a magic trick used eye-tracking analysis of subjects watching either live performances or short video clips of magic tricks that primarily used gaze direction as a means of physical misdirection (Kuhn & Tatler, 2005; Kuhn & Land, 2006; Kuhn, Tatler, Findlay, & Cole, 2008b. These studies have provided a novel approach to examine the influence of social cues (gaze direction) on attention and offer a novel paradigm to investigate inattentional blindness (Mack & Rock, 1998; Simons & Chabris, 1999; Kuhn & Tatler, 2011; Kuhn & Findlay, 2010; Memmert, 2010; Memmert & Furley, 2010; Moran & Brady, 2010).

13.1 Time Misdirection

In addition to physical misdirection, there is yet another, less intuitive, albeit equally strong principle of misdirection that is related to subjective time perception and described by magicians as "time misdirection." This form of misdirection has to date not been explored scientifically, so what follows are mostly hypotheses and speculations that attempt to explain the basic concept and provide hints at possible connections to studies on time perception, in hopes of furthering the renewed dialogue between science and the conjuring arts.

Time misdirection is a pervasive aspect of misdirection (as is physical and psychological—e.g., verbal or mental—misdirection), and in one form or another applied in almost every performance of magic (Sharpe, 1988; Lamont & Wiseman, 1999; Ganson, 2001; Ascanio & Etcheverry, 2005; Ortiz, 2006; Tamariz, 2007). The term subsumes various similar concepts that aim to manipulate subjective time perception, and all are centered around the basic strategy of manipulating *when* a spectator is focusing his (critical) attention, instead of *where* (e.g., Lamont & Wiseman, 1999, 38).

Moreover, the concept of time misdirection is far less intuitive and accessible to an observer than physical misdirection, since it manipulates aspects of an audience's subjective time perception while watching a magic performance. Directing attention not only in the spatial but also in the temporal domain is effective because it enables the magician "to put a temporal wall between method and the effect" (Ortiz, 2006, 45). This temporal wall is aimed at breaking the causal relationship between the secret actions and their intended (magical) effect on an observer (Ascanio & Etcheverry, 2005, 59).

The metaphor of the temporal wall illustrates the core concept of time misdirection: to inject a time interval between the moment of the secret action ("the method," which is usually covered by physical misdirection) and the moment when the observer actually experiences the illusion ("the effect," e.g., the disappearance of a coin in the hand of the performer). The length of this interval between method and effect on the physical time line can range from seconds to minutes (or more), depending on the specific trick, context of performance, and interaction with the audience.

The effectiveness of time misdirection is related to the temporal aspects of causal perception and the idea that our perception of causality is a mental construct, one only inferred from the sensory experience of temporal contiguity (Hume, 1739/1888).

For example, Michotte's studies identified particular temporal patterns that give rise to causal perception (Michotte, 1963; also see White, 1995). Scholl and Tremoulet note:

> Michotte's demonstrations and most of the early extensions to his work consisted of discovering the spatiotemporal parameters that mediate these causal percepts, such as the items' relative speeds … and temporal gaps. Perhaps the most crucial result, however, is simply that there are such precise conditions: these percepts seem to be largely stimulus driven, and objectively small manipulations to the displays can cause the causal nature of the percepts to disappear. (Scholl & Tremoulet 2000, 301)

In regard to time misdirection, Michotte's observation that the percept of causation can disappear when the temporal gap between event A and B is too large is of particular relevance for the successful illusion of a magic trick. It means that specific timing aspects of a performance can help to conceal the causal relationship of the secret method(s) due to the automaticity involved in the process of perceiving causality. As Wagemans et al. note, "Michotte developed a theory of the nature of causal perception, which emphasized its automaticity and ... demonstrated that even seemingly cognitive properties such as causality may be processed in the visual system" (2006, 10–11).

A striking example of how the temporal gap between percepts influences our perception of causality is provided in everyday life by thunder and lightning. If lightning strikes near our location, the perception of a causal connection between the two stimuli is automatic and rather obvious: lightning causes thunder. But if lightning strikes sufficiently far away, the different speeds of transmission for light and sound waves become relevant: the sound waves reach our ears with a delay of a couple of seconds and the automaticity of the perception of causality is diminished or broken. Depending on our knowledge, of course, we infer or assume a causal link, but an observer witnessing this spectacle for the first time (and maybe only once) without any prior knowledge of physics might not perceptually (or cognitively) link these events in a causal connection (just imagine if the delay were minutes or hours).

A magician strives for a similar perceptual and cognitive "disconnect" of causal links to guard the secret actions from being detected during a performance (or reconstructed after). For a specific example illustrating one form of time misdirection, imagine the following short magic trick, described from the point of view of a spectator (a short video clip of the performance can be viewed online at http://www.thomasfraps.com/timeandmagic/cointrick1.mp4).

In the trick, the magician picks up a coin from the table with his right hand and puts it in his left hand, which closes into a fist. The right hand picks up a pen from the table, while the left hand and fingers move a little, wiggling the coin inside the fist, which the right hand then taps with the pen, serving as an improvised "magic wand." The magician opens the left fingers to peak inside the fist, but the coin is still there. The right hand makes another tap with the pen, and when the left hand is now opened, it is completely empty; the coin has magically disappeared. The right hand then taps a salt shaker with the pen, and when the salt shaker is lifted by the left hand, the missing coin is found underneath (e.g., Goshman & Page, 1985).

The secret of this trick example is based on the use of sleight-of-hand skills to make the coin disappear and a duplicate coin that has been secretly maneuvered underneath the salt shaker, usually long before the performance begins. Thus, the illusion of an invisible transposition of the coin is accomplished by combining two basic magic effects, the vanish (of a coin from the hand) and the appearance (of a coin underneath a salt shaker) with the aid of the methodological device of duplication (Lamont & Wiseman, 1999, 173).

The exact details of the sleight-of-hand mechanics and physical misdirection are not of interest here. The temporal aspects, however, are, as they illustrate one possible application of time misdirection in the context of a magic performance. The above trick sequence has two essential temporal gaps (interval A and B in figure 13.1), which separate the method from the effect on the physical time line (i.e., the magician). Interval A is the temporal gap between the moment of the secret loading action to deposit the duplicate coin underneath the salt shaker (executed some time before the official start of the performance) and the moment when the left hand lifts the salt shaker to reveal the reappearance of the vanished coin. In a real-world performing context, such as in a restaurant setting after dinner, the duration of this interval would be in the range of tens of seconds to minutes or sometimes even more. What is important is that the secret loading action takes place before the spectator perceives the start of the performance.

In a theater setting, this moment may be fixed by the official printed starting time, but in an impromptu setting of a close-up performance, this moment is defined by the magician, usually by shifting from after-dinner small talk into "performance mode," announcing a trick, and changing the body language from a relaxed position to one with more tension

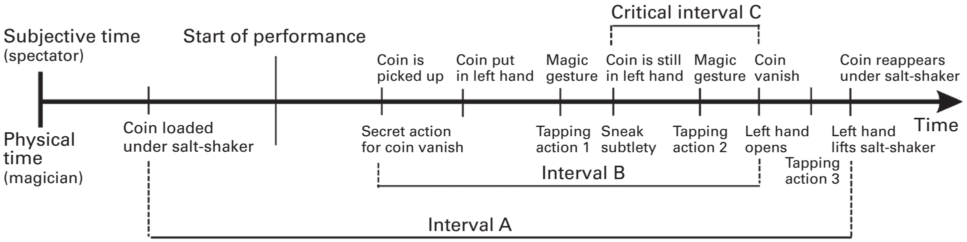

Figure 13.1

The temporal gaps (intervals A and B) separate the secret action (method) from the effect (magic moment, e.g., vanishing and reappearance of a coin), and thus serve as time misdirection blurring the causal links between method and effect.

and focus (Hartling, 2003, 30). This change in attitude defines the beginning of the trick on the subjective time line of the observer, although for the magician the trick has already begun seconds or minutes ago when he used the diverted attention during the small-talk situation to secretly deposit a duplicate coin under the salt shaker. Interval B is the temporal gap between the moment of the secret action to vanish the coin (while apparently picking it up from the table) and the moment of its disappearance when the left hand is opened. The duration of interval B in performance is much shorter than interval A, probably around 3–5 seconds in the context of the given trick sequence.

Most important on the subjective time line of the observer is the critical interval C, which describes the time between the performer's glimpse into the left fist (a psychological subtlety to convince the spectator that the coin is still in the hand) and the perceived effect (the vanishing of the coin). The notion of the critical interval is based on the general definition of a magic effect by Ascanio, which states that the magic effect is the difference between the initial condition, such as "coin in left hand," and the final condition, such as "left hand empty" (Ascanio & Etcheverry, 2005). Based on these notions, Ortiz defines the critical interval as "the time between the audience's last view of the initial condition and the first view of the final condition" (2006, 46). Note that the word "view" is a bit misleading here, since it is not necessarily always identical to an actual perception or physical reality. The definition concerns the subjective perspective of the observer and describes a temporal duration in his subjective time line (although it is framed by actions on the physical time line).

Time misdirection helps to compose a specific temporal structure for a magic trick, so that any secret actions stay outside of the critical interval. This added layer of misdirection usually strengthens the deception and the impact of the trick, since nothing suspicious happens during that interval. Of course, there are also tricks in which this is not possible, since the secret action (the method) has to coincide with the effect (as perceived by the spectator), such as the purely visual change of the face of a playing card without any cover. Since a magic performance, however, almost always consists of various short effects combined into longer routines (or acts), there is always some form of time misdirection involved in the overall composition. In our trick example, the movements covering the secret actions of the coin vanish are executed quite openly and in full view, but outside the critical interval, when the observer's attention is not fully focused yet. These movements imitate natural actions (picking up a coin from the table) and seem motivated as necessary goal-directed actions ("in-transit actions," Ascanio & Etcheverry, 2005, 60) that are also covered by physical misdirection (e.g., social cues to guide joint attention via gaze direction).

In the current example, the coin is only apparently picked up from the table with the right hand, but actually secretly dropped into the lap of the magician (sliding the coin to the table edge), so the right hand is empty and only pantomimes the transfer of the coin into the left hand, which closes into an empty fist. (Note that the gaze of the magician is directed toward his left hand a moment *before* the right hand apparently lifts the coin from the table edge, providing additional physical misdirection by guiding/cueing the spectator's attention toward the left hand.) The right hand is now free to pick up the pen, which serves as a kind of improvised magic wand and provides a fake causal attribution for the disappearance of the coin in the form of the tapping action (Kelley, 1980). This intermediate action, right after the coin was apparently placed in the left hand, is an essential example of time misdirection (Lamont & Wiseman, 1999, 34). It could be any other natural and innocent "magical" gesture, like simply waving the right hand or snapping the fingers; its main purpose is to prolong the temporal gap between the method and the effect (interval B in figure 13.1) by providing a fake sense of causality during the critical interval C (e.g., Ortiz, 2006).

The performer's tapping action with the pen and subsequent look inside the left fist constitutes a psychological subtlety intended to manipulate the spectator's subjective time, focus his attention on the left hand, and, most importantly, make him assume the coin is still in the magician's hand. So on the subjective time line of the spectator, the coin disappears with the second tap of the pen, while on the physical time line of the performer the real method (here, secretly dropping the coin into the lap), has already been executed a few seconds earlier, outside the critical interval C.

This, of course, is only one out of many possible implementations of time misdirection in a specific trick context. So apart from physical or verbal misdirection, the temporal structure of a magic trick and the resulting timing during the performance also contribute to building a cognitive barrier between method and effect.

The temporal composition, and particularly the time frame of several seconds in which basic elements of the example trick take place (e.g., the disappearance of the coin), suggest additional cognitive mechanisms that may be involved in effective time misdirection.

13.2 Working Memory

Apart from exploiting mechanisms of causality perception, time misdirection also seems to tap into the temporal mechanisms and capacity limitations of proposed models of working and short-term memory (Baddeley & Hitch, 1974; Baddeley, 2000; Cowan, 2001; Barrouillet et al., 2007; Lustig et al., 2009).

For example, decay and interference are considered the primary mechanisms of loss in short-term and working memory, acting over a time course of seconds to minutes (Gazzaniga, Ivry, & Mangun, 2009, 314), which happens to be the most common range of applied time misdirection in a magic performance. The insertion of a temporal gap between method and effect therefore seems logical, since it seeks to erase any memory traces of (secret) actions of the method by exploiting the time-related decay of information in working memory.

Of special interest is the time-based resource-sharing model proposed by Barrouillet et al. (2004), which assumes that representations in working memory decay unless they are refreshed by an attentional focus; "the results of the present study suggest that information within working memory suffers from a time-related decay as soon as attention is switched away and captured by concurrent activities," they conclude (Barrouillet et al., 2007, 582). In our example trick sequence, the apparent transfer of the coin from the right hand into the left and the subsequent tapping action with the pen could be considered "concurrent activities" that switch attention away from the moment of the method (picking up the coin from the table), thus additionally acting as interference, since "forgetting is related to … similarity-based interference and failures in the reconstructive process when relevant and irrelevant representations share features and overlap" (Barrouillet et al., 2007, 583).

And since working memory embodies information storage as well as executive mechanisms for the manipulation of this information during cognitive tasks (using an active attentional control system for verbal and visual information, according to Baddeley (Baddeley & Hitch, 1974), these additional actions provide not only visual information to capture executive attention, but also the necessary passage of time to support loss of information from working memory. According to Barrouillet et al., "it is even possible that the sheer passage of time increases the probability of this similarity-based interference if the features between them are weaker and weaker with time" (2007, 582).

Since the working memory model includes short-term storage buffers (Baddeley, 2000), the suggestion that time misdirection exploits decay mechanisms also seems compatible with the focus-of-attention view of short-term memory, which suggests that it is not the integrity of an item's representation itself that changes over time, but the likelihood that attention will be attracted away from it. As Lustig notes: "By this explanation, the representation within the focus does not decay. However, as more time passes, there is a greater likelihood that attention is attracted away from this representation and toward external stimuli or other memories" (Lustig et al., 2009, 578).

In our specific trick example, the tapping action of the pen, or more generally the use of a "magical gesture," serves as an "external stimulus" attracting attention away from the action that conceals the method (e.g., sliding the coin to the table edge and secretly letting it dropping into the lap, while pantomiming picking it up with the right hand). Even though the secret action is simulating an official goal-directed and motivated action ("picking up the coin"), the magician's aim is to make the observer forget that the hand touched the table edge in the first place.

Since forgetting in short-term memory probably occurs due to "similarity-based competition between representations for the focus of attention," as Lustig et al. note (2009, 582), one could argue that the remote similarity of the pen-gesture action to the coin-transfer action (e.g., an object is lifted from the table with the right hand and moved toward the left hand) provides a visual interference for decay.

Thus, time misdirection seems to exploit temporal aspects of causality perception and working memory, both mutually enhancing each other to effectively hide the real link between the method and effect. A central characteristic for both of these mechanisms is the notion of a time interval, which suggests considering time misdirection in regard to the notion of the "subjective present."

13.3 Subjective Present and Effect

It could be argued that the concept of time misdirection implicitly reflects the notion of temporal windows of integration proposed on different timescales (e.g., Pöppel, 1997; Pöppel, 2004; Rammsayer, 1999; Mauk & Buonomano, 2004) as prerequisites for temporally structuring perception and action. For example, Pöppel proposes a temporal integration mechanism with a range of several seconds that forms a potential platform for conscious awareness:

> We are now in a situation to indicate on an experimental basis how long such a subjective present actually lasts. This numerical answer can be derived from a number of different experiments, which all converge to a value of approximately 2–3 s. Support comes from different domains such as temporal reproduction, vision and audition, short-term memory and even cultural artefacts in music and poetry. All these observations suggest that conscious activities are temporally segmented into intervals of a few seconds and that this segmentation is based on an automatic (pre-semantic) integration process establishing a temporal platform for cognitive processing. (Pöppel, 2009,1891)

In our example, the subjective time intervals (critical intervals) of the magic moments as perceived by the spectator (e.g., the vanish and reappearance of the coin) each last around 2–3 seconds. In fact, this is a time range and rhythm to be found repeatedly in many magic performances, not only in sleight-of-hand tricks that compose several short visual effects into a longer routine (e.g., Ganson, 1957; Tamariz, 1988; Kurtz & Kaufman, 1990), but also in the larger effects of stage magic (e.g., Steinmeyer, 2003). So it seems appropriate to extend the range of artists mentioned by Pöppel to include magicians: "possibly artists such as composers and poets have an implicit knowledge of the temporal machinery of the human brain and use the temporal platform of 2–3 s as a formal basis to express a motif or a verse" (Pöppel, 2009, 1893). The motifs of magic, however, are the basic effects (e.g., vanishes, reappearances, transformations) used to build longer and more complex compositions.

Thus, one could argue that time misdirection is implicitly using temporal segmentation by aiming to place the moment of the secret method outside the window of the subjective present, which is centered around the perception of the magic moment (e.g., the disappearance of the coin).

However, the concept of temporal segmentation has further implications in regard to structuring a magic trick. So far, discussion has focused on the role of time misdirection in hiding the causal links between method and effect, but the notion of the subjective present also helps to identify the role of time perception when trying to strengthen the (emotional) impact of the effect itself, the actual "magic moment" as perceived by the observer.

The task can be compared to the signal-noise or figure-ground problem. When conceiving, practicing, and performing a magic trick, the magician has to take care that any perceptual and cognitive links to the secret method(s) are hidden or perceived as unimportant background noise, so the observer is able to recognize the impossible figure, the effect. The clearer the figure is in the mind of the spectator, the higher the impact of the effect and the more it elicits a stronger emotional reaction of amazement and wonder in the audience, which is something a magician is always striving for artistically.

Apart from the theatrical and entertainment aspects, the performance of a magic trick can be compared to M. C. Escher's paintings of impossible objects, such as "Waterfall" or "Belvedere" (Locher, 1992), except that a magician paints the impossible figure not on a canvas, but in reality. The canvas of the magician is the mind of the observer, which perceives, for a moment, a "real impossibility" and not a painted one.

Looking at our specific trick example, the figure or gestalt of the effect is the apparent motion of one coin from the left hand to the salt shaker. Making this gestalt easily recognizable for the observer depends on two main factors: first, the correct timing of the individual components, the disappearance and reappearance of the (duplicate) coin (in a way related to the phi-phenomenon and tunnel effect, which will be discussed below); and second, the seemingly innocent action of using the pen as a magic wand that is used twice (tapping the left hand and the salt shaker) to visually accentuate the illusory trajectory of the coin, and more importantly to provide a fake causal attribution in the form of a magic gesture.

Apart from enhancing time misdirection by redefining the moment when the magic happens in the observer's subjective time (Ortiz, 2006), these magical gestures are an important element of focusing attention on the effect itself, since they are best placed in the critical interval C. They usually happen when nothing else does, and implicitly help to establish the magician as being the cause of the illusions.

Kelley even argues that all magic can be seen through this filter of fake causal attributions: "A successful magic trick is closely linked to a process of causal attribution … the audience sees an exceptional cause-effect-relationship and this process of causal attribution is led astray in the mind of the spectator by the actions of the magician" (Kelley, 1980, 24).

In experiments resembling a magic trick, Subbotsky (1997, 2000) showed that not only children but also adults succumb to "phenomalistic causal reasoning" (Subbotsky, 2000, 70) and magical thinking at the level of nonverbal attitudes and actions. Subbotsky writes: “The data also support the view that beliefs in mental-physical causality persist throughout the life span. In this regard adults are not fundamentally different from children” (2000, 64).

Magicians have implicitly known about these conscious and subconscious beliefs and the principle of fake causal attributions for centuries. One of the most famous examples is a performance in the French colony of Algeria by Jean-Eugéne Robert-Houdin in October 1856. He was the most innovative and influential magician of the nineteenth century and called upon (from retirement) by the head of the political office at Algiers, Colonel de Neveu, to impress the tribes of the colony, who were threatening a revolt against the French government. The rationale was to prove that “the Frenchman’s magical powers were far superior to those of the tribe’s leaders, the Marabouts, who were a religious sect of miracle workers” (Dawes, 1979, 124).

In the historical performance, Robert-Houdin used several tricks to demonstrate his superhuman powers, among them the “Light and Heavy Chest,” an invention of his own that he had performed at his theater in Paris. The effect is simple: by way of a gesture from the magician, a small, light wooden box becomes so heavy it cannot be lifted. The ingenious method was the application of a scientific principle: an electromagnetic coil underneath the stage. When activated, the electromagnet exerted an irresistible force on the metal inside the box (hidden in the box’s wooden base). Due to the clever combination of this at the time rather unknown scientific principle and his supreme understanding of conjuring psychology, Robert-Houdin turned a curious trick into a demonstration of superhuman powers simply by faking causal attribution. During his performances in Paris, the gestalt of the effect was a chest becoming heavy (or light) due to a magic gesture. In Algeria, however, the effect was reframed by Robert-Houdin “to proof my marvellous authority by showing that I can deprive the most powerful man of his strength and restore it at my will” (Robert-Houdin, 1859 in Karr, 2006, 611).

Note that even though the method stays exactly the same, the effect gestalt changes by rephrasing the magic gesture into a magic spell:

> I made an imposing gesture and solemnly pronounced the words: Behold! You are weaker than a woman. Now try to lift the box … the Arab vainly expended on this unlucky box a strength which would have raised an enormous weight until at length, exhausted, panting, and red with anger, he stopped, became thoughtful, and began to comprehend the influences of magic (Robert-Houdin, 1859 in Karr, 2006, 612).

Apart from having averted a simmering rebellion with an electromagnet, this trick is not only a good example for Maskelyne’s statement that magic contains both art and science, but also a perfect illustration of the importance of fake causal attribution, or “magical causation” (Subbotsky, 2010, 5).

Interestingly, one of the first books to explain magic tricks, *The Discovery of Witchcraft* of 1584, was written with the intention to save witches from being burned by revealing their rituals to be as harmless as those of jugglers and magicians, whose tricks and fake causal attributions were exposed within: “These magicians did rather seeme to doo these woonders, than worke them indeed. And if they made but prestigious shewes of things, I saie it was more than our witches can doo. For witchcrafts are but old wives fables” (Scot, 1584/1972,180).

An example from everyday life of a fake causal attribution (due to the automatic visual perception of causality), is the habit of making a “magical gesture” in front of an automatic sliding door, thus apparently causing the door to open. The important factor is the correct timing, which is highly constrained. A split-second too late or too early, and the illusion of causing the door to open by the power of a hand gesture is destroyed. If the timing succeeds, however, the illusion feels real for a split second. Even though we know it’s an electric sliding door controlled by some motion sensor (triggered by an approaching body, or sudden arm movement), we nevertheless “see” the hand gesture opening the door, thus falling for Subbotsky’s “phenomalistic causal reasoning” and Michotte’s automaticity of causal inference. As Choi notes, “a primitive notion of causality may arise from the automatic visual interpretations of simple mechanical events … the perception of causality appears to be largely automatic, often irresistible, resistant to higher-level beliefs and intentions, and driven by highly constrained and stimulus-driven visual cues” (Choi & Scholl, 2006, 385).

Looking at our trick example again, the connection becomes clear. The magic gesture of tapping the pen on the left hand is placed in the critical interval C, so that it happens when nothing else does. If the window of the subjective present is considered to be centered around the magic moment (e.g., opening the left hand to show the disappearance of the coin) then the tapping action of the pen is the only other “simple mechanical event” triggering the “primitive notion of causality” that Choi describes. The pen, in this case, serves as an improvised magic wand, historically an important requisite for magicians, whose function for providing false causal attribution (and covering sleight-of-hand manipulations) was already known early on, as Robert-Houdin’s comments prove: ”a touch of the wand on any object, or even a wave in that direction, forms the ostensible cause of its transformation or disappearance”; such a gesture is necessary “to simulate a cabalistic power and to facilitate the secret manipulation of the cork balls by affording a pretext for closing the hand which conceals them” (Robert-Houdin, 1878 in Karr, 2006, 190).

13.4 Temporal Binding

A further piece of evidence for the intuitive understanding of subjective time perception (and causal attributions) by magicians is the phenomenon of temporal binding: several studies have demonstrated that causes and effects mutually attract each other in subjective time (Buehner, 2010; Eagleman, 2008, Eagleman & Holcombe, 2002; Haggard et al., 2002). This was first shown by Haggard et al. for intentional actions. In these studies, participants had to press a button, which was followed after a certain interval by a tone. Using the Libet clock paradigm to indicate time, subjects reported the button press to have occurred later and the tone earlier in subjective time. Haggard et al. comment:

> Our results show that truly operant intentional actions elicit perceptual attraction or binding effects. This effect associates or binds together awareness of the voluntary action with awareness of its sensory consequence, bringing them closer in perceived time. (2002, 384)

The binding effect also occurs when participants only observe the experimenter pressing the button (Wohlschläger et al., 2003), which supports the more general interpretation of Eagleman and Holcombe, who proposed that the temporal binding effect is a consequence of the causal relationship between actions and their effects: "temporal binding serves a more fundamental purpose than supporting the experience of intentionality: It is driven by impressions of causality" (Buehner & Humphreys, 2009, 1222). Originally demonstrated in the interval range of several hundred milliseconds by Haggard et al. (2000), Humphreys and Buehner also demonstrated a reliable binding effect at supra-second intervals up to 4 seconds (Humphreys & Buehner, 2009), which is the range of interval C in which the vanishing of the coin takes place. This range of several seconds provides ample time for the magician to insert actions serving as magical gestures during a performance.

The tapping action of the pen is the most contiguous event to the unexpected event of the vanishing, so the temporal binding effect works in favor of establishing a new (subjective) causality, while at the same time blurring (ideally breaking) the real causality of the action of picking up the coin from the table, which takes place much earlier (interval B). The same hypothesis applies to the reappearance of the coin under the salt shaker. In subjective time, the actions of tapping and lifting the salt shaker are bound together causally to the surprising appearance of the coin, with the real causal interval A being in the range of tens of seconds to minutes and filled with numerous other events.

A related, interesting observation from performing the trick is the following. If a spectator is asked to lift the salt shaker himself (after the tapping-action), the magic moment has a higher emotional impact. Two possible reasons come to mind. First, it immediately eliminates the suspicion that the coin was secretly placed underneath the salt shaker by the magician (e.g., during his action of lifting it from the table). Second, there is probably an illusion of agency (Shanks et al., 1989; Wegner, 2003) involved on the spectator's side due to his intentional action and perception of causality, which is required for the temporal binding effect to occur (Buehner & Humphreys, 2010; Haggard, Clark, & Kalogeras, 2002).

In conjunction with the notion of the subjective present, temporal binding is not only helpful in creating fake causal attributions, but also in shaping the actual gestalt of the effect in the mind of the observer. In our example, the intended effect is the invisible motion of a coin from the left hand underneath the salt shaker. For this illusion to be perceived, the timing of the two single effects is rather important. The concept of a temporal gap, so beneficial in hiding the real link between method and effect, can also backfire and break the illusion the magician wants to create.

13.5 Timing and Effect

Anecdotal evidence from performance shows that if the time interval between the disappearance and the reappearance of the coin is either too short or too long, the whole trick sequence loses impact, and the magic moment is not as strong. Sometimes the effect gestalt is completely lost, since the spectator does not perceive one coin traveling, but instead almost immediately infers the use of a duplicate coin as an explanation after the trick has finished.

This observation seems related to stroboscopic motion, or the phi-phenomenon (e.g., Ramachandran & Anstis, 1986; Kolers, 1972; Wertheimer, 1912), in which two spatially separate and stationary objects flashed alternatingly give rise to the illusion of one object moving back and forth (instead of two stationary objects being switched on and off). Even though the necessary frequency for the illusion to occur is in the range of 200 ms, which is quantitatively not compatible with our specific trick example, the qualitative observation about apparent motion does match: "It is known that the perceived quality of apparent motion varies with spatio-temporal properties of the display, such as spatial separation and the temporal interval" (Yantis & Nakama, 1998, 509).

There are, however, certain tricks whose effects fall into the time range of stroboscopic motion if performed properly. One is the "toss vanish" (Goshman & Page, 1985), in which a coin is apparently tossed from the right hand into the left, but secretly retained in the right hand. Even though both hands are several inches apart, if the throwing and catching actions are performed correctly, observers report actually seeing the coin flying, thus filling in the motion of an object where there is none, which fits well with the results of an apparent motion study by Yantis and Nakama using stimuli on a computer screen. They suggest that "there is an explicit representation of a motion token in the path of apparent motion" probably caused "by cortical feedback from higher visual areas to lower ones responsible for perceptual completion" (Yantis & Nakama, 1998, 510).

Another trick (Schneider, 1970) uses four coins and four cards (a short video clip of the basic effect can be viewed at http://www.thomasfraps.com/timeandmagic/cointrick2.mp4): the four coins are placed on the table in a square formation and covered by four playing cards. Then the two cards from diagonal corners of the square are quickly lifted at approximately the same time (e.g., in the range of 200 ms), and the coin from the lower-right corner is seen to have "jumped" to join the coin in the upper-left corner. This is repeated two more times with the coins in the upper-right and lower-left corner, which are also seen to apparently jump to the upper-left corner, where finally all four coins have gathered. If performed with the proper timing, the illusion is rather strong and spectators report having actually seen the coins "jump."

Now, if the actions are slowed down and the temporal interval between lifting the two cards is prolonged, the visual effect of a jumping coin, similar to the phi phenomenon, is lost, even though it is still perceived as a magic effect (coins traveling invisibly).

Thus, the (spatio-)temporal aspects can change the perceived quality of the apparent motion of the coins, which means the gestalt of the effect has changed.

The same holds true for our original trick example. There exists a dependency of the effect gestalt from spatiotemporal aspects of the performance (e.g., time interval between the vanishing and reappearance of the coin or spatial distance between hand and salt shaker), albeit on a different (supra-second) timescale, therefore warranting a different explanation.

Ramachandran and Anstis have shown in experiments on apparent motion that a shape can appear to move behind another (Ramachandran and Anstis 1986). Apparently the visual system can construct illusory movement of invisible objects behind an occluder, which is on an abstract level a suitable description of our initial trick: the coin travels invisibly from the left hand to underneath the salt shaker, with the occluder, the space between the hand and the salt shaker, being imaginary.

The spatiotemporal dependencies of this apparent illusory movement of the coin suggest it may be useful to look at the effect from the perspective of object continuity and object persistence, especially in regard to studies on the tunnel effect (Burke, 1952; Yantis, 1995; Flombaum & Scholl, 2006; Flombaum, Scholl, & Santos, 2009).

We know from everyday observation that we are able to see objects as persisting through periods of occlusion, such as a car passing behind some larger stationary object on the street or a toy train moving through a tunnel. This phenomenon, however, is sensitive to spatial and temporal details (Flombaum & Scholl, 2006). If the conditions are not quite right, for example if the temporal gap is too long, observers report seeing two distinct objects, one entering the occluder and another emerging. This matches the observation that spectators more easily jump to the explanation of a duplicate coin being used in the initial trick example (the coin under salt shaker effect).

Even though there is no physical occluder present in our trick example, anecdotal evidence from performing suggests a qualitatively similar dependency on spatiotemporal parameters when trying to create the illusion of an invisible, moving object or coin between the hand and the salt shaker. If the timing is off, the impact is diminished and the illusion could even be destroyed, which illustrates the important role of temporality in shaping the gestalt and impact of a magic effect in the minds of the audience.

Furthermore, the perception of object continuity is so strong that even if the object that emerges from the occluder has different features (e.g., color, shape) than the one that enters the occluder, observers still report seeing a single occluded moving object. Burke termed this phenomenon the tunnel effect (Burke, 1952). According to Flombaum et al. (2009), the explanation for the tunnel effect is that the visual system adheres to “a principle of spatio-temporal priority: correspondences favored by spatio-temporal considerations will almost always trump those favored by featural similarity. … This spatio-temporal bias is more than just a quirk in perception. Instead it appears to be a central feature of our underlying representations of persisting objects” (Flombaum, Scholl, & Santos, 2009, 140).

One could hypothesize that the duplicate coin underneath the salt shaker isn't recognized as such immediately, despite its slightly different surface features, because of the spatiotemporal bias toward featural similarity (and the emotional surprise element).

In essence, it could also be considered a special kind of change blindness (Rensink et al., 2000), which depends on the correct timing during performance, since it is based on the principle of spatiotemporal priority. This enables an expanded and improved version of the initial trick, which can also be performed with a borrowed, signed coin (e.g., initials with a black marker). By adding a another (repetition) phase, after the salt shaker, the magician is able to switch out the duplicate coin, which now has been endowed with a fake signature, for the original one during that repetition phase (a video clip of this extended version can be viewed at www.thomasfraps.com/timeandmagic/cointrick3.mp4).

This technique successfully cancels the weakness of the original method: the fact that by analyzing the trick in retrospect, a spectator could find the correct solution—the use of a duplicate coin—simply by reasoning. However, if the coin is borrowed and signed by a spectator and handed back to him at the end, the "duplicate coin" solution is effectively canceled from the search space of possible solutions (Newell & Simon, 1972; Tamariz, 1988), thus increasing the impact of the trick. This is an example of how magicians effectively interweave different forms and layers of misdirection, the impact of which reach beyond the actual duration of the trick. The spectator's initials on the coin act as a form of mental misdirection, a barrier against the top-down problem-solving analysis that usually happens in retrospect after the perceptual stimuli of the performance are long gone (Danek et al., 2012).

Given the perceptual automaticity inherent in the principle of spatiotemporal priority, one could even argue that in order to explain away the cognitive dissonance (Festinger, 1962) caused by the violation of object permanence, the brain jumps to the "next best" perceptual mechanism as an explanation. It resolves the cognitive dissonance of a disappearing and reappearing object, taking into account the timing of both events, by automatically assuming object persistence and interpreting the perceived events as the apparent movement of one identical object behind a nonexistent, invisible occluder, which obviously is an(other) illusion.

This seems to illustrate the argument by Leslie that the existence of illusions can be regarded as evidence for a modular organization of perceptual mechanisms (Fodor, 1983) and that "illusions are a necessity" (Leslie, 1988, 185 to resolve incongruities in a Bayesian observer, as Kersten, Mamassian, and Yuille (2004) note: "An ideal observer does not necessarily get the right answer for each input stimulus, but it does make the best guesses so it gets the best performance averaged over all the stimuli. In this sense, an ideal observer may 'see' illusions" (Kersten, 2004, 274).

And since the Bayesian approach is at the core of the predictive coding framework which assumes that the brain makes inferences on the hidden causes of its sensory input (the state of the world) by implementing a probabilistic hierarchical predictive coding mechanism with prediction error minimization (Clark, 2013; Hohwy, 2013; Friston, 2010; Fletcher & Frith, 2009), it seems reasonable to speculate that magic tricks are *maximizing* perceptual and cognitive prediction errors by providing (high-precision) sensory input that violates the (innate or learned) prior beliefs, and makes the brain jump to conclusions that are illusory, as Hohwy notes:

> … the perceptual system is not interested in veridicality as such. Rather it is interested in the most efficient route to minimising as much prediction error on average as possible. In that light it seems quite reasonable for the visual system to tolerate some measure of illusions. (Hohwy, 2013, 143)

In magic tricks, however, the prediction error cannot be explained away on the cognitive and semantic level since a highly improbable and unpredictable bottom-up sensory input (e.g., disappearing coins) generates a very strong mismatch with the (top-down) predictions representing a certain model of the world, for instance the learned or innate "hyperpriors" (Clark, 2013, 47) of object permanence and persistence, so "an inferior hypothesis about the state of the world may jump in to minimise prediction error" (Hohwy, 2013, 135). Or as Brown and Friston note, "the perceptual inference can be optimal in a Bayesian sense, but is still illusory" (Brown & Friston, 2012, 2).

In the context of our trick example, the "inferior hypothesis" is triggered by the effect-gestalt based on the correct timing of the trick-choreography and verbal clues (see 13.5 Timing and Effect): one coin traveling between two points A and B behind an (illusory) occluder is a simpler hypothesis than assuming two different coins are disintegrating and appearing at A and B (which in turn is a simpler hypothesis than the actual causal link of events, the hidden manipulative methods of the magician). Thus, "if both hypotheses can explain away the sensory input then it is better to opt for the simpler hypothesis, which in this case happens to lead to illusory inference to a superficial hidden cause" (Howhy, 2013, 110–111).

Since the inferior hypothesis results in an illusory percept that creates a strong illusion of impossibility by contradicting physical reality ("invisibly jumping coin"), a cognitive or semantic prediction error still persists and probably triggers the "magic moment," the pleasurable feeling of amazement and wonder, which is after all the artistic essence of magic. Perhaps magic then depends on the conjunction of very efficiently explaining away relatively low-level prediction error and at the same time generating relatively high-level prediction error concerning longer term regularities.

Interestingly, there is evidence that purely perceptual prediction errors also activate the dopaminergic midbrain reward system, striatum and habenula (Schiffer & Schubotz, 2011; Schiffer et al., 2012; den Ouden et al., 2010), fostering the speculation that magic moments are pleasurable because they "hijack" those parts of the dopaminergic system which provide valence to prediction errors themselves (e.g., the habenula—Schiffer et al., 2012, 9) and reward the detection of mismatches with prior beliefs, an evolutionary important motivation for learning and updating internal models of the world (Hurley et al., 2011; Fiser et al., 2010; O'Doherty et al., 2003; Geisler & Kersten, 2002). This confirms Van de Cruys and Wagemans' account of the role of prediction error and reward in (visual) art, since "in their artistic endeavors people seem to deliberately seek prediction errors. Prediction errors intrigue us, especially when they violate strong default expectations" (Van de Cruys & Wagemans, 2011, 1053).

The art of magic certainly violates strong default expectations thus creating emotionally rewarding illusions of impossibility making the "fantasies of our brains coincide with reality" (Frith, 2007, 135) and to achieve this aim, manipulating aspects of subjective temporality seems to be one of magic's most pervasive and powerful principles.

13.6 Conclusion

The goal of this chapter was to point out possible bridges between selected phenomena of subjective time perception and methodological principles of magic. Due to the complexity of both time perception and the art of magic, it is not intended to be comprehensive and should be considered an attempt that necessarily remains highly speculative (also owing to the limitations of the author, who is a professional magician, not a professional scientist).

Nevertheless, it may shed some light on possible connections, and thus contribute to the cautious dialogue between science and magic that is still in its infancy. Although limited by the scientific constraint of examining a complex live-performance art like magic "in vitro" in an artificial laboratory setting (e.g., via video clips on a computer screen), the initial steps (e.g., Kuhn & Tatler, 2005; Kuhn et al., 2008b; Kuhn, Kourkoulou, & Leekam, 2010) provide interesting insights, and time will tell whether this unusual collaboration not only reveals secrets of magic tricks, but can also help to uncover yet-hidden secrets of cognition.

It is important to mention, however, that the trick example used throughout the chapter is only one out of a vast number of options, chosen to fulfill the constraint of conveying a trick in words and on video without the option of live audience interaction. It is meant to illustrate the basic principle of time misdirection, the concept of fake causal attributions, and the importance of timing for the effect gestalt and magic moment. These principles obviously also apply (albeit in altered forms) to other types of magic, be it large stage illusions or more abstract, nonvisual mental effects, like the illusion of mind reading, predicting the future, or impossible coincidences.

As Maskelyne mentioned over a hundred years ago, there is both art and science in magic, although as a creator and performer together with David Devant, he cared mostly about the art in magic: "Then, magic being admittedly an art, let us investigate the real nature of the Art in Magic; for, upon that investigation depends the disclosure of the real secrets of magic" (Maskelyne & Devant, 1911).

It is an art whose real secrets, similar to music, dance, or theater, are hidden in the performances of its interpreters, who succeed time and time again in creating the illusion of magic in the consciousness of their spectators, thus celebrating the precious moment in time that is the “specious present,” proving that magic actually is a timeless art.

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14 Subjective Duration in the Laboratory and the World Outside

John Wearden, Alan O'Donoghue, Ruth Ogden, and Catharine Montgomery

This chapter deals with the topic of *subjective duration*, defined as judgments of various sorts about how long stimuli and events last, or judgments about how fast time seems to pass. Studies of subjective duration have formed the major part of the study of time perception by psychologists (see Fraisse, 1964, for example), although duration judgments are only part of the broader psychology of time, encompassing as it does such things as judgments of temporal order, as well as the study of rhythm perception and production.

The literature on the perception of duration is far too voluminous to be reviewed here, but fairly recent discussions of some aspects of duration judgments are to be found in Wearden (2003) and Wearden and Lejeune (2008), as well as edited volumes such as Meck (2003) and Grondin (2008). Readers interested in the early history of research on duration perception might also read Lejeune and Wearden (2009).

This chapter is intended to discuss some studies of duration judgment in situations intended to mimic aspects of real-life situations, although data come from rather artificial laboratory experiments or results obtained from questionnaires posing questions about time experience in ordinary life. Its principal ideas may be briefly summarized as follows: (a) there are two fundamentally different sorts of questions that can be asked about subjective duration, and these concern *duration judgments* (questions about how long some stimulus or event appeared to last) and *passage of time judgments* (questions about the phenomenal "speed" of time during some event); (b) both duration judgments and passage of time judgments can be based on either *direct experience* of the event judged, or some kind of *inference* about the event, which may not involve the same direct experience of time, in the sense that attention was not paid to time during the event.

Lack of clarity about what people are doing when they make different sorts of duration judgments (in particular when verbal responses are obtained from participants) is a major source of confusion in the field and can lead to pseudo-problems where common explanations are sought in vain for what are probably quite different phenomena, as well as a pervasive lack of focus about what is being discussed. Particularly confusing is the question of what people mean when they say that "time flies" or "drags," and what the implications of this are for measurements of subjective time. The case of "flying" time could mean that duration estimates are systematically changed compared with some control condition, although it is unclear what the exact prediction would be if "time flies" during some interval. Would the estimate of the interval duration be longer if "time flew," or shorter? If time "goes faster" during some event, is there "more time" in the event (so judgments are increased relative to a control condition), or is the event shortened in time, just as journey time is shortened if we go faster?

Adding to the confusion is what the implications are of time judgments being based on some clocklike mechanism that can "tick" at different rates. To strip internal clock theory down to its simplest, suppose that the estimated duration of some event is ordinally related to the number of "ticks" that occur in it: more ticks therefore give rise to longer estimates. The effect of increasing the rate of ticks ("clock speed") would be to increase duration estimates (as more ticks accumulate than before), so external stimuli would seem to last longer, presumably giving rise to the sensation of time "dragging." So, if the clock "speeds up," perceived time would appear to "slow down," and the reverse is also true of clock slowing: slower clocks make events seem shorter, so (at least presumably) give rise to time "speeding up" (see Penton-Voak et al., 1996 and Wearden, 2008a). As will be seen later, however, estimates of duration in laboratory situations can often be changed without any apparent change in the passage of time at all.

Perhaps statements that "time flies" or "drags" are best related to passage of time judgments rather than duration judgments. Here, the implications are at least clearer: presumably, by definition, the statement that "time flies" is a statement about the feeling of passage of time (feelings that can be quantified, as will be seen later). The question then arises of what the relation is, if any, between differences in passage of time judgments in different situations, and changes in duration judgment, and this question will be addressed in a later section.

Another definitional issue is that we need to address what we mean by "subjective" in subjective duration. To us, the situation is simple: *all* psychological judgments of stimuli and events are subjective, whatever the unit the judgment is expressed in (ranging from physical units like milliseconds for duration, which seem to confuse some people into thinking that these time judgments are in some way "objective," to ratings of the beauty of film stars and models). All involve some kind of translation of a physical stimulus into something internal, a *psychophysical process*, as Fechner described in his *Elements of Psychophysics,* 1860, section VII, "The Measurement of Sensation," in Langfield's (1912) translation; see Herrnstein and Boring (1965, pp. 66–75).

> It must be remembered that the stimulus does not cause sensation directly, but rather through the assistance of bodily processes with which it stands in more direct connection. The dependence, quantitatively considered of sensation on stimulus, must finally be translated into one of sensation on the bodily processes which directly underlie the sensation—in short the psycho-physical processes; and the sensation, instead of being measured by the amount of the stimulus, will be measured by the intensity of these processes.

In addition to the issue of what "subjective duration" means in timing studies, there are further distinctions that are useful. A particular complexity of time perception research is that judgments (both of duration and passage of time) can be based on *direct experience* or on *inferences*. In the first case, people actually appear to experience the passage of time directly, and in the other case something intrinsically nontemporal is used to make duration judgments. This interacts with the well-known distinction between *prospective* and *retrospective* timing. The terms "prospective" and "retrospective" are somewhat confusing to readers outside the time perception field, since they do not involve differences in *when* the time judgment is made: almost all time judgments are made retrospectively, when all or part of some event has elapsed. The distinction refers, rather, to the instructions given to participants before the study begins: in *prospective timing* people are told that the task involves time judgment (e.g., "hold down this button for one second," "when the tone finishes tell me how long it lasted"), whereas in *retrospective timing* people are asked to perform a task, with time not being explicitly mentioned, and then at the end of some time period they are, unexpectedly, asked how long the period has lasted.

It is tempting to map the "experience-inference" distinction directly onto the "prospective-retrospective" one and to conclude that prospective timing is based on *experienced* time, and retrospective timing based on *inferences* about nontemporal "information" processed during the event judged, but this would only be partially true. Prospective duration judgments in the sense defined above can be based on inferences: for example, a person could be asked to give a series of estimates of the time needed to travel between pairs of places (so they know in advance that time judgments are required, thus the time judgments are prospective by definition), but use distance to make the judgments. Indeed, people can estimate the time needed to go from A to B, possibly quite accurately, without having been to either place. Retrospective duration judgments, on the other hand, are certainly almost always inferences of some sort, as the instructions given for the task did not involve any requirement to "pay attention" to time.

It might also appear that passage of time judgments are based on experiences, the idea that people "feel" that time is passing slowly or quickly, so passage of time judgments are based on phenomenal experience of time passage. This is almost certainly true in many or most cases, but passage of time judgments can also be based on inferences. A person may believe that "time passes quickly when you're enjoying yourself " (more on this later), so an enjoyable period may be *assumed* to have passed quickly, yet the person in fact may not have experienced the passage of time as fast or slow during the time period in question.

We should admit at the outset that this brief discussion of types of timing does not exhaust the domain of judgments that people can make about duration, and some others are mentioned later. Neither is the "experience-inference" distinction entirely unproblematic; for example, a person will still have some phenomenal experience of time when in a retrospective timing experiment, even though time does not appear to be the focus of interest of the study from the person's point of view. A more detailed discussion of these matters could, however, occupy this entire chapter, and may try the patience of readers. Rather, we attempt to wrestle with some of the questions about how duration judgments and passage of time judgments are made by reference to empirical data.

How are duration estimates and passage of time judgments related? In some cases, marked differences in duration judgments may not be accompanied by any feeling that passage of time differs between the conditions compared. Figure 14.1 shows an example. This shows verbal estimates (in ms) of the duration of auditory and visual stimuli (tones and squares of color on a computer screen, respectively). Durations actually ranged from 77 to 1183 ms, and people were asked to use a scale where "1000" = 1 second. The upper panel shows results obtained when people received either visual or auditory stimuli, and the lower panel the effects of receiving both, so essentially the study replicates the main results of Wearden, Todd, and Jones (2006) that auditory-visual differences can be manifested when verbal estimation is used, even when different groups receive the stimuli to be judged. For present purposes, the important result is that the very marked difference in prospective duration judgments is not accompanied by any feeling of difference in the passage of time: auditory stimuli do not seem to "rush" or "drag" compared with visual ones. Other examples of this are the effects of "filled" versus "unfilled" intervals (e.g., Wearden et al., 2007), or the effect of click trains on subjective duration. It has been known since Treisman et al. (1990) that click trains can make both auditory and visual stimuli seem longer. For example, Penton-Voak et al. (1996) found that both auditory and visual stimuli were estimated as lasting longer when preceded by a 5 second train of clicks than without clicks, a result replicated in a number of studies since (e.g., Wearden et al., 1998). Work by Jones, Allely, and Wearden (2011) has shown that the click trains can enhance performance on reaction time and memory tasks, possibly by giving people "more time" to perform the tasks required, although that is not the only possible explanation of the effects obtained. In no case, however, was the change in performance, whether a time judgment or something else, accompanied by any sensation that the passage of time had been changed by the clicks.

In contrast, there are situations, some to be described later, where passage of time changes between conditions, but duration estimates are unaffected. Wearden (2008b) reported one such effect, in which instructions to process a film clip differently changed passage of time judgments but had no effect on duration judgments, and everyday life furnishes other examples. A person may be in a queue in a supermarket with a clock visible. There is no ambiguity as to the actual time elapsed, so duration estimates would be 100% accurate if required, yet the passage of time experience may be different from the same known time period spent in some more enjoyable activity. The relation between the "content" of time intervals, how the duration is estimated, and passage of time experienced is discussed in more detail later.

14.1 Retrospective Timing and Passage of Time Judgments

In the world outside the laboratory, people have many potential cues that they can use to judge duration, such as the events occurring during time periods, distances traversed, and

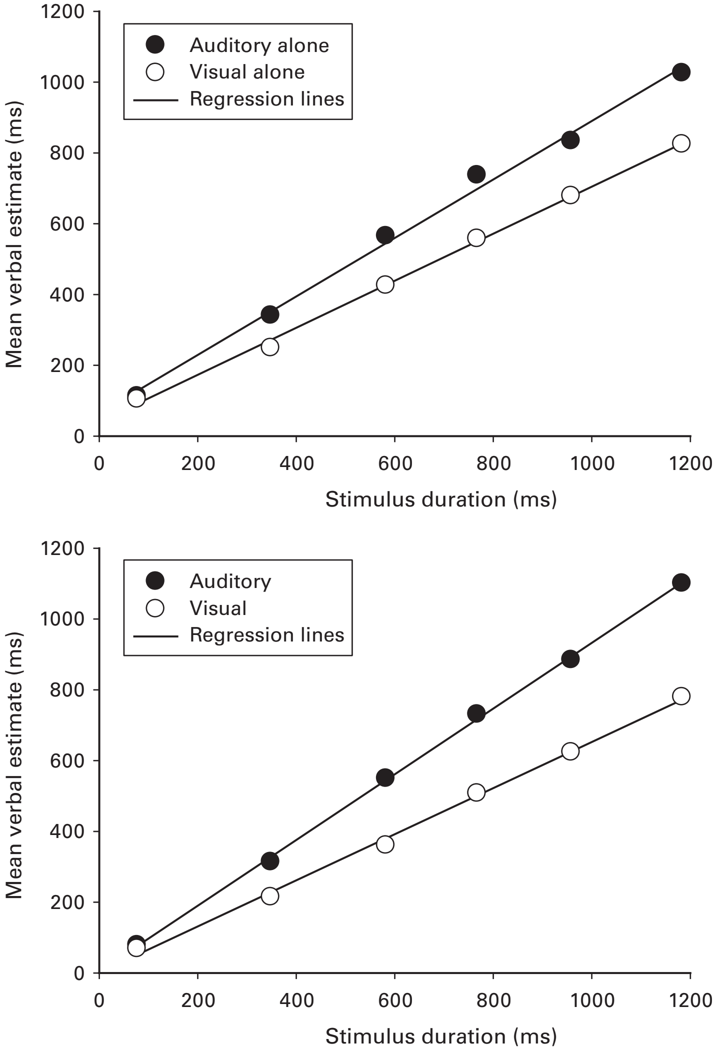

Figure 14.1

Upper panel: Mean verbal estimate (in ms) plotted against stimulus duration for judgments of the duration of auditory and visual stimuli in conditions where participants received either auditory or visual stimuli. Lower panel: the same measure from participants who received intermixed trials with auditory and visual stimuli.

so on. The common use of such cues suggests that many real-world duration judgments might be largely retrospective in nature, which is not to deny that the "deliberate" timing of events is something that people do in some circumstances in their everyday lives. In addition, many statements about time experiences in real life, such as those related to time passing quickly or slowly, at parties or in queues, seem more closely related to passage of time judgments than duration judgments of any sort, either retrospective or prospective. These considerations lead us to the conclusion that attempts to investigate phenomena related to outside-world timing in the laboratory might be more usefully focused on retrospective timing rather than prospective timing (although studies of prospective timing are overwhelmingly common in the timing literature), and that passage of time judgments might also form a fruitful area of research. Unfortunately, both retrospective timing and passage of time judgments have received relatively little previous research compared with prospective timing, so we will try to fill the gap with some studies of our own, which, alas, are not sufficiently extensive to investigate all the issues of interest. We start with some discussion of the differences between prospective and retrospective timing, and then move on to some of the factors said to influence both sorts of judgments.

Many studies have indicated fundamental differences between prospective and retrospective timing. For example, Hicks, Miller, and Kinsbourne (1976) used a card-sorting task in which cards contained varied amounts of information. Judgments of the duration of the entire task were made under either prospective or retrospective conditions. Hicks et al. (1976) found that, under prospective conditions, the more information processing was involved in sorting the cards, the shorter the duration estimate, but no effect of information-processing load was found for retrospective judgments.

A common idea (e.g., Ivry & Hazeltine, 1992) is that prospective time judgments involve "timing with a timer"; that is, they are based on the operation of some timing-specific mechanism, such as an internal clock. In contrast, retrospective timing involves "timing without a timer," where the time judgment is not based on the activation of timing-specific mechanisms, but instead derived from something else. So what are retrospective duration estimates based on?

Ornstein (1969) with his "storage-size hypothesis" suggested that the amount of information stored in memory since a given start point can be used to produce a retrospective time estimate. So, for example, the more information processed during a time period, the longer the retrospective duration judgment of that period. However, Block and colleague (Block, 1982; Zakay & Block, 2004) have proposed that varying the level of information processing in a time period affected only prospective judgments, and that retrospective timing judgments were based on the amount of cognitive "contextual changes" (e.g., changes of environment, mood, task type, and shifts of cognition) that occur. This contextual-change hypothesis has gained support from a number of studies. For example, Zakay and Block (2004) showed that a task involving resolving syntactic ambiguity shortened prospective estimates, whereas retrospective estimates were lengthened, a result Zakay and Block (2004) suggest is due to contextual changes arising while solving the ambiguity. Likewise, when carrying out a task-switching procedure, prospective estimates remained unaffected, while retrospective durations were lengthened.

The claim that the amount of “information processing,” “memory storage,” or “contextual change” is used to make duration judgments in retrospective conditions sometimes receives striking confirmation in experimental data. The upper panel of figure 14.2 shows an example from research conducted at Keele University. People made verbal estimates of a 181-second interval either in two retrospective (conducted first) or two prospective conditions. The conditions differed only in the amount of “information processing” required. The task was always the same: the participant received a display containing the numbers “0” to “9” arranged in a 3 × 3 matrix, and had to identify which number was missing. In the low information-processing condition, the numbers were arranged in numerical order, while in the high information-processing condition the numbers were in random order, which made finding the missing number subjectively much more difficult and took longer. The upper panel shows mean verbal estimates: here, the prospective estimates were significantly longer overall, but there was a just-significant interaction between information-processing load and timing condition. A higher information-processing load made the retrospective estimates longer, but the prospective ones shorter. In contrast, passage of time judgments (on a scale from 0 to 100, where higher numbers mean faster) were not affected by the timing condition (prospective or retrospective), but were significantly faster in the high information-processing condition.

The data on duration judgments replicates work by Block (1992) that information-processing load had different effects on retrospective and prospective timing, lengthening estimates in the former case and shortening them in the latter. The effect of information-processing load on passage of time judgments was significant, but did not depend on timing condition, illustrating a dissociation between duration judgments and passage of time judgments similar to that noted elsewhere (e.g., Wearden, 2008b, who reported manipulations that changed passage of time judgments but did not affect retrospective duration estimates at all).

The finding that “more information processing” increases retrospective duration estimates is in line with most previous work (see Block, Hancock, & Zakay, 2010 for a review) but, alas, other data from our own studies suggest a more complicated picture. A well-known manipulation in memory studies is “levels of processing” (Craik & Lockhart, 1972). The basic idea here is that the same verbal material can be processed to different levels of “depth.” For example, a judgment might be “shallow,” such as deciding whether a word presented is in upper or lower-case letters, or might be “deep,” such as deciding whether the word is the name of an animal. The first of these is supposed to engage only superficial visual processing, the latter a deeper, semantic processing. The normal finding from such manipulations is that the words are remembered better after “deep” (e.g., semantic) processing, a finding so robust as to be a standard manipulation in psychology laboratory classes.

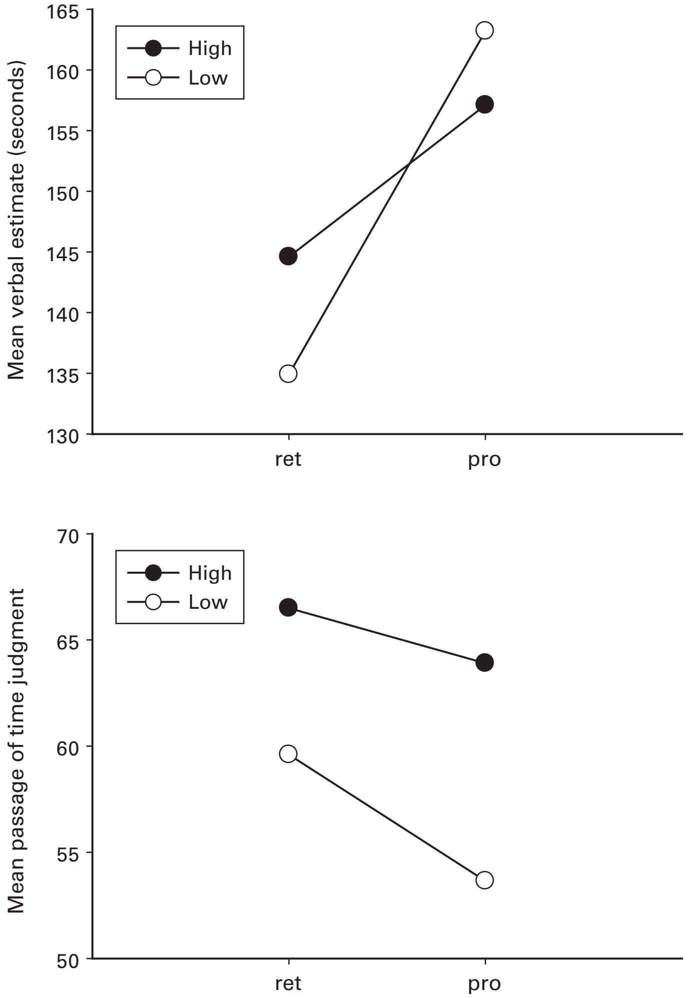

Figure 14.2

Upper panel: Durations estimates (in s) from retrospective (ret) and prospective (pro) duration judgments, under conditions of high and low information-processing load. Lower panel: Passage of time judgments from the same condition. The scale runs from 0 (slowest possible) to 100 (fastest possible), with 50 as "normal."

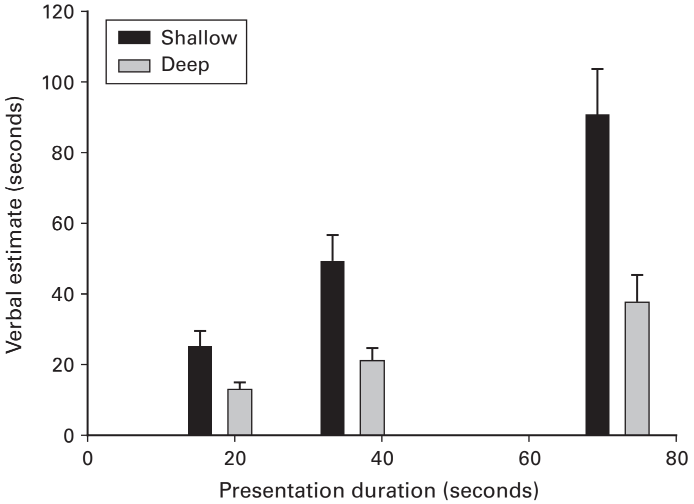

Figure 14.3
Mean retrospective time estimates (in s) of word sequences lasting 18, 36, and 72 s. Different groups received shallow (graphemic) or deep (semantic) processing of the letters. Vertical bars show standard error of the group mean.

Given that, almost by definition, semantic processing is "deeper" than processing the superficial appearance of words, this manipulation was used in a retrospective timing task. Participants received three series of words lasting 18, 36, or 72 seconds. Then, after all three had been presented, the participant had unexpectedly to judge how long each series had lasted. Different groups received either "shallow" processing of the words (upper- or lowercase), or a "deep" processing condition involving identifying whether each word was the name of an animal. Results from the duration estimates are shown in figure 14.3. Obviously, estimates were much shorter in the deep processing group than the shallow one: there were significant effects of event duration (18–72 seconds), group (shallow and deep), and an interaction between the two, suggesting that the between-group difference increased as the word series got longer. Here, we appear to have a result contrary to expectations: the form of processing that is defined as deeper (and presumably thus involves more information processing) produces retrospective estimates that are much shorter than the shallow processing.

A replication of this study produced similar results, and additionally included passage of time judgments. As in other studies (Wearden, 2008b), longer events were associated with slower passage of time, but there were also effects of processing type. For the 18 second sequence, passage of time was judged slower with deeper processing, whereas for the 72 second sequence the deeper processing produced relatively *faster* passage of time judgments. Once again, therefore, passage of time judgments and duration judgments seem to be dissociated: events can differ significantly in reported passage of time, while being virtually identical in judged duration (Wearden, 2008b), and faster or slower passage of time can be associated with longer or shorter duration judgments.

Another experiment attempted to manipulate both information-processing load and contextual change in combination. Participants received displays of letters and were directed to activate a counter every time they saw an E (low information-processing condition), or either an E or A (high information-processing condition). To produce differences in contextual change, letter strings were either presented in white on a black background (low contextual change) or alternated between white letters on a black background and green italic letters with a green box surround on a black background (high contextual change). These two manipulations have considerable face validity. It seems true by any reasonable definition of information processing that searching for two letters involves a higher load than searching for one. In addition, the manipulation of letter color, letter font, and background color has been a standard manipulation in studies of context-dependent memory. Thus, in terms of current understanding of "context," our different conditions involve different amounts of contextual change.

Figure 14.4 shows duration estimates (upper panel) and passage of time judgments (lower panel) from the different conditions. There were no significant effects on retrospective duration judgments of either information-processing load or the contextual change manipulation, nor any interaction between the two. In contrast, passage of time judgments were significantly higher when information-processing load was greater, but there was no effect of contextual change, nor any interaction with contextual change. The effect of information-processing load on passage of time judgments is, of course, the same effect as shown in figure 14.2.

The results shown in figures 14.2, 14.3, and 14.4 come from a much larger series of studies of retrospective timing and passage of time judgments carried out over the last few years in the first author's laboratory, and their results are depressingly representative of those obtained more generally. Attempts to manipulate retrospective duration judgments by changing the content of the period to be judged sometimes produce significant effects (figure 14.2), and even, on occasion, dramatic differences between conditions (figure 14.3). On the other hand, as Wearden (2008b) showed, some manipulations produce little or no effect on duration judgments, even though these seem to clearly involve differences in the amount of "information processing" or "contextual change" between conditions (e.g., figure 14.4). The factor that does reliably manipulate retrospective duration judgments is, of course, the actual duration of the events timed. Although judgments may not be accurate, they are invariably sensitive to differences in real duration. There is no doubt that participants are exhibiting sensitivity to actual duration in retrospective timing studies, so they must be basing their judgments on *something* that has occurred during the interval, but discovering exactly what they are using is proving difficult, in spite of the fact that previous theory sometimes works well (e.g., figure 14.2). An obvious problem is defining what exactly is meant by "information processing" or "contextual change." Results from our experiment

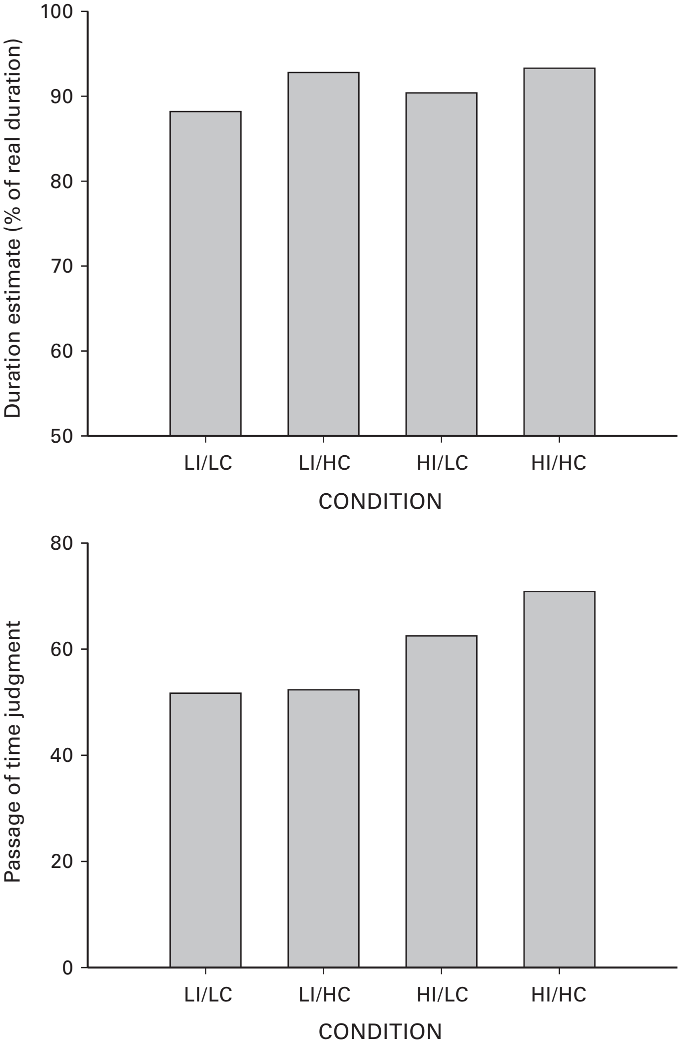

Figure 14.4

Upper panel: Retrospective duration estimates (percent of real duration) from four different conditions: LI, low information load; LC, low contextual change; HI, high information load; HC, high contextual change. Lower panel: Passage of time judgments from the same conditions. The scale runs from 0 (slowest possible) to 100 (fastest possible), with 50 as "normal."

show that increasing information-processing load by making the same task more or less difficult, or varying the "depth" of processing, which presumably change processing type, do not have equivalent effects on retrospective timing.

On the other hand, passage of time judgments appear very sensitive to content of the events timed. We have found that if film clips are used, clips judged as more exciting almost always receive "faster" passage of time judgments than boring ones, although effects on duration judgments are unpredictable (sometimes exciting clips are judged as relatively longer, sometimes shorter, with no effect often being found). Passage of time judgments seem to be affected by hedonic qualities of the events experienced, with more pleasant-exciting-involving events being associated with faster passage of time. So, it appears that "time flies when you're having fun" (or at least the fun that laboratory experiments can provide), but this does not translate reliably into judgments of duration. We return to this question later, in a discussion of the way in which "time flies" outside the laboratory.

Another experiment attempted to explore potential correlates of passage of time judgments, but in addition tried—so far as we know for the first time in an experimental study—to try and capture what might be described as "feel judgments." "Feel judgments" reflect the common situation that events "feel" longer than a person knows them to be. So, in response to the question, "How long were you in the queue for?" a person might reply, "Only five minutes, but it seemed a lot longer." The five-minute duration estimate might be retrospectively or prospectively produced or might come from observation of a clock, so can be completely accurate, but something about the experience of this particular interval is conveyed in the answer.

The experiment attempted to capture "feel judgments" by presenting the same film clip (which lasted 150 seconds) four times. The first duration judgment was retrospective, the subsequent ones presumably prospective, but, as the upper panel of figure 14.5 shows, this judgment hardly changed at all (and did not change significantly) with repeated viewings. This is perhaps only expected, as the events repeated were identical. On the other hand, when people were asked how long the interval "felt," judgments significantly, and very markedly, increased with repeated viewings. Obviously, from a single experiment it is difficult to be absolutely sure what is being measured, and further work is needed, but the commonplace dissociation in real life between how long a person knows an interval to be and how long "it feels" clearly transfers to a laboratory study, and what this dissociation actually means might be elucidated by further work.

The center panel of figure 14.5 shows passage of time judgments for the repeated viewings, with lower values indicating slower passage of time, as well as judgments of how much attention was paid to the clip, with lower values indicating "less attention." In accord with intuition, both measures decreased with repeated viewings, so changes in the "feeling" of duration were associated with ratings of slower passage of time and decreasing attention. The lower panel shows ratings of how much participants enjoyed or liked the film, how exciting they thought it was, and how it engaged, bored, or annoyed them. Once again,

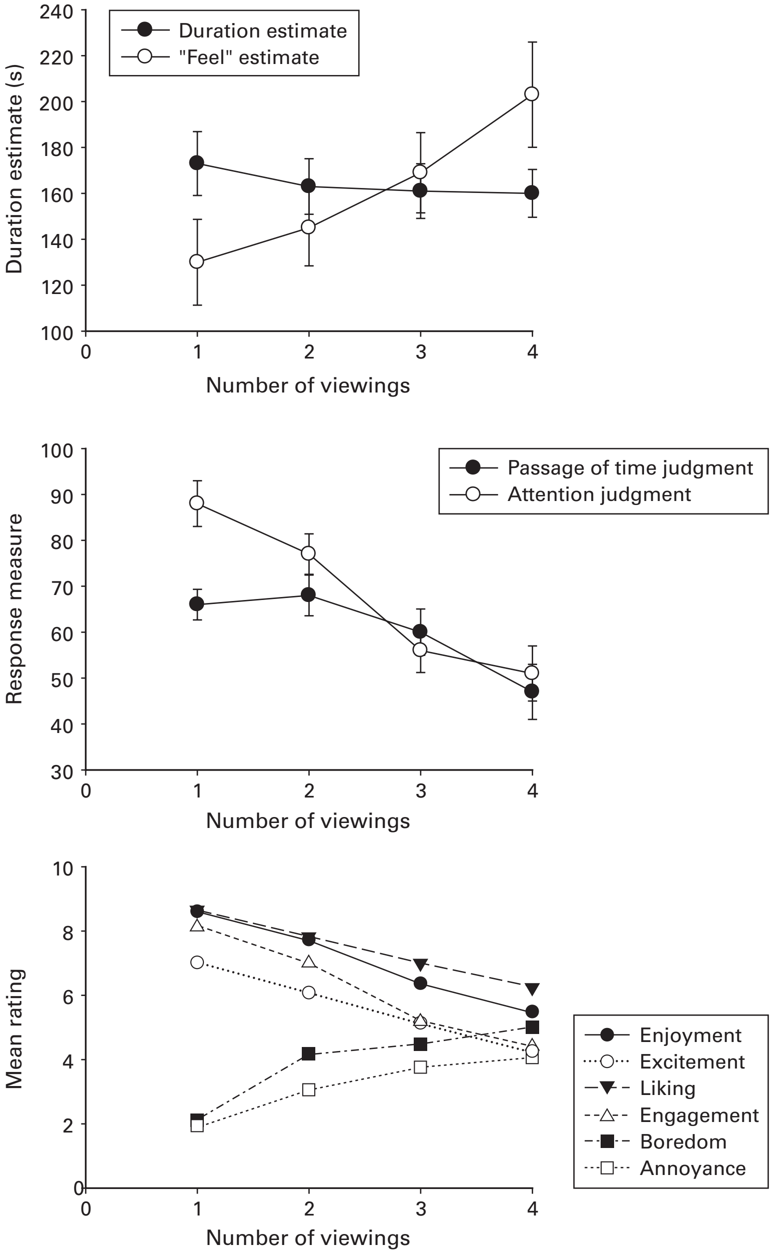

Figure 14.5
Upper panel: Duration estimates and “feel estimates” (in s) as a function of repeated viewings. Center panel: Passage of time judgments, and ratings of attention paid. Scale runs from 0 (slowest/least) to 100 (fastest/most). Lower panel: Ratings of enjoyment, excitement, liking, engagement, boredom, and annoyance as a function of repeated viewings. Scale runs from 0 (least) to 10 (most).

higher scores indicate more of the quantity rated. Boredom and annoyance increased with repeated viewings, whereas "positive" ratings decreased, and ratings on all scales changed significantly over repeated viewings.

The data in the lower part of figure 14.5 show similar variation in passage of time judgment and hedonic features of the participant's experience, and this fits with the common notion that hedonically positive events are the ones for which "time passes quickly," although the "time" that is affected appears to be passage of time judgment, rather than retrospective duration judgment, which has little systematic relation to event content, at least in our studies.

The "feel" experiment also shows ways in which laboratory studies can be designed to try to capture aspects of real-life time experiences, which may not simply relate to judged duration. How validly the procedures used in these experiments capture aspects of real-life time experiences is hard to judge, but they represent a transition between "psychophysical" studies of duration, usually involving very simple stimuli such as tones or patches of color, and investigations that try to find what people report happens in "real life," and it is to a study of this type that we now turn.

14.2 Time Outside the Laboratory: When Does "Time Fly" or "Drag"?

In one of the few studies of passage of time judgments, Flaherty (1991) suggests that "extraordinary circumstances make for abnormal temporal experiences" (Flaherty, 1991, 77). Flaherty examined 326 narratives taken from popular biographical books and 316 stories taken from undergraduate students during interviews, and focused on incidents in which subjective time appeared to pass more slowly than objective time. Data from the narratives and the interviews were coded according to whether they were higher or lower in complexity than "average" activity: 41.1 percent of descriptions contained reference to a lower than average level of complexity, and 58.9 percent referred to situations of higher than average complexity. No descriptions reported a slowing of the passage of time under normal circumstances. Flaherty concluded that there was a U-shaped relationship between the level of stimulus complexity and the passage of time, with both extreme complexity and low levels of complexity leading to a slowing in the passage of time.

We recently conducted a study rather similar to Flaherty's, and in our work real-life time experiences were obtained using an anonymous web-based questionnaire in research conducted at Liverpool John Moores University. A total of 203 undergraduate students participated for course credit. The questionnaire involved three structured sections asking questions about passage of time after (a) drug consumption, (b) common activities, and (c) psychological states. In addition, an open-ended question was also posed to allow participants to describe an occasion in which they had experienced a distortion in the passage of time. Participants who had reported taking drugs within the last year were advised to describe a situation in which drugs or alcohol had been consumed wherever possible. For example, In the box below please describe a situation in which time appears to have elapsed at a different rate to normal (e.g. faster or slower). Please use as much detail as possible, describe what you were doing at the time, how you felt, who you were with and whether you thought that time was passing more quickly or more slowly. Please also indicate which drugs you had taken at the time.

Responses to this question were analyzed using content analysis by two researchers. Analysis focused on reports of drug use, activity, emotion, and the direction of temporal distortion (fast or slow) within the participants' descriptions.

The upper part of table 14.1 shows the frequency with which participants reported time passing more quickly and slowly under drug-taking conditions. Examination of the data suggests that distortions in which time passed more quickly than normal were more commonly

Table 14.1

Drug	Time passing more quickly	Time passing more slowly
Alcohol	74*	6
Cannabis	9	12
Cocaine	14	0
MDMA	9	5
Ketamine	1	2
Poppers	1	2
No drug taking mentioned	32	35
Activity	**Time passing more quickly**	**Time passing more slowly**
With friends or family	58*	5
Alone	0	2
Busy	12	0
Bored (at work)	0	25
Partying (e.g., at a nightclub)	63*	6
Emotional adjective	**Time passing more quickly**	**Time passing more slowly**
Afraid	7	13
Anxious or stressed	46	58
Aroused	12	12
Bored	2	181*
Busy	149*	3
Concentrating	79*	15
Distracted	46	34
Excited or anticipating	55	31
Happy	103*	10
Intoxicated	37	9
Sad	5	71*
Tired	17	117*

reported than distortions in which time passed more slowly than normal. In particular, alcohol and cocaine intoxication appear to be associated with increases in the passage of time. When drugs were not consumed, or cannabis or MDMA were consumed, increases and decreases in the passage of time appeared equally likely. Among the qualitative reports were:-

> Time flies when I'm out with friends either drinking or had some coke. Dancing, chatting. Next minute you know, it's 3 a.m.

Of respondents who reported having taken drugs, 66 percent agreed that distortions occurred more frequently when under the influence of drugs than when not.

The middle part of table 14.1 shows the frequency with which different activities were reported in participant descriptions of an event in which time was distorted. Examination of the data suggests that time passing more quickly than normal was associated with being around friends and being at parties. Both of these activities were also consistently reported in conjunction with alcohol consumption. Time passing more slowly was associated with being bored at work. There were statistically significant associations between being with friends or family and increases in the passage of time, and being at parties was also associated with increases in the passage of time. As one participant reported:

> When at work and very busy time seems to fly really quickly, or when at work and not busy at all, time goes really slow and I seem to be working forever.

The lower part of table 14.1 shows the percentage of responses in each category to the question, "When time passes more quickly/slowly I am generally (tick up to 3 responses)." Examination of the data reveals that participants associated slower passage of time with boredom, sadness, and fatigue, whereas an accelerated passage of time was associated with busyness, happiness, and concentration.

With respect to effects of drugs, the study examined what people said the effects of drugs were, rather than measuring actual pharmacological effects, as in a laboratory study. With respect to alcohol, this was almost always consumed in social situations, as one participant noted:

> Alcohol consumption seems to lead to time speeding up—possibly due to the fact that I am socialising at the same time and therefore having fun.

In laboratory studies, effects of alcohol are varied and complex and do not generally support the idea of time "speeding up" (e.g., longer duration estimates). A study by Ogden et al. (2011), which also provides a review of the literature on alcohol and time perception and is one of the few to examine passage of time judgments after alcohol administration, did, in fact, find faster passage of time judgments when participants were mildly or more moderately intoxicated, although there was no effect on retrospective time judgments, and effects on prospective time judgments were complex. In general, then, reports of associations between real-life time experiences and drug states may not always correspond with effects obtained after laboratory administration of the drug. Obviously, there could be many reasons for this, such as events in the environment in which the drugs are consumed, and the fact that participants know they have taken the drug.

An important aspect of the reports of passage of time in real-life situations was that anecdotes often strongly suggested that the reports were based on *inferences*, sometimes involving clock-measured time, rather than direct experiences. For example,

> After taking cocaine with 2 friends and sitting round her house after a night out which ended at approximately 3am, it seemed to all of a sudden be 7am, so therefore time had passed quicker than I thought it had.

or

> When I have consumed alcohol time passes quicker. I no longer take note of time. I generally only become aware of the time when the bar/pub I am in begins to close or someone around me makes me aware of what time it is.

These reports suggest that the judgment of rapid passage of time is occasioned by an external time marker (a clock, or the pub closing), which prompts the person to then make the judgment that time has passed quickly. Before that, they had no "sensation" of rapid time passage, and may have been not have had any clear sense of time at all, as in one report:

> After consuming alcohol, time has gone a lot faster when I have been in a nightclub and having a lot of fun from really enjoying all the music being played, concentrating only on having fun and dancing, and not what time it is.

The role of external time markers in people's judgments of passage of time, or "feel judgments," which may be closely related, is an under-researched area. All of us have had the experience of being engrossed in some activity (reading, for example), then looking up at a clock and thinking "Is it x o'clock already?" This question implies a discrepancy between clock-measured time and something else, and this may be responsible for reports of "abnormal" passage of time. There are few data on what happens in these situations. Our qualitative reports suggested that reports of "fast" passage of time were usually inferences (as in the examples above), where people had not actually experienced anything particular about time or paid attention to elapsing time at all during the event reported. On the other hand, reports of "slow" passage of time seemed to be based on direct experience, as in

> Time appeared slower, in work, on a really quiet day with hardly any customers, only two other staff members, really bored.

Here, the participant seems clearly to be reporting some phenomenal effect of "slow time" that is actually experienced during the event. Some caution is obviously necessary in interpreting anecdotes from a single study, but one possibility is that real-life time experiences can involve asymmetries. When "fast time" is reported, the report is generated on the basis of an inference, often prompted by an external time marker, without any actual "feel" of fast time during the event. In contrast, "slow time" seems to have been directly experienced during the event itself. Obviously, further research on what happens when judgments are made about temporal aspects of real life events is warranted.

14.3 Discussion and Conclusions

Psychological judgments made in real life are complicated. The stimuli that people perceive are highly complex compared with some of the material used in psychological laboratories, and may be multidimensional in ways that make different stimuli hard to directly compare. Judgments of all kinds of psychological quantities, from duration to attractiveness, may be influenced by the current actions and emotions of observers, to say nothing of individual differences in previous experiences, biases toward certain sorts of responses, or differences in preference for one thing over another. The complexity of real life provides an excellent reason for experimental psychologists to avoid it, yet in order to explore what people experience about time in everyday life, we need to find some way of bridging the gap between psychophysical laboratory studies and events in the "real world."

A particular problem is that statements about real-life time experiences may not in reality be based directly on experiencing the event reported. When people say that "time passes quickly when you're enjoying yourself" they may, as shown above, be reporting the results of an inference based on information received from a clock or other externally timed events. Likewise, does time pass more quickly as you get older? Studies of timing in normal individuals older than students has found rather small effects of aging on performance on timing tasks (e.g., Wearden, Wearden, & Rabbitt, 1997; Wearden, 2005), and larger effects that are found (e.g., Craik & Hay, 1999) may have unspectacular causes, such as slowing in the rate of counting as people age. Perhaps the reported "speeding up" of time in the elderly is mostly an inference: when some external timing signal is received from a clock or a television program, the person infers that the day has flown by, possibly because of discrepancies between the events that they have done, or remembered, and the time cued by the external time marker. In terms of moment-to-moment time experience, older people may experience a slowing of time, just as responses in older people are often slowed by aging.

Research that is intended to help us understand real-life time experience may need methodological developments beyond increasingly sophisticated forms of tasks originally used for psychophysical prospective timing studies. What people say about time is, after all, a behavior like any other, and may not necessarily be unmeasurable objectively, or unreliable from one measurement to another. However, we do need to ask the right questions, and to develop the tools to answer them.

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VI Intersections: Timeless Philosophy and Timely Experiment

15 Subjective Time: From Past to Future

Valtteri Arstila and Dan Lloyd

It is in my own mind, then, that I measure time. I must not allow my mind to insist that time is something objective.
—St. Augustine

15.1 Introduction

It is natural to think of passing time as a kind of motion. But in this metaphor, what moves and what does not? With respect to the river of time, do you stand on the bank and watch time flow by? Or are you floating in the river, flowing along with time as it passes by the landscape? In the chapters preceding, we saw a distinction in metaphorical framework that deepens the rift between retentionalism, extensionalism, and cinematism. Interpretation one: the objects of perception move past a fixed Now. (You stand on the riverbank of the stream of time.) For example, gazing upstream toward the future, you foresee the upcoming weekend. The weekend ahead is presently a certain distance away, but it approaches as the hours go by, looming, arriving, and parading through your experience. Then it is Monday again, and the weekend slowly recedes into the distance. Interpretation two: Your personal Now moves through a fixed terrain of objects and events, floating in time's stream through a landscape of events. The weekend ahead is a fixed point in time, found on the embankment ahead. As the hours pass, you draw closer to it, arriving at the threshold Friday night. Two days later you depart for Monday, inching along the time line of your life.

Phenomenology recommends a "bracketing" of objective reality, a suspension of belief in the reality of things outside of conscious awareness. So it is not surprising that Husserl understands temporality via interpretation one. The protention–primal impression–retention structure is fixed, a *nunc stans* or "stationary now." As Husserl (chapter 4, section 4.4.) puts it in the C manuscripts:

> Thus, in *toto*, there is constituted a fixed continuum of form in which the primal now is a primal welling middle point for two continua taken as branches of the modes of [temporal] modifications: the continuum of what is just-past and that of futurities. This is a lasting and remaining form-continuity for what streams through it.

The same thought is more vivid in James (chapter 1), commenting on the specious present:

> Its *content* is in a constant flux, events dawning into its forward end as fast as they fade out of its rearward one, and each of them changing its time-coefficient from "not yet," or "not quite yet," to "just gone" or "gone," as it passes by. Meanwhile, the specious present, the intuited duration, stands permanent, like the rainbow on the waterfall, with its own quality unchanged by the events that stream through it.

In the passage, the experience of events is modified continuously. Temporality inflects everything with its relentless progress. In retentionalism, this idea is implemented by referring to the temporal modes of presentation that accompany the experiential contents: each experiential content is presented as something that is either just-past or further past (retended content), occurring now (primal image), or anticipated to occur next or a little bit later (protended content). Furthermore, retentionalists often maintain that the retended contents include the previous protended contents (i.e., we retend what we thought would happen in the near future).

The extensionalist view, in contrast, favors interpretation two. On this interpretation, the Now slides over a time line of experienced events. It is natural to think of these events as fixed, but apprehended from evolving viewpoints, since objects on the stream bank offer a different face to an observer floating by. The diagrams in Barry Dainton's chapter reflect this metaphorical outlook, along with passages like this:

> Take a visual example, and reflect for a moment on what it is like to observe a skier smoothly negotiating a slalom. Focusing on the experiencing of three successive brief phases of the skier's run, which we can label r_1, r_2, and r_3, isn't it evident that r_1 flows into r_2, and that r_2 (and not some copy or facsimile of it) flows into r_3? Doesn't the same apply to the successive brief phases of all directly perceived transitions, in all sensory modalities?

Here r_1, r_2, and r_3 are understood as moments in the slalom run, or in the immediate perception of the run. Each of the three events is self-identical despite the passing by of consciousness. Significantly, in the same way as we immediately experience spatial extension, extensionalism maintains that we experience temporal extension and notice temporal relations among its objects. Hence both extensionalism and retentionalism maintain that the subjectively experienced present is not a punctate phenomenon—it is *specious* present. Adopting *the doctrine of the specious present* means that we accept the idea that there is a "short duration of which we are immediately and incessantly sensible" (James, chapter 2).

The cinematic view also fits smoothly with interpretation two, differing from extensionalism only in the expanse of riverbank available to awareness. Extensionalism allows for looking ahead and back, while cinematism allows only a sidewise glance at the immediately passing vicinity.

The two metaphors express the same underlying reality of subjective time, differing in a figure-ground reversal of the subjective experience of time. Like the examples of trains and embankments introduced by Einstein to explain Galilean relativity, the river and its bank are exchangeable in subjective time. We can regard the riverbank as moving beside a stationary observer, or an observer as moving past a stationary embankment. What differs across the three views of temporality is the metaphorical distance "seen" by subjective awareness. Cinematism blankets the time stream in dense fog, limiting subjective temporal awareness to the most immediately co-occurring events. Extensionalism lifts the fog to afford a little foresight and hindsight, and in retentionalism the fog burns off to a faint haze. Or perhaps there is only clear air in the retentionalist view, and events up and down the river suffer only a loss of detail in the distance.

The poetics do not matter, however, except to argue that the choices among theories of temporality are not necessarily exclusive. The question is not, is there retention or instead a specious extension, but rather, how far does retention extend? Conversely, how broad is the specious present? Husserl favors a long comet-tail of retention-protention, while the extensionalists want it trimmed. Or, using the other interpretation, Husserl favors a wide specious present, while the self-described extensionalists prefer a narrower window, and the cinematists a thin slot. Retentionalism, extensionalism, and cinematism mark a continuum of possibilities.

Although it is customary to emphasize the differences between these positions, if we are correct to fit these theories of temporality together as figure and ground, then the path ahead alters. The correct account of subjective time will depend less on a set of decisive examples (or counterexamples), but become more a matter of preferred boundaries. Retentionalists and extensionalists agree that at short timescales we have a particularly rich awareness of events in temporal relationships to the immediate Now. Within a fraction of a second, we enjoy a window during which we can attend to events perceptually—or so it seems. They also agree that at longer lags a different subjective process engages. We can remember events from last weekend or anticipate the weekend to come, but in neither case would we regard the subjective experiences of memory or anticipation as quasi-perceptions. Retentionalists and extensionalists agree on this as well. Their disagreement, then, concerns the fuzzy edges of the special window of the specious present.[1] Dainton conjectures that it is less than a second. James ventures guesses from a few seconds to a minute, and Husserl might find it to be considerably longer.

These reflections lead to an additional synthesis to consider. Perhaps the retentionalists and extensionalists are both right. Perhaps the features extensionalism finds in the specious present are indeed limited to a subsecond window. Outside of that window, and up to perhaps 20 seconds, something like retention occurs. Beyond that, explicit processes of recall and anticipation anchor the longer time line of experience. As these options proliferate, the need for careful distinctions increases, so we should look again at what is possible and presupposed at different timescales. This means that rather than trying to find some decisive empirical experiment that would refute theories in one of the groups, below we combine philosophical investigations on subjective time with the more detailed and empirically motivated consideration of the temporal phenomena that inspired the doctrine of specious present in the first place.

15.2 The *Explanandum* of Subjective Time: Three Themes

15.2.1 The Duration of the Specious Present

What is the length of the specious present, the interval of which we are "immediately and incessantly sensible"? Different views have been expressed. Dainton (2000) argues for half a second. Lockwood (2005) claims that it is between a second and second and half. Pöppel and Bao (chapter 12), and Wittman (chapter 24) maintain that the duration of the specious present is around three seconds. James, on the other hand, maintained (based on calculations) that the specious present can be even twelve seconds long (and fringes of consciousness could cover up to half a minute). For Husserl, the duration may have been even longer.

Although it is common to regard these as competing estimations of the same phenomenon, a closer look suggests that different theorists hinge their "specious presents" on different phenomena.

Consider the experience of succession, for example. Given that the specious present is supposed to provide us the experience of succession (rather than mere succession of experiences), then the longest interval between the two stimuli when we can still experience succession would determine the duration of the specious present. Dainton (2011) argues that two knocks occurring within a one-second interval are not experienced together.[2] With a half a second interval, an experience of succession can occur. Hence, the experience of succession indicates that the duration of the specious present is at least half a second and less than a second, and that Pöppel, Bao, Wittman, and James are all wrong.

On the other hand, philosophers such as Dainton, Husserl, and Gallagher have maintained that we can directly experience certain durations. What is more, psychologists have studied our ability to track and distinguish different durations by using various methods (such as time estimation, production, reproduction, and temporal bisection tasks) and shown how surprisingly well we can perform in these tasks given that we do not have a sense organ to do it.[3] Wittman furthermore agrees with the mentioned philosophers and maintains that there is a phenomenological differences related to different durations. Importantly, however, based on our performance in the various duration tasks and tasks involving rhythms, Wittman argues that the durations we can feel should not exceed (roughly) three seconds. If this is true, then the duration of the specious present is likely to be closer to Pöppel and Bao's estimations. Consequently, the estimation for the duration of specious present that Dainton provides (based on the experience of succession, not duration) is far too short.

Insofar as the different estimations are based on well-established temporal limits, the following dilemma arises: we use temporal phenomenology to motivate the existence of the specious present and its possible duration, and yet the concept of the specious present cannot explain all temporal phenomenology. Let us assume, for example, that one is shown dot A for 2,100 ms, and 2,000 ms after the onset of A one is also shown dot B, which lasts 100 ms—that is, the sequence ends with B. This scenario creates the following paradox: On the one hand, if we do experience short durations of 3 seconds long, then we have a specious present that embraces the whole interval of the stimuli. On the other hand, we do not have an experience of succession between A and B, which in turn suggests that the specious present does not embrace the whole interval. That is, none of these estimations can provide an explanation for all the phenomena that philosophers of time consciousness have been interested in.

One way to respond to this is to maintain is that there are two different specious presents in play—after all, the specious present is supposed to explain the experiences of succession and duration. This conclusion has the unwanted consequence that the specious present would no longer describe the temporal structure of unified consciousness. In other words, there would not be a single temporal structure of consciousness. Another option is to deny the phenomenology as regards one of the felt temporal phenomena. This would mean that some of the phenomena that have been prominent in the philosophy of time consciousness do not in fact relate to it. Again, such a departure would be unfortunate, and it would mean that virtually all philosophers have been mistaken.

The third alternative, the one that we opt for, is based on the idea that behind our temporal experiences are intra- and multimodal mechanisms that have different temporal characteristics. In this alternative, subjective time is not a unity, at least in the sense that all the relevant phenomena are explainable with one specious present. More concretely, the proposal we want to put forward is the following: the experience of succession (and similarly other phenomena that are likely to occur only in short timescales, such as experiences of change and causality) are indeed explained via a specious present, but one with a short duration. Recall that retentionalists and extensionalists agree that within a fraction of a second, we enjoy a window during which we have a particularly rich awareness of events in temporal relationships to the immediate Now. It is also worth noting that our temporal-order judgments are thought to be due to “some kind of time-organizing system that is both independent of and central to the sensory mechanisms” (Hirsh & Sherrick, 1961, 431). In other words, they are due to mechanisms that are in this respect similar to the postulated temporal structure of consciousness in which all experiential contents are embedded. Thus, it is possible that such a mechanism could account for our experiences of succession. But this short specious present would only comprise part of a larger account of subjective time. What remains to be explained is temporally longer phenomena, beginning with continuity in the stream of consciousness.

15.2.2 Continuity

As we saw above, an instantiation of a one-second-long specious present cannot explain all those experiences that philosophers of time consciousness have been interested in. It is in fact doubtful that they are accounted for even by a specious present that lasts three seconds. To begin with, even though this longer interval is based on various experimental results (e.g., on temporal grouping and segmenting of spoken language), the performance is not particularly decreased in all time perception tasks for longer than three-second intervals—rather, it only concerns duration reproduction (and not, say, temporal bisection or estimation tasks).

Other challenging phenomena include experiences of persistence, hearing a melody, and understanding spoken language. While current philosophers often speak about the first, Husserl was very interested in the latter two. Nevertheless, these phenomena all share the feature that they can easily last longer than three seconds. Kelly (2005), for instance, provides a much-discussed example of the experience of persistence, in which a soprano keeps the high C for a long time. The experience of persistence here is something that evolves when the soprano keeps singing, and it is arguably something that does not evolve in a mere two or three seconds. Likewise, even though melody is constituted by one note following another, melody is not merely a matter of hearing (experiencing) the succession of these notes. Although we hear the notes as separate and succeeding notes, we also hear them as forming a unity, and it is this unity that makes these notes form a melody. Depending on melody, such integration can easily span a longer interval than a three-second period. The same applies to language comprehension, where spoken sentences often last longer than three seconds (even if language is segmented into two- or three-second periods, as Pöppel and Bao claim in chapter 12).[4]

In order for us to have longer and continuous experiences, we need to either be able to keep track of an steady event for long time (experiences of duration and persistence), or somehow form a unity of a temporal object that is composed of parts presented in succession (melody and language comprehension). Such a feat requires continuity in our stream of consciousness.

This continuity has been repeatedly challenged, however. The aforementioned Pöppel and Bao, as well as Wittman, for example, maintain that the three-second temporal integration window is composed of shorter, succeeding moments during which we do not feel as temporally extended (von Baer's moment). For these scientists, such moments are usually determined by the temporal resolution of our temporal-order judgments. That is, one "moment" lasts roughly 30–40 ms, although they also refer to results pointing toward 100 ms. Another, and very recent, way to challenge continuity is by referring to the results showing that the ongoing phase of perception is mediated by attentional sampling that occurs in phases (chapter 8). In particular, the top-down attention-modulated EEG phase was found to correlate with the probability of perceiving a shown stimulus (a brief flash).

These two means of challenging the continuity in our stream of consciousness question it only partially, however. In the philosophical debates, we can distinguish at least three different meanings for the continuity in the stream of consciousness. To begin with, what Dainton (chapter 6) calls moderate continuity ("a stream of consciousness is moderately continuous over an interval of time if it contains experience throughout this interval") can be understood in two ways. First, there is the *objective continuity*, which means one episode of experiencing follows another continuously. In this sense, continuity means that we are conscious or have an episode of experiencing at each moment during certain intervals (measured by the clock). Second, if the *subjective continuity* holds, then we do not notice any gaps between two episodes of experiencing, even if there might be such.

Subjective continuity does not entail objective continuity. In fact, there are empirical reasons to think that there could be the former without the latter (and thus some justification for their separation). One example of this is mentioned by Holcombe (chapter 9), who invites us to look at our eyes through the mirror while we move our gaze from one eye to another. When we do this, what we do not perceive is our eyes moving—our visual experiences have a gap during the saccades. Another illustration of the same effect concerns duration tasks, where it has been found out that the time that it takes for eyes to move is simply "lost" in the estimations of the duration of visual stimuli (Morrone, Ross, and Burr 2005). To sum up these examples, while objectively speaking our stream of visual experiences appears to contain a gap, subjectively we do not notice it. For all practical purposes, objective continuity implies subjective continuity, however. If there is an episode of experiencing at each moment during the interval that we are conscious of something, then how could we be subjectively aware of the gap between two episodes of experiencing that do not exist?

James was not merely interested in a subjectively gapless stream of consciousness, however. Instead, he maintained that we experience the continuity itself. When describing his view, which he called "radical empiricism," James writes, "what I do feel simply when a later moment of my experience succeeds an earlier one is that though they are two moments, the transition from the one to the other is *continuous*. Continuity here is a definite sort of experience" (1904, 536). The notion of continuity that James discusses can be called the *experienced continuity*, because here in addition to the subjective continuity we also experience the relations that connect experiences. (Dainton calls this strong continuity.)

Given these three notions, it appears that at best the empirical results refute only experienced continuity. This is because two brief moments would be separate and follow one another discretely in the empirical cases above. Thus there would not be continuity between them that we could experience as continuity. This does not mean that there could not be objective and subjective continuity, however. In fact, for Pöppel, Bao, and Wittman, and for Busch and VanRullen, there are no gaps in successive moments or discrete snapshots. Accordingly, the requirements for objective continuity are satisfied. Then again, if the argumentation above has been sound, then this also implies that subjective continuity holds too.

On the other hand, one can also question whether the previous results refute even experienced continuity. In order to do it, the short snapshots should result from general mechanisms. For Pöppel and Bao and Wittman, this is not obvious. Quite the contrary, the temporal characteristics of the effects they describe appear to be at odds with some other phenomena. For example, if the moment lasts 30–40 ms, then most of the time two very short auditory stimuli presented less than 5 ms apart should fall into the same moment. Consequently, we should experience them as simultaneous. Yet, as is well known, with such intervals we can determine their asynchrony. Likewise, sometimes the experience of apparent motion can be induced by two flashes separated by less than 10 ms. In short, there are temporal phenomena that have higher temporal resolution than what these scientists suggest. An obvious way to overcome this puzzle is to maintain that all phenomena that occur in very short timescales are due to separate mechanisms, each of which has its own temporal characteristics, rather than from discrete processing blocks for all experiential contents. But if this is the case, then none of the mechanisms is central, in the sense that our experiences would be a succession of states realized by this state. In other words, while one mechanism processes stimuli in certain discrete steps, another processes in other steps, and at all times there is a continuous temporal flow at which the results of such mechanisms are embedded.

Discrete attentional sampling, however, is more likely to refute the experienced continuity, since it is often thought that attention is necessary for conscious experience. Hence, if attention samples discretely, then our conscious experiences would be jointed in a similar fashion. On the other hand, the attentional sampling did not determine whether the stimuli was perceived or not; rather, it only correlated with the probability of perceiving the stimuli, and hence without further studies it is too early to refute James's view.

15.2.3 Self and Time Consciousness

The discussion concerning subjective time thus far has focused mostly on our experiences of temporally extended events. As a result, we have ignored the issue of subjectivity related to our time consciousness. In fact, it is almost as if subjectivity has been introduced only to highlight that the *explanandum* concerns our experiences of temporal characteristics of various events and not something related to objective time (measurable by clocks). Many prominent phenomenologists have maintained, however, that we cannot separate subjective time from the issue of the subject as such. Although it is safe to say that this idea has not received much interest outside of the phenomenologist tradition, it deserves to be revisited briefly because of recent empirical research.

To begin with, one of the reasons why Husserl developed (and abandoned) so many ideas and suggestions concerning time consciousness (including the ideas he put forward in *On the Phenomenology of the Consciousness of Internal Time*, and the Bernau manuscripts and C-manuscripts) was his discontent for his explanation of the interrelation between self and temporality of consciousness. The problem he was facing was how to provide a satisfactory account of prereflective self-awareness, which is needed to account for our reflective self-awareness, our ability to take ourselves as objects of our consideration. Because this ability presupposes subject-object relations, it cannot explain subjectivity.

According to Husserl, such prereflective self-consciousness was a ubiquitous feature of consciousness, similar to the temporal structure of consciousness. What matters for the issues at hand is that Husserl maintained that retention provides prerequisites for reflective self-consciousness—our ability to take ourselves as objects of our reflection depends upon time consciousness. Hence, to provide an acceptable account of time consciousness was also to provide an acceptable account of prereflective self-awareness.

Husserl's theory of time consciousness was later criticized by Merleau-Ponty on the basis that it reduces or abstracts the subject away (this criticism is not justified, yet understandable given that Merleau-Ponty did not have access to many of Husserl's later manuscripts where the ideas were presented). These two philosophers did agree, however, that time and subject are inseparable; Merleau-Ponty writes, for example, that "we must understand time as the subject and the subject as time" (1962, 490). What separates their views is Merleau-Ponty's emphasis on the embodied subject—for him, the body is an essential part of the subject, and it is intentional in the same way other parts of the subject are too. In this way, time and body are equally dimensions of our existence.

What brings this debate to the spotlight again is that recently psychologists, too, have addressed the interrelation between time perception and the subject who has the temporal phenomenology. This approach is developed furthest in Wittman's theory, in which the awareness of passing time is simply the same as the awareness of our body. In his theory, and resembling what Pöppel and Bao argue (although without the bodily aspect), self and the subjective Now are grounded in an integration process of a two- to three-second window.

15.3 Subjective Time from Short to Longer Timescales

Extensionalism and retentionalism are usually seen as rival theories. Above we suggested, however, that a synthesis may be possible between them. Such an idea received support from the fact that regardless of the duration of the specious present (the interval of "which we are immediately and incessantly sensible"), it cannot explain all our temporal experiences. If it accounts for our experience of succession, it cannot account for our experiences of duration. Conversely, if it accounts for our experience of duration related to a stimulus lasting two seconds, we are left without an explanation why two stimuli presented with the same interstimulus interval do not bring about the experience of succession. In short, to account for all the phenomena that philosophers have been discussing, we need more than either extensionalism and retentionalism can provide alone.

To revisit this synthesis, we begin again at the limit of temporal perception. We return to the filmstrip, now accommodating an idea of "temporal acuity." Like spatial acuity, there are limits to our abilities to resolve small differences in time. Some distinctions are just too small to notice. For example, a sequence of three flashes, each lasting a thousandth of a second and separated by equally small intervals, cannot be sorted in time. We won't be able to tell which flash is first, or which between-flash interval is longer, or whether any is simultaneous with another. Let us modify our time line to capture time perception nearer to its limit:

{ . . . *abc* . . .}
[*a*] [*b*] [*c*]

Events *a, b*, and *c* are objectively distinct but subjectively agglomerated, at least in time. (That is, if these are three flashes in three different locations, we can tell that there are three events, but can make no temporal distinctions among them.) Subjectively, *a, b*, and *c* are all squeezed into one Now, a single subjective present. Perhaps this subjective present overlaps with the real timing of events, but even so it is not a "true present." As the example is imagined, then, the subjective Now does not match the duration or the time of occurrence for any of its component events.

The example draws attention to a significant difference between subjective and objective time, namely that the "atoms" of subjective time are not equivalent to the atoms of objective time. Clock time is a dense continuum of instants, temporal points in an infinite parade. But subjective temporal acuity is not that sharp. Accordingly, one blurry frame {. . . *abc* . . .} is as close as we come to discerning events *a*, *b*, and *c*. But this blurry frame occupies more than an instant. The subjective now has extension—it takes time. Within the heuristic "frame world," a single subjective frame extends over multiple objective frames.

This, then, is the minimal sense of "specious present," an interval too small to accommodate any subjective temporal discriminations. To keep this sense distinct, we can refer to it as *the atomic specious present*. This minimal specious present is less articulated than the specious present described by the extensionalists. Turning once again to Dainton's account, the extensionalist needs a specious present sufficient to account for a "direct" experience of change or motion. In this specious present, two events must be distinguishable to some extent. If light flashes *a, b,* and *c* are now more spread out, at a certain point, around 30 ms of separation, we begin to distinguish a sequence of events. As the lag increases, our judgments of which event occurred first become increasingly reliable. So we have another window, longer than the atomic specious present, within which some fundamental temporal distinctions appear. We can call this *the molecular specious present*, the smallest subjective interval during which events can be experienced as one thing *and then* another.[5]

Notice that even at the molecular level the full-blown mystery of subjective time is already before us. Even in the stroboscopic example, whenever the subjective experience of *a-then-b* occurs, it cannot be simultaneous with both *a* and *b*, and quite likely is not cotemporaneous with either one. So how does *a* (or *b*) inform the subjective experience? A process of some sort will have to bridge event *a* and the (later) subjective awareness of *a-then-b*. We can call this retention—or not. Every theory must commit to something like this.

As the window of time opens wider, beyond the threshold for temporal-order judgments, other aspects of the molecular chemistry of temporality appear. A succession of events comprises perceived motion, which might be smooth, or jerky, or simply one thing after another (i.e., not moving at all). Events perceived by different senses can be combined or fail to unify. Sequences with certain timings will appear to involve cause and effect. The rate of events leads to judgments of time passing, sometimes flying and sometimes dragging. Experiences can "feel fast" or not, and these judgments can shift as events move from anticipated to recalled. And so forth. All of these properties have their experimental versions, and are taken up in this volume.

The molecular specious present also has an upper limit. Where then does "retention" begin and end? It depends! It depends on what we want to regard "retention" to be. But notice that there is no longer a single, essential phenomenological distinction drawn. There are many thresholds, many windows that are long enough for one form of temporal awareness but not yet long enough for another. In this discussion, then, the philosophical yields to the empirical, and an array of contemporary research on the psychology and neuroscience of subjective time. Our suggestion has been that the change from the molecular specious present to retention occurs around one second or less. This is not only in accordance with our experiences of succession, but also with the fact that the direct "perception" of causality is already weakened when the temporal gap between the cause and effect is 150 ms (Roser et al., 2005).

When retention is at play, past contents are not as vividly present as they were during the molecular specious present. Nevertheless, they linger in our consciousness and enable us, say, to have experiences of longer durations and to understand language. One possible explanation for how this is achieved and how retention differs from the molecular specious present is that only retention is closely related to working memory. (Gallagher, for instance, has in passing comments linked retention to working memory.) Likewise, as Thomas Fraps (chapter 13) argues, due to limitations of working memory, the cognitive link between the cause and effect breaks at three seconds.[6] If this is the case, it should also be noted that working memory can sustain and manipulate its content, and hence the three-second limit is not absolute. This, in turn, provides an explanation for our experiences of melodies.

15.4 Conclusion

For the moment, then, we propose that subjective time could well be replaced by subjective *times*. The chapters above reveal several different interpretations of the core concepts of the phenomenology of temporality. They are compatible if they refer to different phenomena at different timescales, and empirically this seems plausible. The psychology and phenomenology of subjective time could thus rest on mechanisms that operate at different scales, but that overlap at their edges.

The multiplicity of psychological capacities gives rise to a troubling possibility, namely that the experiences or behaviors involving time might conflict. Some evidence of dissociation is already at hand, in the chapters above. But—exciting and perplexing—this is only the beginning. In the following sections, we shall see an amazing array of experiments that split subjective time into fragments. In the end, what will remain of the seemingly simple experience of time?

Notes

1. Retentionalists, following Husserl, adopt the convention of stacking protention and retention vertically around the horizontally flowing time line of the present primal impression. Dainton depicts the specious present as a (horizontal) window sliding alongside the objective timeline of world events. Nonetheless, these geometries are also compatible. The window of the extensionalist specious present is wider than an instant, and so only a slice of each window corresponds to the objective present. Ahead and behind this "primal" content, the immediate future and past must be constructed, just as in retentionalism. In other words, the sliding window could be rotated into Husserlian verticality; likewise, the vertical convention could be tipped over and depicted as a sliding window.

2. You can try this with a simple experiment: Ask a friend, for example, to knock twice so that the interval between the knocks slowly decreases down from half a minute. At what point do the knocks temporally bind and produce an experience of succession?

3. It is safe to say that philosophers have paid little attention to this line of research. Presumably, one of the main reasons for this is that the central questions have remained unresolved. For instance, it is not clear how intervals and durations are coded in the brain, how such time representations are generated and stored, or how the behavior related to them is generated. It also remains a mystery how many kinds of timing mechanisms there are and how they relate to each other. These fundamental questions have been addressed especially in part VII, and we encourage visiting there for the current view on the matter. Nevertheless, as long as these issues are not understood better, the importance of the mechanisms of time perception to philosophical debates remains an open question.

4. It is worth noting that the previous does not directly refute the claim that three seconds forms an important temporal integration window. Quite the contrary, it could be, for example, that there should not be longer than three-second intervals in melodies or spoken sentences. It does mean, however, that such a general temporal integration window does not account for all of the interesting phenomena either.

5. Prior to the discrimination of order is the discrimination of nonsimultaneity, the window within which we can tell that *a* and *b* were not simultaneous, even though we cannot tell which came first. Arguably, this is the first of the "molecular" time discriminations. However, it is not clear whether the detection of nonsimultaneity is yet an instance of the awareness of change.

6. That is, there is a separation between perceptual and inferential causality. The former is explained with the specious present while the latter is explained with working memory (or Pöppel and Bao's three-second cognitive unit). Such separation is empirically justified (Fonlupt, 2003; Roser et al., 2005).

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VII Off the Clock

If we had an organ for sensing time, how would it work? The phenomenology and psychology of time lead naturally to this question, the theme of the second half of *Subjective Time*. In physical (and metaphysical) terms, Time may be simple, a dimension among others. But the previous chapters confirm that subjective time is far from simple. Our lived experience of time has an intricate structure, and its phenomenology is distinct from its psychology. Our immediate experience of the present moment is laden with an awareness of the past and an anticipation of the future, neither of which could be directly caused by the environment right here and now. These perceptions of temporal context must arise through nonsensory means, adumbrating the push of sensory information. One might imagine the continual updating of temporal context as a smooth and continuous process, a subjective flow tracking the progression of time itself. However, the psychology of previous chapters exposed various gaps in the flow. It is possible that subjective time progresses in halting chunks, a cinematic succession of packets of information with very short and unnoticed intermissions. The chunks may come in two lengths, windowing a momentary experience of 10–30 milliseconds and then stringing psychological moments together to form temporal phrases of 2–3 seconds. Moreover, it appears that different sensory processes keep their own time, that the Now of vision might not coincide with the Now of hearing, or even that the Now of color perception might dissociate from the Now of motion detection. Taken together, the evidence implies that we should talk of subjective *times,* in the plural, and that our sense of flow is a largely illusory construct whose many facets are only very loosely related to the objective progression of physical time.

The various psychological phenomena of time ultimately constrain the proposed mechanisms for explaining temporal behavior. On the one hand, the laboratory observations point to mechanisms that are not simple. In chapter 16, Dean Buonomano summarizes the case for different mechanisms operating at different timescales, a thread that runs through several chapters in *Subjective Time*. Buonomano and Ryota Kanai in chapter 17 present evidence that timing can be spatially discontinuous, a theme that returns in subsequent chapters. For example, under the right conditions, the same stimuli in different regions of visual space might elicit different time judgments.

Notwithstanding this multiplicity, all timing tasks share some common functional components. Accordingly, a useful starting point might be conceptual. What would a system need in order to detect time? Consider a mundane case, the legendary watched pot that never boils. The pot at the moment looks like it did ten seconds ago, but you are aware (as usual) that time has passed. If (we assume) nothing sensory has changed, then your awareness of passing time is driven from within. Something is indeed changing. This trivial implication applies when any organism (or system) executes time-specific behavior. Various lab animals learn to peck one button after a two-second tone, and another after an eight-second tone. A website plays an annoying commercial for exactly ten uninterruptible seconds. And so forth. Fundamentally, any mechanism of time perception or temporally structured behavior must involve a counter or *accumulator*, something that changes as time passes; its changes serve as a counter of passing time. The accumulator must have something like a reset button, a starting gun, and some capacity to broadcast its current value, so that it can trigger the appropriate response, whether that is a simple awareness of passing time or some complex behavior.

An accumulator by itself is not enough. Timing behavior is inherently comparative. The simplest time perceptions include the judgments of simultaneity and temporal order—these are necessarily the comparison of two or more events. For the sake of argument, we will valorize this as a functional black box called a *comparator*. What is compared to what? The world demands delay, the ability to produce a behavior governed by an internal timekeeper rather than any external cue. Any task that involves intervals thus requires the capacity to compare a target to the value in the accumulator. For example, a laboratory subject hears many examples of tones, some sounded for one second and some sounded for two. Then a test tone sounds, and the subject decides whether it is closer in duration to the short tone or the long. (This is known as the bisection task, and it works handily with infrahumans as well as humans.) Or, to use another paradigm, a subject hears many examples of one-second tones, and is rewarded for reproducing the duration (by pressing a button one second after a signal, for example; this is known as the peak procedure). In both of these, subjects must have some way of keeping the target duration in mind and comparing that to the inner stopwatch—the advancing tics of the accumulator. Even in the basic discriminations of simultaneity and time-order judgments, subjects need the accumulator-comparator team in order to compare the time that has passed since each of the events occurred.

The water is "too long" in boiling, then, at the conclusion of a sequence like this: (1) the accumulator starts—I put the pot on the stove. Meanwhile, (2) I have in mind a target time, a rough feel for how long boiling should take. Ten seconds is too short, an hour much too long. The comparator continually holds this target time against the current value of the accumulator. Eventually, the two roughly coincide. But the water continues unboiled—an adage confirmed. The same functional story applies at every timescale in systems like us. For example, we are alert to pregnant pauses (in conversation, two seconds; in teenage text messaging, two minutes; in email exchanges, two days). Likewise in systems not like us: alarm clocks and seventeen-year locusts, for example.

The notional and functional division of labor affords a starting point for probing timing mechanisms in nature. The functional timing system we've now imagined runs in several stages, and experimental manipulations might influence subprocesses of timing separately. Suppose, for example, that a group of lab rats have been trained to press a bar two seconds after a flash of light. Now we inject them with cocaine, and observe that the timing curve has shifted left—the rats are now faster at the bar, underestimating the interval linked to their expected reward. What may have happened? Possibly, their accumulators have been speeded up. Subjectively the rats are still counting off the same number of tics as in their untreated condition, but the pulse rate has increased. But, importantly, other changes may have occurred:

- the animals may have been sensitized to the stimulus, and are quicker to detect the flash. That is, their *sensory latency*—simple reaction time—has decreased. So, the accumulator starts ticking sooner. The accumulator pulse rate is unchanged, but with an earlier starting gun it reaches its target faster.
- the drug may have altered the memory of the target duration. The representation of the appropriate waiting period may have been foreshortened. Everything else is working normally, but the rats think that the target duration is shorter, and thus underestimate the timing for the bar press. This memory-compression factor is known as the *memory constant,* and may play a role in addictive behaviors (see chapter 27).
- the subjects have been made impatient. That is, the drug may have altered their decision criteria, causing them to jump the gun, pressing the bar earlier (when the right time is "almost now," rather than "right now"). This *decision bias* is the main topic of chapter 18.

None of these are exclusive possibilities, of course. In the chapters to follow, each phase of the processes of timing will be scrutinized, often through ingenious experiments.

At the heart of this hypothetical process is the accumulator, which we have so far imagined as a sort of stopwatch. But, functionally speaking, there are different ways in which the accumulator might work. A stopwatch includes a pacemaker, a ticking oscillator whose job is simply to produce a regular series of identical pulses. The watch measures time by counting the pulses. Must pacemaking and counting be separate? At this point, proposals for the basic mechanisms of subjective time divide into two broad categories. One type envisions a pacemaker separate from the accumulator, while the second bases time on the state of the accumulator alone. An example of a pacemaker-accumulator is a digital watch. At its heart beats a quartz crystal, a pacemaker that produces identical pulses at a constant rate. Each tic is the same as tics before and after, so the pacemaker by itself tells us nothing about elapsed time. For actual time measurement, then, the watch needs a counter of pulses, an accumulator that increments the digital readout as the count of passing pulses increases.

Timekeepers need not employ this division of labor between pacemaker and accumulator, however. An hourglass, for example, accumulates grains of sand at a fixed rate. No separate counter is needed, since the volume of the sand pile itself indicates elapsed time. To anticipate the terminology of Buonomano in chapter 16, an hourglass is a *state-dependent* timekeeper. Its evolving internal state is itself the indicator of passing time.

In ordinary situations both examples, the digital watch and the hourglass, are dedicated timekeepers designed and used exclusively to signal intervals. But timekeeping could be piggybacked on mechanisms with additional jobs as well. For example, the turning wheels of an automobile could be the pacemaker for an odometer-as-timekeeper. Or, in a pinch, the level of the gas gauge could be one's hourglass.

Animals (including *Homo sapiens*) house neither vibrating crystals nor piles of sand, but their functional equivalents abound in the nervous system. Oscillators—potential pacemakers—are everywhere and essential, since at every timescale animals have to maintain cyclical functions. Even single neurons can pulse rhythmically. But just as ubiquitous are components that change in state as time passes. Neural information processing takes time. So, on top of whatever else the neuron is doing, it serves as a "delay line," inserting a pause between input and outputs. In addition, every neuron has a refractory period between action potentials, a brief interval in which the cell "settles" back to its baseline. If one input follows another closely, the second will arrive while the neuron is recovering from the first. This will change the response properties of the cell overall; a second or third spike will not be identical to the first, and that difference reflects in part the interval between inputs. Synapses also display short-term variability depending on their inputs, another state variation that depends on intervals between inputs. These are time-dependent effects that clever adaptation might harness to manage timing over short (millisecond) intervals, as needed to coordinate action patterns or interpret temporally intricate stimuli (birdsong or speech, for example). Within slightly longer windows (up to a few seconds), the overall state of circuits and networks of neurons offers a shifting tapestry in which patterns recirculate, allowing the immediate past to leave its inflective traces on the present.

In chapter 16, Buonomano makes the case for state-dependent timing at short timescales. But at the same time, he reminds us that the mechanisms for time consciousness and timing will likely be manifold. Timing in fractions of seconds is likely to be handled very differently from seconds. Minutes, hours, and days could all have their special mechanisms. Furthermore, these mechanisms could be repeated, with variations, in many parts of the brain—Buonomano cites evidence for this, a recurrent theme of these chapters.

Whatever the mechanism, it is a most unreliable clock. Chapters 17 and 18 describe variations in time behavior under different circumstances. These phenomena add to observed character of the psychology of subjective time, while adding to circumstantial evidence constraining the mechanisms of timing in the brain. Any horologist will tell you that the essential ingredient of an accurate clock is a steady pacemaker. Pacemakers need to be isolated from the influence of everything else, a desideratum also relevant to the blind watchmaker, natural selection. Circadian bioclocks meet this standard, being both reliable and hard to change in healthy adults of many species. On the other hand, state-dependent timekeepers are multitaskers; their timing functions piggyback on other operations, which may themselves be unfolding at different rates. These other operations will affect the state of the system, and in turn affect state-dependent time perception and behavior. Meanwhile, state-dependent timers will be more sensitive to perturbation, by this reasoning. These are loose constraints, however, and must always be modulated by the confounding influences of sensory latency, memory constants, and decision biases, subprocesses which take time themselves and can be altered.

The time distortions reviewed by Ryota Kanai in chapter 17 generally highlight the sensitivity of time perception to other nontemporal variables, dramatic and short-lived effects that might be expected if the brain is a nest of local state-dependent timers. Then, in chapter 18, Jeremie Jozefowiez, Armando Machado, and John E. R. Staddon explore decision bias and its modifications through learning. They distinguish associative and cognitive decision rules for detecting the right time for a timed response, a distinction that parallels the distinction between state-dependent and pacemaker-accumulator timing. On balance, timing decisions seem based on associative rules.

Time in the world may be a single dimension with a steady rate of passage (at least at terrestrial speeds and distances), but time in the brain emerges more and more as the distributed and variable product of many time-givers.

16 The Neural Mechanisms of Timing on Short Timescales

Dean V. Buonomano

In modern society, our lives are dependent on the technological innovations that have allowed us to keep track of time—from the nanosecond accuracy of the atomic clocks used for global-positioning systems to the clocking of our yearly trip around the sun. In between these extremes we track the minutes and hours that govern our activities. We rely daily on the technological innovations that have allowed us to accurately tell time over scales that span fifteen orders of magnitude.

In nature, animals also keep track of time over an equally impressive range of scales: from tens of microseconds, necessary for sound localization, to the anticipation of yearly seasonal changes. In between these extremes lie arguably the most sophisticated forms of timing. It is on the scale of milliseconds and seconds that complex forms of sensory and motor processing, including speech recognition and motor coordination, operate. The mechanisms by which animals tell time remain incompletely understood; nevertheless, in contrast to man-made timing devices, it is clear that the biological solutions to telling time are fundamentally different across different timescales. That there are numerous biological solutions to the problem of telling time likely reflects two factors. First, the biological components—be they biochemical reactions occurring within a cell or the emergent behavior of large networks of neurons—lack the digital precision of modern clocks. Second, the features required of a biological timer vary depending on whether its function is to process speech, anticipate when a traffic light will change, or control the circadian fluctuations of sleep-wake cycles.

The technological and biological solutions to the problem of telling time have little in common. Technologically, we can use the same devices to tell time across the full spectrum of timescales: atomic clocks are used to time nanosecond delays in the arrival of signals from different satellites, as well as to make adjustments to the calendar year. Similarly, digital wristwatches are used to time hundredths of a second as well as the months of the year. In stark contrast, while animals need to discriminate microsecond differences between the arrival of sounds to each ear and the hours that govern their sleep-wake cycles, the biological clocks responsible for both these tasks have nothing in common. The “clock” responsible for the millisecond timing does not have an hour hand, and our circadian clock does not have a second hand.

The mechanisms biology has exploited to tell time provide insights not only into the function and importance of timing on different scales, but the relative limits and flexibility of different strategies. The fact that there are different biological functions, constraints, and implementations of timing across different timescales highlights the need to carefully define the problem and timescale of interest when addressing the neural basis of timing.

16.1 Taxonomy of Time

Historically, the understanding of the neural mechanisms of how the brain tells time has been complicated by the fact that we have at times failed to take into account that distinct mechanisms are likely used to tell time on different scales. Indeed, failure to take into account the diversity of timescales and computational tasks that require timing can generate erroneous conclusions. The history of the study of memory provides a valuable analogy. In the early twentieth century psychologists and neuroscientists often studied memory as if it were a unitary process—for example, it was sometimes assumed that the neural mechanisms and locations of different forms of learning were shared. This assumption contributed to Lashley's theory that memories are widely distributed throughout the cortex (the principle of cortical equivalence); specifically, it was not appreciated that the maze-learning task he used could involve multiple strategies and different types of memory. Later studies that conclusively demonstrated memory is not a unitary process laid the ground for dramatic advances in our understanding of the neural basis of memory—as well as to a taxonomy of memory rooted in neuroscience (Cohen & Squire 1980; Squire, 2009). Similarly, the realization that temporal processing is not a unitary neural process is critical to the study and understanding of the neural basis of timing.

The relevant dimensions of a neuroscientifically based taxonomy of temporal processing are not entirely clear; however, the distinction between scales of time is of clear importance (Lewis et al., 2003; Buonomano, 2007). The time range addressed here will be on the scale of between tens of milliseconds to approximately a second. This is the range in which most animals generate and decipher the complex temporal structure of auditory signals used for communication. For example, in human language, the duration and interval between different speech segments is critical both to speech recognition and for the determination of prosody (Shannon et al., 1995; Schirmer, 2004). For example, the pauses between words contribute to the disambiguation of "black bird" versus "blackbird," or of the mondegreen "kiss the sky" versus "kiss this guy." Most notably, perhaps, the brain's exquisite ability to process complex temporal patterns on this timescale is well demonstrated by the fact that language can be reduced to a purely temporal code, as occurs in Morse code.

Timing in this subsecond range is sometimes classified as perceptual or automatic, and contrasted with timing on the suprasecond scale, which is often referred to as time estimation. This longer range is associated with our subjective "sense" of time, and it is responsible for anticipating when a traffic light will change or how long we have been waiting in line

(Michon, 1985; Rammsayer & Lima, 1991; Rammsayer, 1999; Buonomano & Karmarkar, 2002; Lewis & Miall, 2003). It is important to emphasize that while it is convenient to distinguish between subsecond and supra-second forms of timing, the true boundary is not known. Indeed, there is probably no discrete boundary; rather, different neural mechanisms may be used for different but overlapping timescales. Additionally, within the subsecond range there are likely different mechanisms involved in sensory and motor timing. The mechanisms discussed here will focus primarily on sensory timing.

In regard to the neural mechanisms of timing, two questions in particular are widely recognized as being fundamental (Buonomano & Karmarkar, 2002; Ivry & Spencer, 2004; Mauk & Buonomano, 2004; Buhusi & Meck, 2005; Ivry and Schlerf, 2008; van Wassenhove, 2009), and are explored in the following sections.

16.1.1 Is Timing Dedicated or Intrinsic?

The distinction between dedicated and intrinsic timing mechanisms in many ways revolves around whether there are "clocks" in the brain—that is, whether there are specialized systems that were "designed" to tell time and are exclusively devoted to the problem of timing. The counterview is that timing is a general and intrinsic ability of neurons and neural circuits. In this view, the same circuits responsible for timing may process other aspects of sensory stimuli in a multiplexed fashion.

16.1.2 Is Timing on the Subsecond Scale Centralized or Local?

An issue related to the question of whether the neural mechanisms of timing are dedicated or intrinsic is whether they are centralized or local. If the neural mechanisms of timing are dedicated, timing could rely on a single centralized area of the brain, or the dedicated mechanisms could be replicated in many different parts of the brain in a manner such that the timing used for an auditory and visual task would be performed by different specialized circuits. In contrast, if the neural basis of timing is intrinsic, it is more or less implicit that timing would be localized—timing would be performed locally by neural circuits on an as-needed basis.

16.2 Neural Basis of Timing

From discriminating the speed of a moving object to the pause between words, many sensory tasks require that the brain estimate the interval and duration of sensory events. In the laboratory, timing is often studied via testing the ability to discriminate the interval and duration of stimuli. In an auditory interval discrimination task, subjects would typically be presented with two very brief tones (each might last 15 ms) separated by a target interval, 200 ms for example. A second later, a second pair of tones would be presented separated by a different interval (250 ms, for example), and the subject would be asked to perform a judgment as to whether the first or second interval was the longest.

A number of different models have been proposed to explain how the brain may perform a temporal discrimination. The models involve a range of principles, including those that rely on oscillators, delay lines, or on the dynamics of networks of neurons.

16.2.1 Internal Clock Model

When considering the mechanisms of timing, it is perhaps most intuitive to think in terms of clocks. Indeed, the dominant model of timing, often referred to as the internal clock model, relies on clock-like oscillators (Creelman, 1962; Treisman, 1963; Gibbon, 1977). Specifically, an oscillator beats at some constant frequency, and each "tic" would then be counted by an accumulator or neural integrator. This integrator would thus establish a linear metric of the passage of time in which the level of activity would be linearly related to elapsed time. Oscillations are commonly observed in many neurons, and it is established that changes in the period of oscillations control the timing of many periodic behaviors, such as breathing or locomotor control. However, in periodic behaviors there is not generally an integer integration of each cycle to provide a metric of time on a scale that far exceeds the period of the oscillator. Thus, while there are abundant examples of oscillators or pacemakers in the nervous system, there is currently little evidence that these oscillations are "counted" to provide a linear measure of time. In its simplest form, if such a clock were to be used for the discrimination of 100 ms intervals, and allow the discrimination of a 100 ms and a 105 ms interval, there would have to be at least one additional tic in the second case; thus the oscillator would have a period of 5 ms (a frequency of 200 Hz). While neuronal oscillations at these frequencies exist, they are rare; but furthermore, the accurate integration or counting of each event seems particularly unlikely.

16.2.2 Spectral and Energy Models

A number of models of timing have proposed that timing may rely on an array of neuronal elements that differ in terms of some temporal property, effectively implementing what is commonly referred to as a delay line. These models assume there is a population of cells that react to a stimulus with a range of different latencies (Desmond & Moore, 1988; Grossberg & Schmajuk, 1989). A number of biologically plausible implementations of such spectral, or delay line, models have been proposed, including the time constants of neurotransmitter receptors (Fiala et al. 1996); the time constant of slow membrane conductances (Hooper et al., 2002); the decay time of inhibitory postsynaptic potentials (Sullivan, 1982; Saitoh & Suga, 1995; Aubie et al., 2009); or even cell thresholds (Antón et al., 1991). In these models all elements share a common implementation, but at least one of the variables is set to a different value, which endows each unit with the ability to respond selectively to a different interval. In specialized cases, such as the auditory system of the bat, there is evidence that the duration of postsynaptic potentials contributes to the detection of temporal windows below 50 ms. Such mechanisms, however, seem unlikely to generalize to complex forms of temporal processing, which require the discrimination of the patterns generated by consecutive intervals (Buonomano, 2000).

Since, as a result of temporal integration, there is a relationship between duration and the magnitude of neural responses, it has also been suggested that timing may be related to the "energy" of the stimuli (Divenyi & Danner, 1977; Rammsayer, 1994; Eagleman & Pariyadath, 2009). For example, much like the loading of a capacitor, neurons could potentially respond selectively to specific durations as a result of input integration or their overall response level. Experimental studies, however, suggest that energy models are unlikely to account for timing on short timescales. Specifically, experiments that have systematically controlled the intensity of auditory stimuli do not appear to disrupt temporal processing (Rammsayer, 1994; Wright et al., 1997; Alder and Rose, 1998).

16.2.3 Multiple Oscillator Models

Multiple-oscillator models of timing are a distinct class that incorporate elements of the internal clock model and the notion of a population of elements with different temporal properties (Miall, 1989; Matell & Meck, 2000, 2004). These models are composed of a population of neurons with a range of different frequencies. Here timing does not require integrating or counting the pulses in any of the oscillators, but on detecting specific "beats" or synchronous patterns among the population of oscillators. This detection process can be performed by readout neurons that detect the coincident activity of a subset of oscillators that establishes a specific point in time. This coincidence-detection mechanism is considerably more biological than the notion of the counter postulated in the internal clock model. However, for intervals on the scale of a few hundred milliseconds, it seems unlikely that such a mechanism would account for the internal and duration timing critical to speech and music perception.

16.2.4 State-Dependent Network Model

Like the internal clock model, man-made timing devices, such as a pendulum or an analog or digital watch, share the common principal of a stable oscillator with a fixed period and a mechanism to count or integrate the number of oscillations. Time, however, can be kept by mechanisms other than the integration of the cycles of an oscillator, or the delays imposed by the time constants of some neuronal properties. The Greek philosophers associated time with change and motion (Turetzky, 1998)—loosely speaking, with dynamics. In principle, any system that exhibits distinct states that evolve in time can be used to tell time: whether it is the position of a ball rolling down a track or the level of sand in an hourglass, both systems can be used to tell time on scales less than the time it takes for them to complete their trajectory.

A distinct class of neural models proposes that timing does not depend on oscillators or delay lines, but rather on time-dependent changes in the state of neural networks. The ripples on a pond provide a useful analogy. If a pebble is dropped into a pond, it will produce a characteristic spatiotemporal pattern of ripples. From a snapshot of the pond, one could use the amplitude and the diameter of the ripples to determine how long ago the pebble was thrown in. Thus it could be said that the state of the pond encodes the amount of time elapsed since the pebble was thrown in.

Networks of neurons represent very rich dynamic systems, and like the ripples on a pond, the state of neural networks evolve in time in response to either a brief or a continuous input. Consider a network of hundreds of recurrently connected neurons that receive two brief inputs 200 ms apart—we can think of this scenario as two auditory tones presented at a 200 ms interval arriving in the auditory cortex. The first event should activate a population of the neurons in the network. At the arrival of the second pulse, 200 ms after the onset of the first, the response of the network will not be the same, because like a second pebble being dropped in a pond 200 ms after the first, the second input will arrive in a network that is in a different state. State-dependent network models propose that a consequence of this fact is that networks of neurons can inherently encode for elapsed time as a result of the interaction between the internal state of the network and incoming stimuli. To understand the nature of these internal neural network states, it is useful to discriminate between two types of internal states referred to as the *hidden* and *active* states (Buonomano & Maass, 2009).

Neurons are computational units whose responses are strongly dependent on their recent history of activity. Many neuronal properties have time constants on the order of tens to hundreds of milliseconds, which ensure that their behavior will be dependent on their previous activity. At the cellular level, the ionic currents of neurons exhibit time constants in the range of ten to hundreds of milliseconds. Additionally, the strength of the synapses between neurons is not constant on short timescales; rather, the strength of virtually all synapses varies dramatically in a use-dependent fashion. Specifically, the strength of a synapse can become much stronger (or weaker) when it is used twice in a row within a time frame of less than a few hundred milliseconds (Zucker, 1989; Markram et al., 1998; Dobrunz & Stevens, 1999; Reyes & Sakmann, 1999). This process, referred to as short-term synaptic plasticity, provides an ephemeral memory of what has happened in the past few hundred milliseconds. When two brief auditory tones are presented 200 ms apart, the input pattern representing each tone will activate a subset of neurons in the auditory cortex. However, because the strength of many of the synapses may be different at the arrival of the first and second tone, each may result in the activation of distinct subsets of neurons. The difference in these populations can be used to code for the interval between the tones (Buonomano & Merzenich, 1995; Buonomano, 2000). Because, in this example, the difference in the network state is attributable to synaptic (and potentially other cellular) properties that are only expressed in response to an external stimulus, these changes are referred to as the hidden state of the network.

In addition to the hidden state, the response of a network to a stimulus is strongly dependent on any ongoing activity in the network—referred to as the active state. In the case of two brief tones separated by 200 ms, neurons in the auditory cortex generally return to a silent or baseline state by the time of the arrival of the second tone. Thus, the active network state will not contribute to the response of the network. However, in the case of a continuous 200 ms long tone, or the cortical activity produced by ongoing speech, the response of the network at any point it time will likely rely on the complex interaction between the current input pattern and the ongoing activity of the network. In this manner, the active state can play an important role in shaping the response of a network to time-varying stimuli and the encoding of time.

16.3 Experimental Evidence for Local Timing

The state-dependent network model proposes that networks of neurons are inherently capable of timing in the range of tens and hundreds of milliseconds. As such, this model explicitly predicts that timing is local—that the detection of the temporal features, order, interval, and duration of both simple and complex stimuli can occur in different parts of the brain on an as needed basis. A second prediction of the state-dependent network models is that neural responses should be state-dependent; that is, whether or not neurons fire to a stimulus should be dependent on the temporal signature of the preceding stimuli. Both the specific predictions of the state-dependent network model, as well as the more general issue of whether timing is local or centralized, have been addressed in some psychophysical and neurophysiological studies.

16.3.1 Psychophysical Experiments

The state-dependent network model predicts that the arrival of each sensory event is encoded in the temporal context of previous events. For example, the second tone of a 200 ms interval arrives in the network state established by the first tone; consequently, the population response can encode this interval. However, a potentially undesirable consequence of this framework is that if a 200 ms interval demarcated by two tones is preceded by a distractor tone, the state of the network will be different than that of a 200 ms interval presented in the absence of the distractor tone. In the same manner that previous ripples on the surface of a pond will establish a "context" or state that will alter the ripples produced by the next pebble thrown in, each sensory event will alter the response to the next. So during an interval-discrimination task that requires the comparison of two intervals, one preceded by a distractor tone (irrelevant to the task) and one not, one would expect a significant decrement in performance. This effect can be thought of as a "reset" issue. To compare two intervals, the network should be in the same state at the onset of both stimuli—while a distractor tone can interfere with the processing of the interval if the network has not had time to "reset." Psychophysical studies have addressed this issue by showing that the presence of an unpredictable distractor can dramatically impair interval discrimination. Additionally, simply presenting the two intervals to be compared close together also impairs interval discrimination. This effect, again, is interpreted as meaning that the network did not have time to reset before the arrival of the second stimulus. Such reset effects are robustly observed when the distractor and target interval are 100 ms, and observed to a lesser extent with intervals of 300 ms (Karmarkar & Buonomano, 2007; Buonomano et al., 2009; Spencer et al., 2009). These types of experiments, which support the state-dependent network model, have been used to test the hypothesis that timing is local by examining cases in which the two intervals were presented at different frequencies. Because of the tonotopic organization of the auditory system, tones of different frequencies are processed in different neighboring areas of the cortex. Thus it would be expected that if the interference between stimuli is occurring locally in the early stages of auditory processing, and if the intervals being compared are presented at different frequencies (pitches), they should not interfere with each other. Indeed, if two 100 ms intervals of the same pitch are separated by 250 ms interval discrimination is impaired; in contrast, if one of the auditory intervals is presented at 1 kHz and the other at 4 kHz, the decrease in performance is not observed (Karmarkar & Buonomano, 2007).

Experiments in the visual modality have also concluded that timing in the subsecond range is local. In these experiments, it was shown that presentation of an adapting stimulus produces a distortion of time estimation of subsequent visual stimuli. Specifically, the estimation of the duration of a 600 ms long image of a moving grating (a pattern of moving, fuzzy black and white bars) is perceived as being shorter in duration when it is preceded by an adapting stimulus in the same spatial location. Importantly, if the same stimulus is present in a different location (a nonadapted position in visual space), then the duration of the stimulus is correctly perceived as lasting approximately 600 ms (Johnston et al., 2006; Burr et al., 2007).

16.3.2 Electrophysiological Experiments

As previously mentioned, the state-dependent network model and local models of timing in general predict that neural responses specific to the order, interval, and duration of stimuli should be able to be observed in a wide range of different cortical areas depending on stimulus modality and the task at hand. Neurons should respond selectively to the global temporal structure of stimuli; for example, firing in response to a stimulus composed of two components *A* then *B* (where each component could be a tone of different frequencies), but not *A* or *B* individually or the sequence *BA*. Furthermore, responses should be selective to the interval between both components. Such temporal-combination sensitive cells have been observed in the auditory systems of a number of species, including songbirds (Margoliash & Fortune, 1992; Lewicki & Arthur, 1996; Doupe, 1997); rats (Kilgard & Merzenich 1999); cats (McKenna et al., 1989; Brosch & Schreiner, 2000); and monkeys (Brosch et al., 1999; Bartlett & Wang, 2005). One experiment demonstrated that some neurons in the auditory cortex of monkeys responded selectively to the patterns of tones the animals had been trained to recognize. Specifically, some neurons responded to sequences of tones *ABC*, where each tone lasted 100 ms, but fired little in response to either tone in isolation or to the same tones arranged in a different sequence (Yin et al., 2008).

The notion that timing is a general ability of cortical networks suggests that it may be possible to observe timed responses even in cortical networks in vitro. Indeed, it has been shown that cultures of isolated circuits of neurons can exhibit selective order and temporally selective responses. Other studies have demonstrated these cortical cultures can adapt and reproduce the intervals they are exposed to (Buonomano, 2003; Johnson et al., 2010). While these in vitro experiments support the notion that networks of neurons are inherently capable of temporal processing, it remains to be determined if these same mechanisms are present and are used by the intact brain.

Together psychophysical and electrophysiological experiments provide compelling support for the notion that timing on the subsecond scale is local. And to a lesser extent, these experiments support the notion that sensory timing relies on the internal dynamics of neural networks as postulated by the state-dependent network model.

16.4 Conclusion

The invention of accurate man-made clocks laid the foundation for the industrial revolution, advances in navigation, and many other cultural and technological changes (Falk, 2008). Most man-made clocks rely on the accurate counting of the oscillation of a known frequency—such as the period of the pendulum or that of the quartz crystals used in digital watches—and are used to track time over scales spanning many orders of magnitude. There is currently little evidence that biological “clocks” on any timescale rely on the counting of the “tics” of an oscillator. Indeed, even the circadian cycles of animals, which rely on the oscillatory behavior of biochemical reactions, code time in the phase of these reactions, not by integrating the number of cycles.

The brain seems to have developed fundamentally different mechanisms for timing across different timescales (Buonomano, 2007). To discriminate the microsecond differences between the arrival of sounds in the left and right ear, the nervous system relies on the delays imposed by the conduction velocity of the bioelectrical signals along axons. The circadian clock, in turn, relies on the biochemical feedback loops between the synthesis of proteins, which in turn inhibit their own further synthesis. The fact that mother nature resorted to distinct solutions to the problem of timing should not come as a surprise. During the evolution of the nervous system, selective pressures to time microseconds, milliseconds, seconds, and hours were all independent computational problems involving different parts of the brain. Evolution would not have the luxury of developing a centralized general-purpose clock. Furthermore, a centralized cross-scale timing mechanism would have likely provided a functionally inferior solution. Different forms of timing have different requirements regarding precision and the need to accurately stop, start, and reset the timer. For example, the circadian clock is among the most precise (in mice, the period of the circadian clock can vary by less than 2 percent in the absence of any external cues). But despite its precision, the circadian clock is notoriously difficult to reset—as evidenced by the phenomenon of jet lag.

Although the mechanisms underlying timing in the range of tens to hundreds of milliseconds remain to be elucidated, current evidence supports the notion that timing on this scale relies on the inherent dynamics of neural networks. Dynamics-based timing can take various forms. In the case of the discrimination of sensory stimuli, as proposed by the state-dependent network model, it may rely on the interaction between incoming stimuli and the internal state of neural networks. This mechanism provides a powerful means to time both simple temporal features, such as interval and duration, as well as the complex temporal structure characteristic of speech and music. Specifically, the inherent dependence of the response of a population of neurons to a given stimulus on previous stimulus history ensures that temporal information is naturally encoded in the brain. A potential weakness of a dynamics-based or state-dependent timing device is precisely that it depends on the previous stimuli, independently of whether these recent stimuli are relevant to the task at hand. In other words, state-dependent networks do not generate a simple linear metric that reads out time independent of context—there are no clear "tics" that establish an absolute measure of elapsed time. Although local timing may run counter to our intuitions about the passage of time, it is entirely consistent with the fact that in most cases time is not an independent dimension of sensory stimuli, rather, spatial and temporal processing are often intimately entwined components of sensory and motor processing. Given the biological importance of time, it seems appropriate that timing would rely on local and general properties of our neural hardware, rather than on a dedicated architecture that would require communication between a central clock and the diverse sensory and motor circuits that require timing.

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17 Illusory Distortion of Subjective Time Perception

Ryota Kanai

17.1 Introduction

Our conscious experience is remarkably diverse, including as it does experiences ranging from seeing the marvelous red and orange colors of a sunset to the unpleasant feeling of pain that makes you moan. The experience of the passage of time constitutes an essential dimension common across diverse forms of conscious experience, since subjective experience of any event—both internal events like thought and external events of the world—necessarily endures and unfolds through time.

The passage of time can be introspected to gauge how long our experience lasts. Such capacity to process temporal information in sensory events is essential for organisms to coordinate interactions with the environment and predict future events. Humans and other animals are equipped with the ability to utilize multiple scales of temporal information from milliseconds to days (Buonomano, 2007; Mauk & Buonomano, 2004). Both psychological and neuroscience research suggests that the processes for estimating short durations ranging from a few hundreds of milliseconds to a few seconds are distinct from those for longer durations (Buhusi & Meck, 2005; Fraisse, 1984). The processes for short durations are considered to rely on a relatively automatic mechanism whereas the processes for longer durations require more cognitive control (Lewis & Miall, 2003, 2006). The critical duration for the transition from short to long is thought to be around 1 second to 3 seconds (Drake & Botte, 1993; Pöppel, 1997; Rammsayer & Vogel, 1992).

When we actively try to estimate the duration of an event, our estimates are susceptible to distortions from various factors. In this chapter, I will provide a brief overview on illusory distortions of short intervals, which are associated with automatic sensory aspects of time perception. Examples of illusory distortions of time will not only demonstrate how our subjective experience of time could be dissociated from the duration of an external event, but will also help us understand how subjective time emerges from the working of the brain.

17.2 A Conceptual Framework of Time Distortion

Based on a classical psychological theory of time perception (Creelman, 1962; Gibbon, 1977; Treisman, 1963), I propose that there are at least four possible mechanisms that give rise to a report of time distortion. First, the latencies for time markers indicating the beginning and the termination of an event can be affected by various manipulations of external events (e.g., stimulus contrast) and internal states (e.g., attention). If the registration of an event onset were delayed, the estimated duration would be shorter, whereas a delay in registration of the termination would lengthen the estimated duration. Second, the rate of "pulses" that indicate the speed of the passage of time can be modulated both by external stimuli and internal states. For example, time distortion by attention and number of events is thought to influence how fast time flows subjectively. If the speed of the internal clock were to become faster, the subjective estimate of duration would be longer. Third, decision factors could also introduce a systematic bias in the report of subjective time when the durations of two intervals are compared. For example, a Stroop-like situation between perceived time and numerical magnitude could introduce response errors when observers make a more-versus-less judgment in a discrimination task. Fourth, memory regarding the duration of an event could be distorted during maintenance of the memory. While this last possibility is theoretically possible, little research has been conducted to explore it (see Stetson, Fiesta, & Eagleman, 2007 for an exceptional example).

In addition to these four classes of time distortion, there is a fifth possibility: that time is distorted by systematic differences in specific contents of stimuli. Many theorists have proposed that the number of changes present in a stimulus might be used as a cue to estimate the passage of time (Ahrens & Sahani, 2011; Fraisse, 1984; Poynter, 1989). According to this simple idea, elapsed time is a psychological construct inferred from the characteristics of stimuli. This suggests the amount of change contained in a stimulus is a critical factor for time distortion. Similarly, the intensity of a stimulus and the magnitude of the evoked neural response have been proposed to modulate perceived duration. These types of time distortion are attributed to characteristics of stimuli that define a temporal interval. Taking these possibilities together, I propose that reports of time distortion can be classified into the following five categories:

1. shifts in the processing latency for time-marking events (latency)
2. modulation of pulse rate (pulse rate)
3. response bias at a decision stage (decision bias)
4. distortion of memory (memory)
5. distortion from stimulus contents (stimulus contents).

Although these five accounts of time distortion are conceptualized as distinct mechanisms, it is in practice often difficult to distinguish which components contribute to a particular type of time distortion. While I introduce various forms of time illusions below, possible mechanisms most likely to be associated with them will be discussed in terms of these hypothetical mechanisms.

17.3 Classes of Time Distortion

17.3.1 Time Distortion by Changes

A well-known classic example of time distortion is the so-called kappa effect. When three flashes are successively presented and separated by equal temporal intervals, one of the temporal intervals appears to last longer as the relative spacing between the flashes defining the interval increases. In other words, the spatial distance between two consecutive flashes modulates perceived duration between them. The kappa effect is found when the total duration of the two intervals is between 0.6 s and 11 s (Cohen, Hansel, & Sylvester, 1953; Price-Williams, 1954). The kappa effect is also reported in the auditory domain (Grondin & Plourde, 2007; Henry & McAuley, 2009), and therefore seems to reflect a general organizational principle of time perception, not one specific to vision.

The finding of the kappa effect was motivated by the earlier finding of the *tau* effect by Helson (Helson, 1930; Helson & King, 1931), which was originally found in spatial judgments in the cutaneous modality. Spatial judgment of the relative magnitude of first and second intervals (s1 and s2) is strongly influenced by the relative durations of the first and second intervals (t1 and t2). If t1 is longer than t2, then s1 was perceived greater than s2. This distortion of perceived spatial extent by time is known as the tau effect and has been demonstrated in other modalities such as vision (Bill & Teft, 1969; 1972) and audition (Christensen & Huang, 1979; Sarrazin, Giraudo, & Pittenger, 2007). The kappa and tau effects together demonstrate interdependency of space and time in the human mind.

The kappa effect is most compatible with the idea that elapsed time is inferred from the characteristics of stimuli. Thus this phenomenon is likely due to distortion from stimulus contents. Indeed, it has been proposed that perceived duration is constructed from implicit attribution of a constant speed to discrete apparent motion (Collyer, 1977; Goldreich, 2007; Jones & Huang, 1982). According to this idea, the brain has a bias toward perceiving the series of events as changing at a constant rate. Therefore, if one interval covers a greater distance, it is inferred that the event would have lasted longer. With this hypothesis, the kappa effect could be viewed as a dilation of subjective time by the amount of change between the two events defining that temporal interval (see section 17.3.5 for details).

17.3.2 Dynamic Changes Expand Time

If the number or amount of changes provides a cue for time (Ahrens & Sahani, 2011; Fraisse, 1984; Poynter, 1989), motion might be one of the most informative temporal cues, because motion by definition involves changes in position over time. This idea has been supported by the fact that visual motion expands perceived time (Brown, 1931; Brown, 1995; Kanai et al., 2006). However, visual motion can be characterized by several components, such as velocity, temporal frequency, coherence, and so on. In fact, spatial displacements seem to play little role in time dilation, because local flickers suffice to produce the same time-dilation effect as a stimulus displaced over space (Kanai et al., 2006; but see also Kaneko & Murakami, 2009). Moreover, time dilation was observed in noise (zero-coherence) displays and simple flicker stimuli. The observation that local flickers rather than global coherent motion serve as an indicator of rapid changes in a scene provides a strong constraint on the change-based models of time perception. One possible interpretation of these findings is that temporal frequency in vision serves as a virtual "pulse rate" from which interval durations are estimated. Alternatively, temporal frequency could be viewed as a form of intensity. Indeed, neuronal responses increase as a function of temporal frequency up to 8~10 Hz in the visual cortex, and such response amplitude could be used as a source of inference for estimating elapsed time. Moreover, low-level temporal frequency is not the only factor that induces time dilation in dynamic displays. Expanding stimuli that appear to be moving toward the observer, for example, are perceived to last longer (Tse et al., 2004; van Wassenhove et al., 2008), suggesting that time dilation in moving stimuli also has a component related to specific stimulus contents. Since expanding stimuli are ecologically highly relevant, they could thus produce stronger neuronal responses.

17.3.3 Adaptation Induces Time Compression

The perception of time is distorted after adaptation. Perceived duration of a dynamic stimulus is shortened for a stimulus presented at a location that has adapted to motion or flickering (Johnston, Arnold, & Nishida, 2006). The distortion of apparent duration does not seem to reflect corresponding changes in perceived temporal frequency, because 5 Hz adaptation increased the perceived frequency of a subsequent 10 Hz stimulus but did not have any effect on perceived duration. Furthermore, this localized distortion is spatially finely tuned (Ayhan et al., 2009) and can be induced by adaptation to invisible stimuli that flicker above the flicker fusion frequency limit (Johnston et al., 2008). These findings suggest that time perception has a low-level, spatially localized mechanism.

This adaptation paradigm provides an important methodological tool when trying to determine the visual pathways and regions crucial for time perception. Specifically, whether adaptation takes place retinotopically or spatiotopically is a critical question, as it would inform us of the neuronal processing stage crucial for perception of time. A study by Burr and colleagues investigated this issue (Burr, Tozzi, & Morrone, 2007) and found that the effect of adaptation was specific to the location in real-world coordinates regardless of eye position. However, this is currently controversial (Bruno, Ayhan, & Johnston, 2010; Burr, Cicchini, Arrighi, & Morrone, 2011; Johnston, Bruno, & Ayhan, 2011) and requires further scrutiny in future research. Regardless of the exact locus of adaptation, one plausible mechanism mediating the time compression after adaptation is reduction of neuronal responses to test stimuli following adaptation. This can be interpreted both in terms of reduction in the amplitude of neuronal response and reduction in the pulse rate.

17.3.4 Time Compression from Repetition

Repeated presentations of a stimulus have been shown to compress perceived duration possibly via a very quick form of neuronal adaptation called repetition suppression (Pariyadath & Eagleman, 2008). For example, imagine a situation in which a picture of shoes is repetitively shown every second, and then suddenly a picture of a teacup is inserted. Even if all the pictures are shown for the same duration, the new picture (i.e., teacup) is perceived to last longer (Pariyadath & Eagleman, 2007, 2008) than the old ones (i.e., shoes). An interpretation of this phenomenon provided by Eagleman and Pariyadath is that the repetition of the same picture produces neuronal repetition suppression. When a new stimulus is presented, the neurons for that stimulus are not adapted and are therefore perceived longer than the adapted stimuli. This phenomenon of time compression of repeated stimuli can be considered as a form of adaptation effect on perceived duration and is consistent with the idea that greater neuronal responses correspond to longer perceived duration. While the compression of time for a repeated stimulus is compatible with the idea that neural response amplitude represents perceived duration, a possible alternative interpretation is that arousal and attention modulate the pulse rate and thereby expand perceived duration for a salient event (Tse et al., 2004). These two possibilities are currently difficult to distinguish unequivocally.

17.3.5 Time Distortion by Magnitude Information

It has been argued that the human brain contains a common metric for processing magnitude information such as time, space, and quantity—a hypothesis termed "a theory of magnitude" (or ATOM; Walsh, 2003).

As predicted by ATOM, many instances of interference of nontemporal magnitude information with time perception have been reported (Bueti and Walsh 2009). For example, the perceived duration of a digit is modulated by its numerical magnitude (Oliveri et al., 2008). The number of dots contained in a display (between 5 and 9) also influences the perceived duration of the event (Dormal, Seron, & Pesenti, 2006). Moreover, when perceived size was made larger by a geometric visual illusion, the perceived duration of the stimulus also increased, indicating that size-duration interaction takes place for perceived size rather than physical size (Ono & Kawahara, 2007). More generally, it has been shown that the duration of a stimulus is judged longer (or shorter) when the stimulus is accompanied by nontemporal magnitude information such as number of dots, size, luminance, or digits (Xuan et al., 2007). These examples of magnitude-time interactions suggest that numerical information or other domains of magnitude distort perceived duration, supporting the idea of shared representation of magnitude information.

However, it should be noted that in these experiments, subjects made longer or shorter judgments when stimuli of different durations were presented with each stimulus containing nontemporal magnitude information (e.g., digits). Therefore, it remains unclear whether these findings reflect decision errors due to conflicting information or systematic distortion of perceived duration from the stimulus content. Further investigation is needed to test explicitly whether the actual perceived duration is modulated by nontemporal magnitude information.

17.3.6 Action Triggers Time Expansion

Distortion of perceived duration is observed around the time of action execution. Perhaps the most famous illusion is *chronostasis* (Yarrow et al., 2001). When we look at a silently ticking clock, we sometimes notice that the hand showing seconds takes longer to move to its next position. In other words, the clock appears to have stopped for a short while when we first gaze at it. It was proposed that chronostasis is caused by attribution of time spent on saccade to a subsequent event in order to maintain continuous conscious experience, despite discontinuous visual experience due to saccades (Yarrow et al., 2001). In support of this idea, greater overestimation is observed following a large saccade, which would take longer to complete.

While chronostasis was originally noticed in voluntary eye movements, analogous phenomena have been found in other modalities such as audition, when attention was shifted from one ear to the other (Hodinott-Hill et al., 2002). Chronostasis is also caused by other types of voluntary actions such as key press and voice command (Park, Schlag-Rey, & Schlag, 2003). These findings together suggest that chronostasis may have a general mechanism related to voluntary action, attention shift, or both.

Researchers have generally attributed chronostasis to a sort of back referral of an event onset to the onset of action (or action command). In other words, it has been interpreted as a distortion of time-marker latency. While available data suggest that this is a plausible account, it has been difficult to rule out the alternative explanation that time expansion is induced by transient increase in attention and arousal immediately after voluntary action (Alexander et al., 2005; Yarrow, Haggard, & Rothwell, 2004), which could affect the pulse rate of an internal clock or response amplitude. These possibilities are difficult to distinguish, because motor arousal could be modeled in any way to fit the existing data due to lack of quantitative estimates for such hypothetical arousal. For example, a systematic relationship between saccade amplitude and the size of chronostasis (Yarrow et al., 2001) could be accounted for by arbitrarily modeling the arousal evoked by producing different amplitudes of saccades. On the other hand, chronostasis-like illusions of time expansion that do not involve voluntary actions have been reported (Alexander et al., 2005; Kanai & Watanabe, 2006; Rose & Summers, 1995). While such cases seem to argue against the association between chronostasis and voluntary action, it remains to be resolved whether they are distinct time illusions or are mediated by a common mechanism.

17.3.7 Time Marker and Perceived Time

When a stimulus appears suddenly, the first event is perceived to be longer than a subsequent event of the same duration (Rose & Summers, 1995). Although this is similar to chronostasis, this time expansion occurs without any voluntary action and seems to reflect the differential processing delays for abrupt onset and feature changes, because simple reaction times to the events that define the beginning and the end of an interval were consistent with the amount of time distortion (Kanai & Watanabe, 2006; also see Kanai et al., 2009). Perceived duration was longer when the interval began with an appearance of a new object compared to when the beginning of an interval was defined by a feature change in an existing object. This suggests that this illusion is caused by systematic differential latency in registration of events for the beginning and the end of an interval.

There are several instances in which the properties of time-marking stimuli modulate perceived durations. For example, when the duration of the event that defines the beginning or the end of an interval becomes longer, duration discrimination becomes more difficult (Rammsayer & Leutner, 1996) and perceived duration longer (Grondin et al., 1996). While these examples support the idea that time distortion can arise from differential latency for marking temporal events, it should be noted that it is difficult to completely rule out possible confounds of arousal, for the same reason as discussed in the case of chronostasis.

17.3.8 Attention Modulates Time

According to the attentional model of time perception (Thomas & Weaver, 1975; Zakay, 1989), attentional resources are split between a time-estimation mechanism and a stimulus processor. This hypothesis predicted that when attention is directed to another task, perceived duration would become shorter, because attention would have less access to the time-estimation mechanism and receive less output time signals (pulses). Consistent with this idea, perceived duration of a stimulus is reduced when a nontemporal task is performed concurrently (Hicks et al., 1977; Macar, Grondin, & Casini, 1994; Zakay, 1993). On the other hand, when attention is attracted to a stimulus, the perceived duration is also lengthened. For example, oddball stimuli are perceived to be longer than repeated stimuli (Tse et al., 2004), because more attention is directed to the salient oddball stimuli. Moreover, if transient attention is directed to a spatial location with an exogenous or endogenous cue, a stimulus presented subsequently at that location is perceived to last longer than when it is presented at an uncued location (Enns, Brehaut, & Shore, 1999; Yeshurun & Marom, 2007). While these examples are both compatible with the idea that attention lengthens perceived duration, the underlying mechanisms may be distinct. While the exogenous attention experiment shows a spatially localized effect of time expansion, time expansion by the oddball paradigm generalizes to stimuli presented at spatially distant regions (New & Scholl, 2009). This global time expansion across the visual field by oddballs suggests that this illusion may have to do with arousal rather than specific attention to the stimulus per se.

One problem of this attentional-arousal account of time distortion is that it could be applied to many situations, since the effects of attention and arousal are poorly defined.

For example, chronostasis triggered by voluntary action could be taken as a consequence of transient increase in arousal (Alexander et al., 2005; Yarrow, Haggard, & Rothwell, 2004). Also, time expansion by dynamic stimuli (Kanai et al., 2006) or other magnitude information (Bueti & Walsh, 2009; Xuan et al., 2007) could also be taken as enhanced attention to such salient stimuli. Despite the great explanatory power of the attentional account, this hypothesis is also somewhat dissatisfying because the lack of specificity in the concept of attention does not allow inferences regarding the specific types of sensory information utilized in the brain for estimating short durations.

17.4 Possible Mechanisms of Time Distortion

In this chapter, I have introduced a variety of time-distortion illusions and discussed them in terms of five possible mechanisms that give rise to time distortion. I also tried to illustrate the current limitations of these psychological theories by describing the difficulty of distinguishing these mechanisms in actual examples of time illusions. Whenever stimuli that evoke greater neuronal responses are used to expand subjective time, it can be argued that such stimuli would capture attention and increase arousal level, thereby speeding the pulse rate. Similarly, processing latency would be affected by arousal and attention, and thus it is difficult to distinguish the latency hypothesis from attentional enhancement of the magnitude of evoked neuronal responses. For example, a purely attentional account could be applied to magnitude-induced and action-induced time distortion.

Perhaps a slightly more generalized hypothesis that perceived duration scales with enhanced neuronal responses might be able to account for a large variety of the time illusions described here. This idea is essentially identical to the proposal by Eagleman and Pariyadath that perceive duration is dictated by the energy consumed by neuronal activities (Eagleman & Pariyadath, 2009). A weakness of this hypothesis is that it currently lacks specificity as to which neural responses are directly relevant to subjective time. The next challenge is thus to determine which neuronal responses are directly linked with subjective time. Clearly, not every neuronal activity contributes to time perception. For example, time dilation induced by random-dot motion stimuli suggests that the activation level of motion-processing center MT/V5 may not be directly monitored for time estimation. While it has been shown with functional MRI that the activity of human V5 monotonically increases its activity as a function of motion coherence (Rees, Friston, & Koch, 2000), changes in motion coherence do not modulate to perceived duration dilation (Kanai et al., 2006). On the other hand, the speed of local dots is predictive of the amount of time dilation, suggesting the involvement of lower visual areas in time estimation. Although this is just one example illustrating a possible dissociation between evoked neural amplitude and perceived duration, it will be a fruitful direction to explore to establish a more specific relationship between neuronal activation and perceived duration.

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18 Cognitive versus Associative Decision Rules in Timing

J. Jozefowiez, A. Machado, and J. E. R. Staddon

Though assisted by constructed clocks and calendars, our sense of time is actually deeply rooted in biological mechanisms we share with all other animal species (Lejeune & Wearden, 1991). Our understanding of these mechanisms has been much advanced by operant-conditioning experiments with humans and (infrahuman) animals. In these experiments, an operant response, such as key-pecking or button-pushing, is reinforced or not depending on the time elapsed since a specific stimulus (a so-called *time marker*[1]).

In a fixed-interval (FI) schedule, for instance, a response is reinforced only after a certain, fixed amount of time has elapsed since the time marker (Skinner, 1938). The FI time marker, for the schedule and the organism, is usually reinforcement, but may also be the end of an intertrial interval. The peak procedure (Catania, 1970; Roberts, 1981) is very similar to FI, except that the subject is also exposed to unreinforced probe trials lasting much longer than the reinforced FI trials, allowing us to look at behavior beyond the time of reinforcement. In the bisection procedure (Church & Deluty, 1977; Stubbs, 1968), the subject is reinforced for emitting a response *R1* following a stimulus that lasts S units of time and for emitting a response *R2* following a stimulus lasting *L* units of time (*S*<*L*). Temporal generalization is then tested on unreinforced probe trials where the duration of the stimulus is varied between *S* and *L*.

Various theoretical accounts of the results of these and similar experiments have been proposed over the years. All these accounts have three fundamental components (Staddon, 2001): (a) a short-term memory (STM) representation of the time elapsed since the onset of the time marker; (b) a long-term memory (LTM) representation of the time of reinforcement; and (c) a decision mechanism, which, through a comparison between the STM and LTM representations, generates behavior. This chapter will focus on the decision mechanism, or rule.

Models of timing use two types of decision rule: cognitive or associative. Cognitive rules guide behavior via a comparison between an STM scalar representation of time elapsed since the time marker and an LTM scalar representation of the time of reinforcement. Such a rule is used by *scalar expectancy theory* (SET; Gibbon, 1977; Gibbon, Church, & Meck, 1984), which was for many years the standard account for interval timing. Other models using cognitive-type decision rules are the multiple-time-scale theory (MTS; Staddon & Higa, 1999) and the packet theory (Guilhardi, Yi, & Church, 2007b; Kirkpatrick, 2002), which both use the difference between, rather than the ratio of the STM and LTM representations as their decision variable.

Models using associative decision rules are inspired by artificial neural-network modeling, in which a time marker triggers a series of time-dependent states. In these models, reinforcement strengthens, and nonreinforcement weakens, associations between currently active states and the reinforced response. The process can be modeled by the venerable Bush-Mosteller learning rule (Bush & Mosteller, 1955), but the details of the learning rule are probably not critical. Associative-type rules are used in the behavioral theory of timing (BET; Killeen and Fetterman 1988); the learning-to-time model (LeT; Machado, 1997; Machado, Malheiro, & Erlhagen, 2009); and the behavioral economic model (BEM; Jozefowiez, Staddon, & Cerutti, 2009). Associative rules are natural for any neutrally inspired model of timing (i.e., Church & Broadbent, 1990; Grossberg & Schmajuk, 1989; Ludvig, Sutton, & Kehoe, 2008).

In a model using an associative-response rule, temporal intervals are represented not as single numbers but by vectors: a vector of input activation for the STM representation, and a vector of associative weights connecting the input to the response for the LTM representation. In addition, contrary to what happens in models using a cognitive rule, there is no clear separation between the LTM representation and the response rule: they are both implemented through the vector of associative strengths.

18.1 Reinforcement Effects on Timing

18.1.1 Reinforcement Effects in Choice Procedures

One basic prediction of associative decision rules is that in choice-based timing procedures, subjects should be biased toward the more-reinforced response. For instance, consider a bisection procedure where the subject learns a discrimination between two durations, *S* and *L*. There is a critical duration *I* (the *bisection point*) at which the subject is indifferent between *R1*, the response reinforced after a stimulus duration of *S,* and *R2,* the response reinforced after a stimulus duration of *L*. In an associative decision-rule framework, there is a post–time-marker state (or a series of states, depending on the model), x_I, which reaches its maximum level of activation at the time of the bisection point. By definition, the strength of that state's associative link with *R1* is equal to its associative strength with *R2*. Now, if *R1* is more reinforced than *R2*—because reinforced trials with *R1* are more frequent (trial-frequency manipulation), because *R1* is more often reinforced (probability of reinforcement manipulation), or because *R1* leads to a larger reinforcer (reinforcement-magnitude manipulation)—the associative strength between x_I and *R1* will be higher than the associative strength between x_I and *R2,* leading to a bias toward *R1*.

The most extensive studies of the effect of reinforcement on timing and choice have used the *free-operant psychophysical procedure* (FOPP; Bizo & White, 1994a, 1994b, 1995a, 1995b;

Guilhardi, MacInnis, Church & Machado, 2007a; Machado & Guilhardi, 2000; Stubbs, 1980). In this procedure, a trial lasts T sec, during which the subject can freely choose between two responses, *R1* and *R2*. Responding on *R1* is reinforced with a probability *p1* during the first half of a trial (from 0 to *T/2* sec), while responding on *R2* is reinforced with a probability *p2* during the second half of a trial (from *T/2* to *T* sec). The subject adapts to this temporal contingency by emitting mainly *R1* during the first part of a trial before switching to *R2*. If $p1 = p2$, the subject is indifferent between the two responses roughly around *T/2* sec in a trial. Otherwise, if $p1 > p2$, the subject switches later to *R2* (earlier if $p1 < p2$), even though manipulations of the reinforcement rate leave the temporal contingency—which is the sole input to cognitive-rule models like SET—unaffected. But data like these are readily explained by an associative decision rule. Indeed, Machado and Guilhardi (2000) showed that the data from the procedure were very well fitted quantitatively by LeT, while Jozefowiez et al. (2009) showed the same thing for BEM.

Cognitive rules have difficulty with those data, because they assume that the subject's decision is based only on the representation of time intervals, which is not supposed to be affected by a manipulation of reinforcement rate. Still, a model using a cognitive rule could be made consistent with data from the FOPP by assuming that the reinforcement rate affects a response-bias parameter. Supporting this argument, Wearden and Grindrod (2003) studied the effect of reinforcement in a temporal-generalization task using human subjects and "points" reinforcement. Subjects were reinforced for emitting one response following a stimulus duration of 400 ms and again for any stimulus duration different from 400 ms. By manipulating the number of points associated with each response, Wearden and Grindrod (2003) were able to bias the performance of the subjects. They showed that SET could account for these effects by adjusting the bias parameter only: the parameters related to the representation of time did not change significantly across conditions.

The problem, of course, is that in the absence of any theory explaining how and why response bias is affected by reinforcement, tweaking the response-bias parameter is an unsatisfactorily ad hoc solution. It does not allow for a fair comparison with associative models such as BEM and LeT. To fit the data from the FOPP, Machado and Guilhardi (2000) and Jozefowiez et al. (2009) adjusted only one free parameter, controlling the level of noise in the STM representation of time, to the control condition where $p1 = p2$. At this point, all the degrees of freedom in the models were exhausted, and the predictions for the conditions where *p1* was different from *p2* were automatically generated. By contrast, when a model like SET is applied to the FOPP, a two-stage process is required. Parameters controlling the representation of time would first be adjusted so the model can account for the data from the control condition. The response-bias parameter would then be adjusted so that the model can fit the other conditions. Under those circumstances, LeT and BEM would be lucky if they do as well as SET, but this is just because the principles governing the response bias in SET are undefined.

This limitation of SET-type models is perfectly illustrated by a study by Machado and Guilhardi (2000; also see Guilhardi et al., 2007a), where, as predicted by an associative-response rule, manipulations of the reinforcement rate did not lead to biased responding in the FOPP. In their procedure, response *R1* was reinforced with a probability *p1* from 0 to *T/4* sec in a trial, and with a probability *p2* from *T/4* to *T/2* sec in a trial. In the same way, response *R2* was reinforced with a probability *p3* from *T/2* to *3T/4* sec in a trial and with a probability *p4*. With this method, Machado and Guilhardi were able to manipulate the local probability of reinforcement for each response (*p1, p2, p3*, and *p4*) while keeping the overall reinforcement rate for each response the same ($p1 + p2 = p3 + p4$). The subjects were biased toward *R1* (or *R2*) only when $p2 > p3$ (or $p2 < p3$). Performance in conditions where *p1* differed from *p4* was identical to performance in the control condition where all four probabilities were equal.

An associative account is as follows. The states sampled from *0* to *T/4* sec and from *3T/4* to *T* sec are already maximally associated with *R1* in one case, and *R2* in the other. Hence, any change in the reinforcement parameters for these two intervals is expected to have little effect. This is not the case for the states sampled around the point of indifference (from *T/4* to *3T/4* sec). Those states have similar associations to both responses, hence are strongly affected by manipulation of the reinforcement parameters that would favor one response over the other (see Jozefowiez et al., 2009 and Machado & Guilhardi, 2000 for more detailed explanations within the context of BEM and LeT). Both LeT (Machado & Guilhardi, 2000) and BEM (Jozefowiez et al., 2009) provide a good quantitative account of those data. By contrast, with no clear principle constraining the response bias, it is not clear how a cognitive model such as SET can account for these data, except in a purely ad hoc fashion. Even the vague "the subject will be biased toward the more reinforced response" principle used by Wearden and Grindrod (2003) fails here, because both responses were equally reinforced overall.[2]

Taken together, data from the FOPP favor an associative-response rule over a cognitive one. Outside of the FOPP, a few other studies have looked at the effect of reinforcement magnitude. We already mentioned Wearden and Grindrod (2003)'s study of temporal generalization in humans. This is consistent with a human bisection study using points as reinforcers by Jozefowiez, Polack, Machado, and Miller (in press), which found that manipulations of trial frequency lead to the type of biased performance predicted by associative models. By contrast, using rats as subjects, Galtress and Kirkpatrick (2010) found that reinforcing one response more than the other in a bisection study led to an overall flattening of the psychometric function, consistent with an overall decrease in temporal control.

18.1.2 Reinforcement Effects in Simple Schedules

Timing manifests itself on an FI schedule by the fact that the subject pauses following the onset of the time marker before reinitiating a response. The duration of the pause (the so-called *wait time*) is roughly a linear function of the FI interval (Dews, 1970). In an associative decision rule framework, this is explained by the fact that states activated early in a trial are poorly associated with reinforcement (either because, as in LeT, they are weakly activated at the time of reinforcement, or because, as in BEM, they are rarely sampled at the time of reinforcement). Hence, increasing the magnitude of reinforcement should decrease the wait time, because it would strengthen the associations of all the states with reinforcement.

Associative decision rules make similar predictions for the peak procedure. The average pattern of responding during an unreinforced probe trial follows a roughly Gaussian function, with a peak around the time of reinforcement (Catania, 1970; Roberts, 1981). While such a pattern would suggest an increasing rate of response as a function of time in a trial up to the peak time, followed by a decreasing one, it has been argued that on individual trials, the behavior actually goes from a phase of low-responding to a phase of high-responding before moving back to a phase of low-responding, reflecting the subject's changing reward expectation as a function of the time-to-reinforcement (Cheng & Westwood, 1993; Church, Meck, & Gibbon, 1994). Trial-to-trial variability in the start time (where the transition from the low-response phase to the high-response phase takes place) and in the stop time (where the transition from the high-response phase to the low-response phase takes place) would be responsible for the Gaussian pattern observed in the average data. The same reasoning that led us to infer that increasing reinforcement magnitude should decrease wait time on FI also predicts a decrease in wait time (and start time) in the peak procedure and an increase in stop time. If the stop and start times are equally affected, the peak time should remained unchanged.

Data in the literature appear at first glance to support those predictions only partially. Although any change in timing behavior as a function of reinforcement manipulation is beyond the reach of cognitive models, the changes that are observed appear to be inconsistent with existing associative models. For example, studies that have transiently changed reinforcement magnitude during a session have actually found longer wait times following a stronger reinforcer (Blomeley, Lowe, & Wearden, 2003; Hatten & Shull, 1983; Jensen & Fallon, 1973; Lowe, Davey, & Harzem, 1974; Staddon, 1970; see also Kello, 1972; Reid & Staddon, 1982). However, as Ludvig, Conover, and Shizgal (2007) have pointed out, reinforcement also acted as a time marker in all those studies due to the absence of an intertrial interval. Because it is a more salient stimulus, a stronger reinforcer will be a better time marker than a weaker one and will induce better temporal control, and hence longer wait time. This is illustrated by the so-called reinforcement omission effect (Staddon & Innis, 1969), where occasional omission of the reinforcer in an FI leads to dramatically shorter wait time on the next trial. Since this time-marker effect goes against the effect on temporal control a stronger reinforcer has, as far as reward expectation is concerned, it probably explains why studies that have chronically changed the reinforcement magnitude (keeping it constant over several sessions) but have still used reinforcement itself to mark the beginning and the end of a trial have failed to find an effect of reinforcement magnitude on timing (i.e., Hatten and Shull 1983; see Ludvig et al., 2007 for more details).

Studies where the influence of the reinforcer as a time marker is weakened by the use of long intertrial intervals (which is always the case in the peak procedure) have, on the other hand, found a clear effect of chronic manipulations of the reinforcement magnitude, either through direct manipulation of its intensity (Galtress & Kirkpatrick, 2009; Grace & Nevin, 2000; Kacelnik & Brunner, 2002; Ludvig et al., 2007) or through an indirect manipulation of the reinforcer value through lithium chlorine-induced food aversion or pre-feeding (Galtress & Kirkpatrick, 2009; Plowright, Church, Behnke, & Silverman, 2000; Roberts, 1981). Overall, it appears that, besides a change in overall response rate probably due to changes in arousal (Killeen, 1998), the most reliable effect of reinforcement on timing performance is, as predicted by associative rules, a shortening of the wait time and start time with stronger reinforcers (Galtress & Kirkpatrick, 2009; Ludvig et al., 2007; Plowright et al., 2000). The stop time, on the other hand, remains relatively unchanged (Galtress & Kirkpatrick, 2009; Ludvig et al., 2007). Most studies also report a leftward shift in the peak time with a stronger reinforcer (Galtress & Kirkpatrick, 2009; Grace & Nevin, 2000; Kacelnik & Brunner, 2002) and a rightward shift following a reinforcer devaluation procedure (Galtress & Kirkpatrick, 2009; Plowright et al., 2000; Roberts, 1981), though this effect might depend on the methods used to assess the peak time. Ludvig et al. (2007) tested various methods and concluded that only the least sophisticated ones detected an effect of reinforcement on the peak time. Still, a leftward shift in the peak time with a stronger reinforcer as well as the rightward shift with a devaluated one is to be expected if the manipulation affects the start but not the stop time from the stop-start-stop view of performance on individual peak trials.

A procedure where an interaction between timing and reinforcement is well documented, even though poorly understood, is the mixed FI schedule (Catania & Reynolds, 1968; Leak & Gibbon, 1995; Whitaker, Lowe & Wearden, 2003, 2008). In this paradigm, the subject is trained simultaneously on two unsignaled FI schedules, so that there is no way to know which schedule is in place on a given trial. A proportion p of trials are reinforced according to the FI with the smallest interval, while the remaining $1-p$ trials are reinforced according to the other FI. For instance, in a mixed FI 10 s FI 30 s, the first response 10 s after trial onset would be reinforced for a proportion p of trials, while it would take 30 s since trial onset for reinforcement to occur in the remaining $1-p$ trials. The average response pattern in a mixed schedule can usually be fitted as the sum of two Gaussian functions, one peaking near the first time of reinforcement, the other near the second time of reinforcement (Catania & Reynolds, 1968; Whitaker et al., 2003, 2008). The relative height of the first peak in responding relative to the other can be manipulated through variations of p (Catania & Reynolds, 1968; Whitaker et al., 2008). Although this changes the height of the peaks, this does not change their timing (Whitaker et al., 2008). This is somehow reminiscent of the manipulation of the number of probe trials in the peak procedure, which also affects response rate without changing the start, peak, or stop times (Galtress & Kirkpatrick, 2009; Roberts, 1981). Yet this simple fact remains unsatisfactorily explained by contemporary theories of timing, no matter if they use a cognitive or an associative-response rule.

Models using cognitive rules, such as SET, do not anticipate the effect of manipulating *p* and have a problem assimilating it, notably because they lack any principle explaining how response rate is generated (Whitaker et al., 2008). Moreover, Machado and Silva (2007) have identified a fundamental conceptual flaw in SET's account of mixed schedule performance (as developed, for instance, by Leak & Gibbon, 1995), which is probably also true of most models using a cognitive rule. This account relies on the idea that the subject stores separately a LTM representation of the time of reinforcement for each FI composing the mixed schedule. However, as Machado and Silva (2007) point out (see also Machado et al. 2009), *there was no way for the subject to know from which FI a specific reinforcement was coming*. Probably for all these reasons, while SET has been successfully applied to the quantitative modeling of FI, the peak procedure, and the bisection procedure, there is no equivalent account of mixed schedule performance.

On the other hand, models with associative rules at least anticipate the effect of *p* on performance, and Machado (1997) showed that LeT provides a satisfactory quantitative account of the data on mixed schedules from Catania and Reynolds (1968). But the model cannot account for data sets where the first response peak is higher than the second, as it is often the case when the ratio between the FI intervals is high, especially in rats (see Whitaker et al., 2003 for instance). Hence, although they might seem at first glance a simple variation of the FI procedure, mixed schedules provide an interesting challenge for models of timing. Very little is known about them since this procedure has been somehow neglected by researchers. Further research on it should be encouraged, as it might provide an interesting testing ground for theories of timing as well as a fertile source of new ideas.

18.2 Contextual Effects on Time Perception

18.2.1 Relative Temporal Coding in the Double Bisection Procedure

Machado and Keen (1999) trained pigeons in two bisection procedures simultaneously. In the first task, response *R1* was reinforced after a 1-s stimulus, while response *R2* was reinforced after a 4-s stimulus. In the second task, response *R3* was reinforced after a 4-s stimulus while response *R4* was reinforced after a 16-s stimulus. On unreinforced probe trials, the pigeons were presented with stimulus duration ranging from 1 to 16 s and had to choose between *R2* and *R3*. Despite the fact that both responses were reinforced following a 4-s stimulus, the pigeons were not indifferent between them: preference for *R2* increased with the stimulus duration, the indifference point between *R2* and *R3* being reached around 4 s.

This paradoxical effect is quite robust as it is observed despite several modifications of the original double bisection procedure. For example, the increasing preference for *R2* as the sample duration increased held up when probe trials were nondifferentially reinforced (Machado & Pata, 2003); when the two bisection tasks were trained independently and never mixed together during the same session (Arantes & Machado, 2008); when, during the training of a bisection task, the two responses were never shown together but were instead differentially reinforced as a function of the stimulus duration (Arantes, 2008); and when each bisection task was signaled by a stimulus (Oliveira & Machado, 2009).

Hence, it seems that the LTM representation of the time associated with a response in a bisection procedure is context-dependent, since it is affected by the time associated with the other response trained in the bisection. This is a critical challenge to cognitive timing models, as context independency of the LTM representation is essential to cognitive decision rules (Machado et al., 2009). On the other hand, context dependency comes naturally to models using associative rules (Jozefowiez et al., 2009; Machado et al., 2009). To see how this works in the Machado et al. experiments, let's parse the input states into three categories: early, middle, and late. Early states are strongly activated/sampled after a 1-s stimulus, mildly activated/sampled after a 4-s stimulus, and weakly activated/sampled after a 16-s stimulus. Late states present the reverse pattern. Middle states are strongly activated/sampled following a 4-s stimulus and mildly activated/sampled following a 1-s or 16-s stimulus. During the course of the 1-s vs. 4-s discrimination, differential reinforcement will lead the early states to be strongly associated with *R1* and weakly associated with *R2,* while the reverse will be true for the middle states. If we assume that every state has an initial weak connection with the responses (Machado & Plata, 2003), connections between the late states and both *R1* and *R2* will remain weak, as those states will rarely be activated during the 1-s vs. 4-s task. In the same way, during the 4-s vs. 16-s discrimination, the middle states will develop strong connections with *R3* and weak connections with *R4,* while the reverse will be true for the late states. Connections between the early states and both *R3* and *R4* will remain weak. Hence, when *R2* is pitted against *R3*, the subjects will prefer *R3* for durations around 1 s (stronger associations between the early states and *R3*), will be indifferent between the two around 4 s (equivalent association strength between the middle states and both responses), and will prefer *R2* around 16 s (stronger associations between the late states and *R2*).

This analysis also correctly predicts the outcome of further probe trials where the pigeons were given the choice between *R1* and *R3* on one hand, and *R2* and *R4* on other. In the first case, the preference for *R3* increased up to a duration of 4 s before the subjects switched back to *R1*. In the second case, preference for *R4* increased up to a duration of 4 s (even though *R2* has been reinforced after a 4-s stimulus duration) before the subjects switched back to *R2*. In all these cases, a model using a cognitive rule predicts that the preference for the response associated with 4-s stimulus, no matter if it has been trained in a 1-s vs. 4-s discrimination or a 4-s vs. 16-s discrimination, will increase with the stimulus duration.

The associative interpretation of the double bisection procedure was further strengthened by a study by Machado and Arantes (2006). After training pigeons in a 1-s vs. 4-s discrimination and 4-s vs. 16-s one, they used *R2* and *R3* (the two responses associated with a 4-s stimulus duration) in a new bisection task pitting a 1-s stimulus against a 16-s one. In group 1, R3 was now reinforced following a 1-s stimulus, while R4 was now reinforced following a 16-s stimulus. The contingencies were reversed in group 2. In the former group, the pattern of associative strength induced by the double bisection task is consistent with the pattern of associative strength required by the new task, while this is not the case for the later group. Hence, Machado and Arantes (2006) predicted that the new task would be much easier to learn for group 1 than group 2. This was indeed the case, as group 1 learned the new task almost without mistakes while performance in group 2 was initially poor. This difference between the two groups cannot be explained by a cognitive rule.

A possible alternative interpretation of the double-bisection result can be found in a study by Zentall, Weaver, and Clement (2004). They trained pigeons in a 2-s vs. 8-s bisection task as well as in a 4-s vs. 16-s one. Note that the long-duration stimulus in the first bisection is located at the geometric mean of the two durations used in the second bisection task, while the short-duration stimulus in the second bisection task is located at the geometric mean of the durations used in the first bisection task. In a bisection study with nonhuman animals, the time at which the subject is indifferent between the two responses (the so-called bisection point) is located at the geometric mean between the two training durations (Church & Delutty, 1977; Stubbs, 1968). Hence, the pigeons should be indifferent between the two response alternatives if they are presented with a 4-s stimulus in the first bisection task and with an 8-s stimulus in the second bisection task. Instead of that, Zentall et al. (2004) observed that responding following a 4-s stimulus was biased toward the 2-s response in the first bisection, while responding following an 8-s stimulus was biased toward the 16-s response in the second bisection task.

Zentall et al. (2004) proposed that the subjects were encoding not only the absolute duration of the stimulus, but also its category, as relatively “long” or “short.” In other words, Zentall et al. added a kind of cognitive encoding to the purely temporal one. When exposed to a 4-s stimulus in the first bisection task, the categorical code would overrun the absolute duration code, since the latter could not be used to decide which response to choose. Hence, since the 4-s duration would have been tagged as “short” because of the training in the second bisection task, while, in the first bisection task, the response reinforced after a stimulus categorized as “short” is the 2-s answer, the pigeon would be biased toward that response. The same reasoning explains the bias toward the 16-s response following an 8-s stimulus in the second bisection task.

Zentall et al.’s scheme might explain the results from Machado and collaborators, albeit at some cost in terms of parsimony. When given the choice between two responses, both reinforced following a 4-s duration, the absolute duration code would be useless to decide which response to choose, and it would overridden by the categorical code. Durations around 1-s would be categorized as “short,” and hence, the subject would tend to associate them with the 4-s response reinforced following “short” durations, that is to say *R3*. On the other hand, durations around 16 s would categorized as “long,” and hence, the subjects would associate with them the 4-s response reinforced following “long” durations, that is to say *R2*. The categorical coding for durations around 4 s would be ambiguous (they were categorized as “long” in the 1-s vs. 4-s discrimination, but as “short” in the 4-s vs. 16-s discrimination), and hence the pigeons would be indifferent between the two responses at 4 s.

Unfortunately, without a proper quantitative formulation to define the category-formation process, it is difficult to know if categorical encoding provides a better account of the double bisection data than associative models such as LeT. Further research is necessary to establish the generality of Zentall et al.'s (2004) result. While Molet and Zentall (2008) were able to replicate their results with humans (using the arithmetic mean instead of the geometric one), Maia and Machado (2009) failed to found the predicted switch in the psychometric curves of pigeons submitted to Zentall et al.'s (2004) double bisection procedure.

18.2.2 Other Instances of Relative Encoding

One of the most interesting conclusions that can be drawn from the double-bisection procedure is that, much like other forms of perception such as brightness or color, the perception of time is not absolute but depends on the context. There are a few other examples of this in the literature outside of the double-bisection procedure.

For instance, Jazayeri and Shadlen (2010) presented human subjects with stimuli lasting *x* ms and asked them to reproduce those durations. Depending on the condition, *x* was drawn from three possible stimulus distributions: one ranging from 494 to 847 ms in condition 1, one ranging from 847 to 1200 ms in condition 2, and finally, one ranging from 671 to 1023 ms in condition 3. They found, that in all conditions, shorter durations were overestimated while longer ones were underestimated. The effect was stronger the further a specific duration was from the mean of the stimulus distribution from which it was drawn and the higher the mean of that distribution. As a consequence, estimates for a specific interval varied as a function of the distribution from which it was drawn. For instance, an estimate of a 847-ms stimulus lasted about 847 ms in condition 2 (where 847 ms corresponded to the mean of the stimulus distribution), while it lasted less than 847 ms in condition 1 (where 847 ms was above the mean of the distribution) but more than 847 ms in condition 3 (where 847 ms was below the mean of the distribution).

Another example of context dependency can be found in a study on choice in starlings by Shapiro, Siller, and Kacelnik (2008). The starlings were trained to choose between stimuli leading to different delays and amounts of food. They were exposed to both choice trials, in which two stimuli were presented concurrently and the animal had to decide which one to choose, and no-choice trials in which only one stimulus was presented. On those trials, the wait time was not only a function of the delay of reinforcement signaled by the stimulus but depended also on the delay of reinforcement signaled by the stimulus against which the target stimulus was pitted in the choice trials.

It would be interesting to see if other examples of relative temporal coding could be demonstrated and whether they can be explained by the same mechanisms, or if different explanations are required for each of them. For instance, it is hard to see how Machado and collaborators' explanations for the context effect in the double bisection procedure could apply to Jozaveri and Shadlen's (2010) results. On the other hand, it seems that they could be very simply explained within the context of a cognitive decision rule. A stimulus lasting *x* ms would lead to a LTM representation *f(x),* which would itself lead to a LTM representation *f*(x)*. When asked to reproduce the interval, the subject would compare the value of its current STM representation *f(t)* with *f*(x)*. The effects observed by Jazayeri and Shadlen (2010) would be the consequence of, on one hand, proactive interference, which would lead *f*(x)* to regress toward the mean of the stimulus distribution, and, on the other, Weber's law (see below), which would increase the degree of proactive interference as the stimulus durations are increased[3].

18.3 The Coding of Subjective Time

18.3.1 Implications of the Decision Rule for the Representation of Time

One important constraint on timing models is the fact that time perception follows Weber's law: the ability for a subject to perceive changes in a stimulus increases linearly with its intensity, in this case its duration (see the reviews, for instance, in Gibbon, 1977, Lejeune & Wearden, 2006 and Wearden & Lejeune, 2007). Various representation schemes consistent with Weber's law have been proposed in the literature. In SET (Gibbon, 1977; Gibbon et al., 1984), a time marker triggers an internal pacemaker whose pulses start to accumulate in STM. The rate of pulses emitted by the pacemaker is supposed to vary on a trial-to-trial basis according to a Gaussian law with mean a and standard deviation k. Hence, the number of pulses accumulated in STM t units of time since the time-marker onset is also a random variable, following a Gaussian law with mean at and standard deviation kat. A popular alternative to this "scalar" encoding scheme is the logarithmic encoding scheme, according to which the LTM representation f(t) of an interval t is a random variable drawn from a Gaussian distribution with $\ln t$ and standard deviation k. It is used, notably, by BEM (Jozefowiez et al., 2009) and somehow by MTS (Staddon & Higa, 1999). BET (Killeen & Fetterman, 1988) assumes that a time marker triggers a series of ordered behavioral states. Transition from one state to the other is controlled by a Poisson process. In order to account for Weber's law, the theory needs to postulate that the rate of the Poisson process is proportional to the reinforcement rate. LeT (Machado, 1997) uses a mathematically equivalent scheme.

While the issue of the LTM representation of time and the one of the decision process might appear to be separate questions, they are not, because Weber's law is respected only for specific combinations of STM representation scheme and decision rule (Jozefowiez & Machado, 2013). In the case of cognitive rules, for instance, it is well known that the Weber's law properties of timed behavior can be explained either by combining a logarithmic representation with a difference rule (a rule where the decision variable is a function of the difference between the STM representation of the time elapsed since the time-marker onset and the LTM representation of the time of reinforcement) or a scalar representation with a ratio rule (a rule where the decision variable is a function of the difference between the STM representation of the time elapsed since the time-marker onset and the LTM representation of the time of reinforcement). Combining a scalar representation with a difference rule or a logarithmic representation with a ratio rule does not work (Gibbon, 1981).

Although a full formal treatment is still lacking (see Jozefowiez & Machado, 2013 for further step in that direction), it seems that similar incompatibilities exist with associative decision rules. Obviously, a logarithmic representation scheme as well as Poisson timing process works, since they are used by BEM, BET, and LeT, which are all using associative decision rules. On the other hand, it seems that a scalar representation scheme does not work well when combined with an associative decision rule. Jozefowiez et al. (2009) showed that, if a scalar representation is substituted for a logarithmic one in BEM, the model fails to accurately predict psychometric functions in the bisection procedure, notably because Weber's law is violated. Similarly, Machado et al. (2009) showed that a modified version of LeT, using a scalar representation instead of the original Poisson timing process, fares much more poorly than the original model when applied to data from the peak procedure and the bisection one.

Roberts (2006) trained pigeons to emit one response when presented with a stimulus whose duration ranged from 1 to 8 s (respectively, 2 to 16 s) and another one when presented with a stimulus ranging from 8 to 16 s (respectively, 16 and 32 s). The closer the stimulus duration was to the category boundary (8 s in one condition, 16 s in the other), the worse the performance of the pigeons. The psychometric curves also displayed some systematic asymmetries. Roberts (2006) fitted those data with various models using associative rules and concluded that in all cases, a model using a logarithmic representation better accounted for the data, especially the asymmetries, than one using a scalar representation.

Yi (2009) used signal-detection theory to analyze the performance of rats submitted to a variant of the bisection procedure: a correct response was reinforced only after a random interval drawn from an exponential distribution (a so-called random-interval schedule of reinforcement). This allowed Yi (2009) to compute not only the probability of a correct response following a specific stimulus but also the rate at which the rats were responding. She postulated that different levels of response rate were akin to different thresholds in a signal-detection model, which allowed her to plot ROC curves for her subjects. She showed that those curves were compatible with a signal-detection model assuming a logarithmic representation of time with constant variance and incompatible with a signal-detection model assuming a linear representation with a standard deviation proportional to the mean. Since models using associative rules are often formally equivalent to signal-detection theory as far as simple discriminations are concerned (models using a cognitive rule share the same relation with another psychophysical model: Thurstone's law of comparison; see Falmagne, 1985 for a review of that theory), Yi's data provide additional evidence that than an associative decision rule is incompatible with scalar time representation.

18.3.2 Associative and Cognitive Accounts of the Time-Left Procedure

Hence, any argument in favor of an associative-response rule is an argument against a scalar representation of time, and so against the idea that interval timing relies on an internal pacemaker. On the other hand, any argument for a scalar representation is an argument against an associative-response rule (Jozefowiez & Machado, 2013).

The most convincing case for a scalar representation is usually considered to come from the time-left procedure, a complex paradigm invented by Gibbon and Church (1981). The basic idea is to compare the preference of the subject for an elapsing time-to-reinforcement C-t on the so-called time-left side over a constant time-to-reinforcement S on the so-called standard side for various time t in a trial. If the subject always chooses the side associated with the shorter delay of reinforcement, it should prefer the standard side early in a trial, before switching to the time-left side. Moreover, if the subjects encode time linearly and use a ratio decision rule, they should be indifferent between the two responses when $(aC - at) / aS = 1$; that is to say, when $t = C - S$. On the other hand, if the subjects encode time logarithmically and use a difference decision rule, they should be indifferent between the two responses when $(\ln C - \ln t) - \ln S = 0$; that is to say, when $t = C/S$. Moreover, we can infer from this analysis that, if the absolute values of C and S are changed but their ratio is held constant, the location of the point of subjective equality should change only if the representation is linear (Gibbon & Church, 1981).

Gibbon and Church (1981) used two versions of the time-left task to test these predictions. In the first version, rats were first trained on two fixed-interval (FI) schedules: the time-left schedule, reinforcing responses C sec after trial onset, and the standard schedule, reinforcing responses S sec after trial onset. Then, as the subject is already responding on the time-left side for t sec, it is given the opportunity to respond on the standard side. Using rats as subjects and with $C = 2S = 60$ sec, Gibbon and Church (1981) were able to show that the rats preferred the standard side for $t = 15$ sec, the time-left side for $t = 45$ sec, while they were indifferent between them for $t = 30$ sec (see Machado & Vasconcelos, 2006 for a replication in pigeons and Wearden, 2002 for an adaptation of the procedure with similar results in humans).

In the second version of the procedure (which used pigeons as subjects), the subject has continuously available the choice between the time-left and the standard side. At a random time t, a response on either commits it to that schedule. The reward is then delivered C-t seconds later if the subject is committed to the time-left side, S seconds later if the subject is committed to the standard side. If preference for the standard side decreased as time in a trial increased, the point of indifference was located well before $C - S$ seconds. This result was also observed by Gibbon and Fairhurst (1994) and Cerutti and Staddon (2004) in pigeons and by Preston (1994) in rats; a similar bias was found by Brannon et al. (2001) in a time-left procedure in pigeons using number instead of time as the relevant dimension to solve the discrimination. Still, holding the C/S ratio constant, the switchover point changed linearly with C, allowing Gibbon and Church (1981) to conclude in favor of a linear representation of time.

Despite its methodological complexity, which may affect interpretations of performance in ways still little understood (see, for instance, the analysis by Cerutti & Staddon, 2004;

Preston, 1994; Machado & Vasconcelos, 2006 and Vieira do Castro & Machado, 2010), the time-left procedure seems to offer a plausible way to compare linear and logarithmic representation, given that the subject uses a cognitive decision rule. But how would a model using an associative decision rule fare in the time-left procedure? Jozefowiez et al. (2009) looked at it in the case of BEM (see also Dehaene, 2001). In BEM, the STM representation[4] x of an interval t is a random variable drawn from a Gaussian distribution with mean $\ln t$ and standard deviation k. The subject then retrieves $V_{TL}(x)$ and $V_S(x)$—the payoff for picking, respectively, the time-left side and the standard side when the representation takes the value x, that it could have learned through a simple associative learning rule such as Bush-Mosteller. The subject simply chooses the side associated with the higher payoff. Overall, at the asymptote, we have

$$V_{TL}(x) = \sum_{i=0}^{n} P(x \mid t_i) I(C - t_i) \tag{18.1}$$

and

$$V_S(x) = I(S)\,, \tag{18.2}$$

where $I(x)$ is the value of a reinforcer delayed by x units of time and $t_0, t_1, \ldots, t_i, \ldots, t_n$ are times in a trial where the subject had to choose between the time-left and the standard side. In the first version of the time-left procedure, where there are only three times like this, including one at C-S and where $2S$=C, we have

$$V_{TL}(x) = P(x \mid t_1) I(C - t_1) + P(x \mid t_2 = C - S) I(S) + P(x \mid t_3) I(C - t_3)\,. \tag{18.3}$$

If t_1, C-S, and t_3 are far enough apart, the states x sampled at each of these three intervals will negligibly overlap. Hence, the value of the time-left side will roughly be equal to $I(C$-$t_1)$ at t_1, $I(S)$ at C-S, and $I(C$-$t_2)$ at t_3. In other words, the subject will prefer the standard side at t_1, the time-left side at t_3, and will be indifferent between the two at C-S. Interestingly, as shown by the simulations of Jozefowiez et al. (2009), as the number of times where the subject has the opportunity to choose between the time-left and the standard side increases (as is the case in the second version of the time-left procedure), the point of indifference shifts to display a strong bias toward the time-left side, a result found in all replications of the time-left procedure—but not predicted by SET. This bias is a consequence of the logarithmic representation used by the model. Yet, the point of indifference remains a linear function of C. Indeed, the predictions of the model concerning the location of the indifference point are very close to the data reported by Gibbon and Church (1981; see Jozefowiez et al., 2009).

Hence, the results for the time-left experiment are compatible with a model combining a logarithmic representation with an associative-response rule like BEM, but incompatible with a model combining a linear representation with a ratio cognitive rule like SET.

Moreover, the associative account predicts that the subject will need some experience with the choice procedure in order to learn the delay to reinforcement on both schedules at the various choice points. Previous training on the time-left and standard side outside of the context of a choice paradigm will not be sufficient. On the contrary, SET predicts that such a training will be sufficient, as it allows the subject to learn the various intervals on which its choice performance is assumed to rely. Machado and Vasconcelos (2006) tested those two accounts in a replication of the first version of the time-left procedure, using pigeons as subjects (see also Vieira de Castro & Machado, 2010). Overall, their results are not consistent with SET, as they showed that extensive experience with the choice paradigm is necessary for the pigeons to reach stable-state performance in the time-left procedure. On the other hand, after as few as nine choice trials (three for each value of t_i), the pigeons already preferred the time-left side more at t_3 than at $t_{1,}$ even though their preference for the standard side was more extreme than what it would be at asymptote. This seems to indicate some carry-over effect of the training of the time-left and standard schedules outside of the choice paradigm, an effect not predicted by the associative rule. The transfer effect between choice and nonchoice procedures are overall poorly understood. At any rate, it would be interesting to see how an associative model (i.e., BET or LeT) using an alternative representation of time would fare in the time-left procedure.

Note that, except when explicitly mentioned, all the data discussed in this chapter have been collected on nonhuman animals, mainly rats and pigeons. Although human timing is thought to rely on the same mechanisms as timing in nonhumans (Allan, 1998), a critical difference between the two can be observed as far as the location of the bisection point in a bisection procedure is concerned. While it is usually located near the geometric mean of the two trained durations in animals (i.e., Church and Deluty 1977), it is usually observed near the arithmetic mean of the two trained durations in humans, although a few experiments have also reported a bisection point at the geometric mean (see Allan, 1998 for a review). These differences are still poorly understood, but they have one major implication. A bisection point at the geometric mean is highly suggestive of logarithmic encoding, just as a bisection point at the arithmetic mean is highly suggestive of a linear encoding. But if it is possible to reconcile a bisection point at the geometric mean with a linear encoding scheme (Gibbon, 1981), it is on the other hand impossible to reconcile a bisection point at the arithmetic mean with a logarithmic encoding. Hence, it strongly suggests that in some situations, at least, humans encode time linearly. If arguments favoring an associative-response rule argue against a scalar representation of time, do arguments favoring a linear encoding of time argue against an associative decision rule? Not necessarily. One encoding scheme assuming a linear representation of time and compatible with an associative decision rule is one where the representation $f(t)$ of an interval t is a random variable drawn from a Gaussian distribution with mean at and constant standard deviation k. In order to get Weber's law, this scheme has to postulate, a little like in BET and LeT, that k is proportional to the rate of reinforcement[5]. The issue of whether the representation of time is affected by the reinforcement rate has been investigated in the animal literature and so far has received mixed support (see, for instance, Fetterman & Killen, 1995 and Oliveira & Machado, 2009 for positive evidence and MacEwen & Killeen, 1991 and Leak & Gibbon, 1995 for negative), but has received comparatively little attention in the human literature.

Given the potential importance of this issue regarding the decision rule most appropriate to accounting for human timing, more research should perhaps be conducted on this topic.

18.4 Conclusion

All in all, the data reviewed in this chapter favor associative rules over cognitive rules, mainly because the latter are able to account neither for the effects of reinforcement on timing nor for the contextual effects evidenced in the double-bisection procedure. Further theoretical additions would be necessary before cognitive rules could cope successfully with those two classes of phenomena. To deal with reinforcement effects, a rigorous theory of how response bias is affected by reinforcement needs to be developed. The double bisection effect is more challenging, as it will necessitate a profound revision of the mechanisms underlying the formation of the LTM representation of the time of reinforcement so as to include the possibility for context dependence. On their side, associative models need to improve their account of reinforcement effects on timing, notably by tacking the challenge of mixed FI schedules. Overall, we believe more research should be devoted to the study of reinforcement and contextual effects on timing. Few studies have yet been conducted on those two issues, and we hope to have shown in this paper that they provide a fertile ground to contrast opposing theories of interval timing.

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Notes

1. Note a time marker is defined behaviorally: tests may reveal that the time marker used by the controlling reinforcement schedule is not always the one used by the subject.

2. Machado et al. (2009) have suggested that SET could account for these results by combining a threshold biased by the difference in absolute reinforcement rate with memory stores that represent

relative reinforcement rates, but careful quantitative analysis is needed in order to see if this explanation is adequate.

3. This explanation is actually much simpler that the convoluted Bayesian model provided by Jazayeri and Shadlen (2010). Moreover, this Bayesian account might actually be flawed, as shown by Taatgen & van Rijn (2011). These authors also provide an alternative explanation of the results by Jazayeri and Shadlen (2010), which is very much in line with the one proposed here.

4. The STM representation is discretized, so that $P(x|t)$ is different from 0.

5. Including rate of reinforcement in a timing model is tricky from a theoretical point of view, because the model must then define the averaging process—linear or exponentially weighted, over what window, etc.

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VIII What and When

Perception is embodied, as many of the previous chapters emphasize. What we sense is interwoven with how we sense it, a function of moving organs and limbs in a dynamical dance with shifting environments. The authors of the previous section considered action governed by prospective timing, where an animal needs to wait before it acts. In this section we turn from action to perception. Perception is often depicted as a synchronous process of information coordination. The pen in my grasp is one object, built out of haptic aspects of weight, solidity, and felt shape, mixed in with glimpses of color and shape. These multiple streams of information comprise the experience of the pen in hand. Nowadays it is naive to suppose that these streams converge into a single arena of unified experience, a place where the pen-experience is realized as a unitary conscious percept. (This mythical terminus is thoroughly dismantled in Dennett's *Consciousness Explained* [1991], as discussed in chapter 11). But if there is no "Cartesian theater," what binds one disparate flock of sensations into a percept of the pen, while another flock coalesces into the coffee mug handle, inches away? Time is sometimes assumed to be the glue. The pen bits are bound together by the simple fact that they occur simultaneously. But a moment's reflection (and review of parts I–V) reveals that the *when* of perception is just as much a construction as the *what*. Information takes time to travel from far-flung sensory neurons to different regions of the brain, lags that vary according to the distance and type of information. When I step on your toe, the sight of it makes it to the brain tens of milliseconds ahead of the grinding feel, but you do not perceive two events.

These basic examples highlight the problems of simultaneity and time order in perception. If we consider that perception is the achievement of sensory systems in constant motion, the time problem is acute. The five glances that I bestow on the pen as I reach for it yield five different retinal images, which must be factored against five saccadic jumps (and other movements) to provide a consistent suite of muscle contractions tailored toward grasping the real object on the desk. These very different sensory streams (the visual and the proprioceptive) had better be coordinated on their time line and kept in order. Clearly, time ordering is a constant process, and like much of subjective time, is usually so smooth as to be nearly invisible.

The following three chapters zoom in on the foundation of subjective time: the perception of simultaneity and the complementary capacity to order events in time. Simultaneity is neither absolute nor constant in the various psychophysical experiments in this section. Instead, the point of subjective simultaneity encompasses a temporal window of near-simultaneous events; events separated by more than this window will be more likely to be perceived as nonsimultaneous. Agnieszka Wykowska and Valtteri Arstila (chapter 21) refer to the fineness of simultaneity as the temporal resolution of a subject. The factors that affect resolution provide us with further clues to the psychological and neural mechanisms of subjective time.

The simplest and most general model of simultaneity imagines the point of subjective simultaneity as the outcome of a race between simple reaction times between events. Events that cross some finish line of action initiation (pushing a button, for example) neck-and-neck are simultaneous. Chapter 19, by Piotr Jaśkowski, reports on several ways in which this model breaks down even for simple stimuli in the same sensory modality. Perhaps simultaneity judgments are a side effect of temporal-order judgments? If one event is perceived to precede another, then we know they are not simultaneous. But even this simple functional integration is undermined by experiments in which stimuli are perceived to be nonsimultaneous, but subjects cannot judge which is first. Indeed, many factors other than timing can modify both simultaneity judgments and temporal-order judgments. The list begins in the chapter by Jaśkowski, and diversifies in chapter 20, by Argiro Vatakis and Georgios Papadelis, who extend the range of stimuli to include speech, musical phrases and gestures, and others, presented in and out of sync to vision and hearing. Then, in chapter 21, Wykowska and Arstila diversify the stimuli along still other dimensions: These short time discriminations can be altered for particular locations in the visual field, or by an act of "temporal focus," paying particular heed to an upcoming moment, or by other manipulations of the task instructions. Not surprisingly, there are time experts who have excellent temporal acuity. Look for them in an orchestra, especially at the podium or back in the percussion section.

Einstein famously demonstrated that two events can be simultaneous (or not) only relative to specific observers. However, we are generally at work in the immediate neighborhood of the body, in a seemingly less relativistic region where simultaneity behaves like a fact about events, awaiting detection by our fast-enough brains. Far from being a simple "given," waiting to be detected, simultaneity turns out to be one of the brain's most sophisticated constructs.

19 What Determines Simultaneity and Order Perception?

Piotr Jaśkowski

All physical objects in the universe are embedded in three-dimensional space, and all physical events are immersed in time. Therefore, to properly act, human beings evolved abilities to orient in space and to put events in temporal order. It seems quite easy to say that an event occurred earlier than another one. However, this task becomes more difficult when the events occur very close in time to the other. It is rather obvious that in judging the order of two events the human mind has to rely on some brain events evoked by the external stimuli. It is, therefore, at least theoretically possible that, for some physiological reasons, two physical events are erroneously perceived in a reverse order. In the last three decades much effort has been put into uncovering the physiological factors underpinning the perception of the subjective temporal order. In this chapter, we review the main findings concerning this topic.

19.1 Measuring Sensory Latency with TOJ/SJ

Two methods have most frequently been adopted to study perception of order and simultaneity: the temporal-order judgment (TOJ) task and the simultaneity judgment (SJ) task.

Let us consider two stimuli, S_x and S_y, stimulating two separate sensory channels, x and y, and presented at t_x and t_y, respectively. The temporal interval between the onsets of the stimuli, $t_x - t_y$, is called stimulus onset asynchrony (SOA) and usually varies from trial to trial. In the SJ task, participants are required to judge whether or not the two stimuli were presented simultaneously. The frequency of a specific response ("simultaneous" or "nonsimultaneous") varies systematically with SOA. One can easily imagine that if two physically identical stimuli are presented simultaneously at some distance, they should also be perceived as simultaneous. Therefore, for SOA = 0 ms, the participants will report "simultaneous" most frequently. If SOA deviates more and more from zero, this response will be less and less frequent. Thus, the psychometric function for SJ should be a bell-shaped curve with maximum for SOA = 0. The SOA at which the psychometric function reaches its maximum is called the point of subjective simultaneity (PSS). For two identical stimuli, we expect PSS = 0 ms.

In the TOJ task, participants are asked to specify which of two stimuli, separated by an SOA, occurred first. If S_x (S_y) is presented much earlier than S_y (S_x) (i.e., SOA >> 0), then it is obvious that participants would report "S_x first" ("S_y first") in all trials. The psychometric function (percentage of "S_x first" responses as a function of SOA) is typically fitted with a cumulative Gaussian distribution. Once SOA is close to zero, observers perceive the stimuli as simultaneous and are unable to report their order. Therefore, the SOA at which participants report equally often "S_x first" as "S_y first" should correspond to the PSS.

It is worth noting that a PSS = 0 is expected only under particular conditions, namely when the two stimuli are identical and stimulate two identical sensory channels, a situation difficult to achieve. Indeed, PSS has proven to depend on many factors, which we will talk about later in this chapter.

19.2 Simultaneity versus Order Judgment

So far, we accepted the assumption that both TOJ and SJ provide identical results, in the sense that PSSs obtained are equal under the same stimulation conditions. This assumption is based on seemingly obvious reasoning, which is accepted in the majority of models: if observers perceive two stimuli as nonsimultaneous, they should be able to tell the order of the stimuli. In fact, this is not as trivial as it seems. There are some empirical findings suggesting rather the reverse. For example, Jaśkowski (1991b) highlighted some peculiarities of the psychometric functions when the so-called ternary response paradigm was used (Stelmach & Herdman, 1991; Ulrich, 1987). In this paradigm, participants responded with three possible responses: "S_x first," "S_y first," "S_x and S_y simultaneous." The psychometric function modeling the probability of "S_x first" ("S_y first") as a function of the SOA was found to be nonmonotonic, having a local minimum. Jaśkowski (1991b) showed that this extraordinary behavior could be accounted for by assuming that there are two mechanisms working in parallel. One of them is responsible for telling apart "S_x first" from "S_y first," while the second assesses whether the two stimuli were simultaneous or not. This nonmonotonicity occurred, according to this model, because in some trials people perceived the stimuli as nonsimultaneous while they were still uncertain as to the order of them. This model has never been tested empirically; nevertheless, there is some evidence that sensory latency estimated by SJ and TOJ is different (Schneider & Bavelier, 2003; van Eijk et al., 2008). For example, Schneider and Bavelier (2003) investigated the effect of attention-directing cues on visual latency. Their participants were asked to respond with which of the two visual stimuli (one cued and one noncued) were presented first or, in another session, to judge whether the two stimuli were presented simultaneously or not. The authors reported significantly reduced PSS when estimated by SJ as compared to PSS obtained with the TOJ task (see also Spence & Parise, 2010 for a meta-analysis). These results are consistent with the idea that there are two centers responsible for SJ and TOJ. Nonetheless, it should be noted that such attention-related effects might also be accounted for by a response bias as noted by Spence and Parise (2010). Indeed, it is plausible that participants in the TOJ task may simply report the modality they had been instructed to attend to, instead of reporting which stimulus was presented first. As no data has been reported thus far regarding potential bias in estimating PSS from SJ data, according to Spence and Parise, many authors argue that it is more appropriate to use SJ rather than TOJ to find PSS.

19.3 Simple Reaction Time

Presentation of a stimulus triggers a series of cognitive processes that can lead to a motor response. Each of these processes lasts some time; therefore, a finite time elapses between the stimulus onset and the motor response to it. This interval is called reaction time. The simplest perceptual task is stimulus detection. If, additionally, participants are asked to respond to this stimulus as fast as possible by making a specific movement, we deal with the so-called simple reaction.

Almost all models decompose overall reaction time (RT) additively into two components: detection time, *D*, defined as the time between stimulus onset to the moment of stimulus detection, and motor time, *M*, defined as the time needed for the activation of specified muscle groups. Additionally, the motor time is usually assumed to be constant: it is assumed that the duration of processes after stimulus detection do not depend on physical parameters of the stimulus such as its intensity. With these assumptions in mind, it follows that changes of simple RT reflect the changes of perceptual latency. This idea is illustrated in figure 19.1.

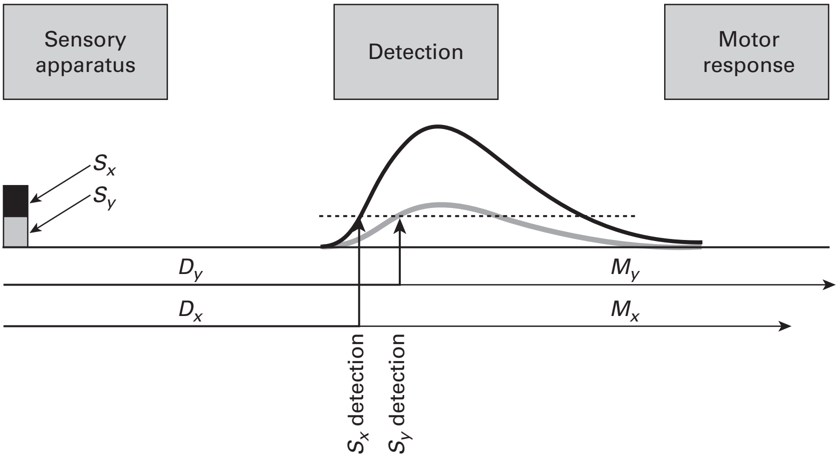

Figure 19.1

Simple reaction time is commonly divided into detection time (D_x and D_y) and motor time (M_x and M_y). A stimulus evokes an internal activity of dynamics depending on its parameters, such as intensity. Here this activity is modeled with a bell-shaped curve (black for a high-intensity stimulus; gray for a low-intensity stimulus). A stimulus is assumed to be detected once this internal activity reaches a given criterion (dotted line). Detection triggers motor processes. Detection time—time from stimulus onset to the crossing of the criterion—is longer for low- than for high-intensity stimulus. Assuming that motor times are constant, changes of reaction time reflect changes of detection time.

19.3.1 Motor Time Constancy

As motor time constancy is an important issue for our further discussion, evidence supporting this view will be described now. The motor component of RT seems to be strongly immune to manipulation of experimental variables. This has been shown usually by measuring event-related potentials. Initially, a proper method seemed to be the comparison of RTs with the latencies of early sensory cortical evoked potentials (EP). EPs have been claimed to reflect durations of early sensory processing stages, but not of late motor components. Thus, if the motor component of RT is independent of a given variable, the changes of RT should parallel the changes of EP latency. Indeed, early comparisons of this kind showed that the curves relating RT and EP latency to stimulus intensity were perfectly parallel (Jaśkowski, Pruszewicz & Świdziński, 1990; Vaughan, Costa & Gilden, 1966; Williamson, Kaufman & Brenner, 1978; Wilson & Lit, 1981). Such results were interpreted as evidence in favor of the hypothesis that RT changes reflect changes in perceptual latency. This also justified the use of reaction time as a simple method for estimating changes of detection time. However, later studies did not replicate these findings. Jaśkowski, Rybarczyk, and Jaroszyk (1994) found a larger effect of intensity on simple RT than on EP latency for auditory stimuli, and more recently, Kammer, Lehr, and Kirschfeld (1999) reported comparable results for visual stimuli. While these findings might be interpreted in favor of an intensity-dependent motor component, this interpretation was generally criticized. Some authors (Callaway et al., 1984; Meyer et al., 1988) have argued that RT and EP latency are not comparable because of their different statistical properties: "The latency of the average is not the average of the latencies," as is stated in the title of Callaway et al.'s contribution. In sum, the parallel dependence of RT or EP latency and intensity (or another independent variable) cannot tell us much about whether the motor component depends on this variable.

Another method based on EEG has been devised and commonly used in mental chronometry studies. This is the lateralized readiness potential (LRP; see, e.g., Coles, 1989; for reviews, see Eimer & Coles, 2003; Leuthold, Sommer & Ulrich, 1996). Prior to the triggering of a voluntary movement, a negative potential can be observed over the human scalp. It is larger over the left than over the right precentral gyrus prior to a right-hand movement; the opposite is observed for left-hand movements. The moment-by-moment difference between the EEG activity over sensorimotor cortical areas contralateral and ipsilateral to the responding hand is called the LRP.

The onset of the LRP serves as a temporal marker for the moment at which response-specific processes become active. This onset can be determined relative to stimulus presentation (stimulus-locked LRP or S-LRP) or to the onset of the overt response (response-locked LRP, or R-LRP). If an experimental factor affects processes occurring prior to response initiation, the S-LRP latency should be altered. Conversely, the effect on the duration of processes taking place between response initiation and the participant's overt response are most clearly seen in the R-LRP latency. Therefore, the latency of R-LRPs and of S-LRPs are useful marks in determining whether an experimental manipulation affects the duration of early processes, late processes, or both.

LRP has been used in a remarkable number of studies to find the loci of the effect of different variables. According to my best knowledge, only the speed-accuracy trade-off has been shown to affect R-LRP latency (Osman et al., 2000; Rinkenauer et al., 2004). Other investigated variables affected only S-LRP latency (e.g., (Leuthold, 2003; Low & Miller, 1999; Miller & Ulrich, 1998; Smulders et al., 1995; van der Lubbe et al. 2006), even such variables as foreperiod duration, which has commonly been assumed to affect very late processes (Müller-Gethmann, Ulrich & Rinkenauer, 2003). In particular, stimulus intensity was also shown to affect only the "perceptual" part of RT (Jaśkowski et al., 2007; Jaśkowski, Szumska & Sasin, 2009; Miller, Ulrich & Rinkenauer, 1999).

To sum up, the evidence supports the view that the motor component of RT is independent of stimulus parameters. Hence, it seems reasonable to use RTs for measuring changes in the speed of perceptual processes.

19.4 Canonical Model of SJ/TOJ

It might seem quite straightforward that, in the TOJ task, observers report as first the stimulus that was detected earlier. Therefore, sensory latency (i.e., the time the stimulus needs to achieve a hypothetical brain center responsible for order judgment, including early perceptual processes) is an obvious factor affecting the perception of subjective order. It is well known that sensory latency depends on physical factors such as stimulus intensity, color, duration, or modality. For example, sensory latency is known to decrease with stimulus intensity. Therefore, if one judges the order of two, say, simultaneously displayed visual stimuli, the dimmer one seems to appear later than the brighter one because the former achieve the TOJ center later. Generally, this was found to be the case (Alpern, 1954; Jaśkowski, 1991a; Roufs, 1963; Roufs, 1974).

This observation was exploited to introduce a new method of measuring the effects of stimulus manipulations on perceptual latency. Let L_i ($i = x, y$) be latency of S_i. If we assume that the two stimuli are perceived as simultaneous when both stimuli reach the TOJ/SJ brain center simultaneously, then to perceive the stimuli as simultaneous, one has to show the stimulus of long latency sooner than that of short latency by the amount of milliseconds being equal to the difference in the latencies. In other words, the SOA at which observers tend to perceive the stimuli as simultaneous is equal to $L_x - L_y$. This is illustrated in figure 19.2. Therefore, one can use TOJ/SJ as a method of assessing changes in sensory latency. By keeping one stimulus constant throughout the experiment (the reference stimulus), one can manipulate the other stimulus (the comparison stimulus) of the pair and measure PSS. The changes of PSS should reflect the latency changes of the comparison stimulus.

Some researchers have treated TOJ/SJ as a useful tool for measuring the speed of perceptual processing, especially because no motor component is involved (Alpern, 1954; Coren

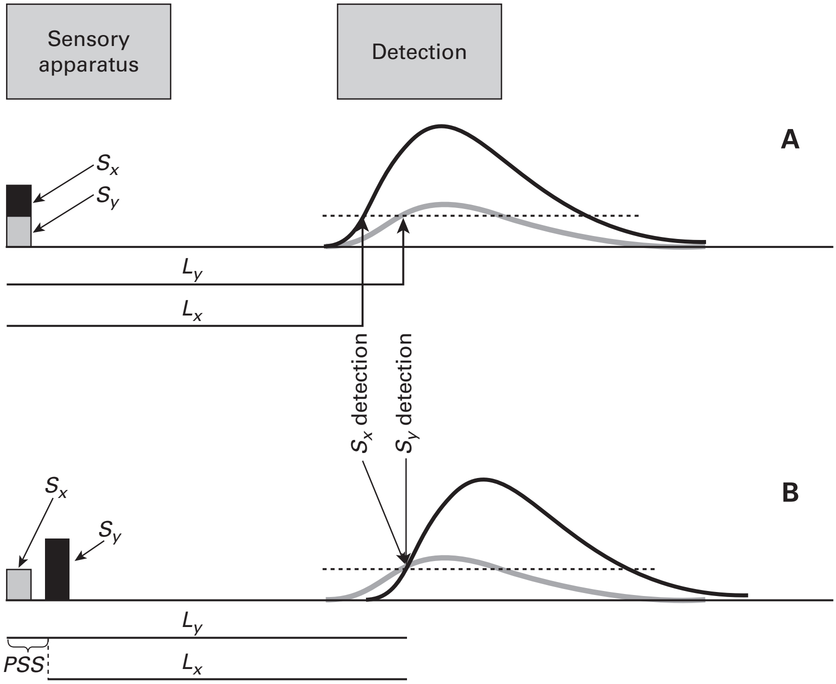

Figure 19.2

(A) If two stimuli of different intensity (black: high-intensity stimulus; gray: low-intensity stimulus) are presented simultaneously, the high-intensity stimulus is detected first due to their different detection time. (B) To get the impression of subjective simultaneity, the high-intensity stimulus has to be delayed by an amount equal to the difference in the detection times of the two stimuli.

& Porac, 1992; Roufs, 1974; Schwarz & Eiselt, 2009; Spence, Shore & Klein, 2001). Taking into account that the motor time of RT remains constant, the idea that the detection time of RT is identical or at least behaves similarly to sensory latency as measured by TOJ/SJ is certainly attractive. The model assumes that the same perceptual processes underlie performance in both RT and TOJ/SJ tasks and that, additionally, detection time in RT is equal to detection time in TOJ (i.e., $D_i = L_i$), and has been referred to as the “canonical model” (Miller & Schwarz, 2006).

Within the canonical model, it seems quite natural to ask whether the results obtained by both methods coincide. This was tested in numerous experiments wherein perceptual latency was measured by simple RT and TOJ/SJ under the same stimulation conditions.

19.5 Simultaneity Constancy

Although at first sight the assumptions of the canonical model seem quite reasonable, clear dissociations of these two latency measures (i.e., PSS and RT) have repeatedly been shown.

More precisely, in the vast majority of studies, the changes of RT were reported to be larger than the changes of latency estimated by TOJ.

As an example, let us first consider a recent study by Kopinska and Harris (2004). They were interested in the following problem. When we look at a distant visible source of sound, the light from this object comes to our senses sooner than the sound. This might lead to some disturbances in perception. For example, when a car moves, its sound should arrive later than its image, a problem we encounter when trying to visually locate a jet flying with supersonic velocity. Such a mislocalization results from the different speeds of light and of sound, and the phenomenon is more evident as the distance from the object increases. For a distance of, say, 30 m, the difference in arrival times of sound and light is about 100 ms. How do our sensory systems cope with this problem? Do we really perceive such an illusion? To answer this question, Kopinska and Harris (2004) compared RT and PSS of an auditory and visual stimulus under different conditions. Three variables were manipulated: distance, visual intensity, and retinal eccentricity. While the former one affected physical arrival times, the latter two are known to affect visual latency. All these variables remarkably influenced RT in a predictable way while PSS remained constant, suggesting the existence of something like "simultaneity constancy."

To account for their results, the authors proposed a quite complicated model wherein "the internal representation of the faster member of the pair is delayed by an amount precisely tuned to the particular situation" (p. 1058). In other words, if two stimuli appear, our cognitive system knows the real difference between arrival times or latencies and compensates for this difference accordingly by antedating the faster one. To work properly, the cognitive system has to know (1) that the same event is the source of both stimuli (for example, when you touch your foot with your hand, you experience it as one event, in spite of the fact that the signal from the foot takes longer than from the hand to arrive at the brain); and (2) that there are some factors affecting the speed of processing, like eccentricity or intensity. This knowledge is presumed to be acquired by experience (Harris, personal information, May 2010).

19.6 Further RT/TOJ Dissociations

The simultaneity constancy seems to be ecologically valid in case of sound and light, especially in situations where both belong to the same source. This hypothesis seems to be hardly acceptable, however, when we consider subjective simultaneity of two stimuli from the same modality, say, two visual stimuli. What would be the ecological purpose of such a constancy mechanism? Why should one perceive two visual stimuli as simultaneous rather than as successive?

These questions are quite justifiable, bearing in mind that for stimuli of the same modality, changes of TOJ latency have also usually been found to be smaller than those of RT when measured under the same conditions. Below some other experimental studies are reviewed, in which the two methods—RT and TOJ—were compared.

Several stimulus parameters are known to affect simple RT. If one endorses the canonical model, it is expected that PSS should be affected by these variables to the same extent as RT. In fact, the agreement between the PSS and RT results is quite poor. Generally, the signs of the changes in these variables, which accompany changes in stimulus parameters, are the same but their magnitudes differ, being usually larger for RT. Such dissociations have been found for stimulus intensity (Cardoso-Leite, Gorea & Mamassian, 2007; Jaśkowski, 1992; Menendez & Lit, 1983; Roufs, 1974); background luminance (Menendez & Lit, 1983); spatial frequency (Tappe, Niepel & Neumann, 1994); attentional focus (Jaśkowski & Verleger, 2000; Neumann, Esselmann & Klotz, 1993); stationary vs. moving stimuli (Aschersleben & Müsseler, 1999); retinal position (Kopinska & Harris, 2004; Schwarz, 2006); and wavelength of isoluminant stimuli (Bowen, 1981; Breton, 1977; Weingarten, 1972). An earlier and more detailed review of the dissociations appears in Jaśkowski (1996) and in Neumann et al. (1993) and Neumann et al. (1992).

A very mysterious phenomenon is the so-called modality dissociation, demonstrated for the first time by Rutschmann and Link (1964), who compared RTs and PSSs for stimuli from different modalities. RTs to auditory stimuli were shorter by about 40 ms than to visual stimuli. However, to obtain an impression of simultaneity, the auditory stimuli had to be presented 40 ms earlier! This means, in terms of changes of perceptual latency, that perceptual latency is 40 ms shorter for auditory stimuli when measured by RT, but 40 ms longer when measured by the TOJ method.

Rutschmann and Link's experiment has been replicated many times since its original demonstration. The results turned out to be rather inconsistent. Jaśkowski, Jaroszyk, and Hojan-Jezierska (1990) found that visual stimuli had to be presented sooner to obtain an impression of simultaneity, although the PSS was still smaller than the RT difference (cf. also Hirsh & Fraisse, 1964; Hirsh & Sherrick, 1961). On the other hand, Neumann et al. (1992) successfully replicated Rutschmann and Link's original findings. One plausible reason for such between-lab inconsistencies could be a large interindividual variability of auditory-visual order judgments. Stone et al. (2001) observed PSSs that changed from about –20 to 150 ms. Boenke, Deliano, and Ohl (2009) recently approached more systematically the problem of high interindividual differences. They investigated the effect of stimulus duration and intensity on the temporal order of visual and auditory stimuli. In keeping with Stone et al.'s observations, they found that PSS varied interindividually broadly in the range ±150 ms. Of interest is that increasing duration stabilized PSS values; that is, they were less variable for longer durations. The authors speculated that this finding might suggest "a mechanism that compensates individual imbalances between sensory modalities, which might arise from attentional biases toward one modality at short stimulus durations" (2009, 233).

According to my best knowledge, no systematic research of the interindividual variability of PSSs obtained with two stimuli of the same modality has so far been done. Nevertheless, according to my experience, visual-visual order judgment is much more stable interindividually. The huge auditory-visual variability is of interest by itself, and we will return to it later in this chapter.

In sum, the studies cited above showed that even though the duration of sensory latency affects both measurements, other factors seem to be involved that make the results inconsistent. This is also a strong motivation to reconsider the canonical model.

19.7 Hypotheses to Explain the Dissociations

Dissociations between the RT and TOJ results need explanation. Although it is obvious that the canonical model seems to be too simplistic and based on assumptions that are too strong, it is still intriguing to consider which of the assumptions are violated. Besides the simultaneity constancy hypothesis, several others were proposed to account for the dissociations, especially the intensity dissociation. Some of them are special versions of the canonical model; others assume completely different mechanisms underlying the RT and TOJ tasks. The rest of the chapter will be devoted to the presentation of these hypotheses, and of the findings supporting and contradicting them.

19.7.1 Prior-Entry Effect and Spontaneous Shift of Attention

Titchener (1908) and Stone (1926) were the first to claim that attention may affect PSS (see Scharlau, 2007 and Spence et al., 2001 for contemporary reviews). Before each trial, they asked their subjects to direct their attention to a particular source of sensory input. Stone (1926) used auditory and tactile stimuli, Titchener (1908), visual and tactile ones. Participants reported more often that the stimuli cued by the experimenter were perceived first. Cueing caused the psychometric functions to be shifted along the time axis by 40 to 60 ms toward shorter latencies (see also Neumann et al., 1993; Stelmach & Herdman, 1991). This phenomenon is usually referred to as the "prior-entry effect."

As cue presentation is known to decrease latency of the cued stimulus, the shift of the TOJ psychometric function is commonly interpreted as resulting from attentional shift toward the cued stimulus. However, experiments such as those by Stone or Titchener suffer from at least one important shortcoming: cueing could elicit response bias. Indeed, because participants are usually asked to indicate the first presented stimulus of the pair, they might tend to simply indicate the cued stimulus, especially for SOAs close to PSS. A lot of effort in the past two decades has been invested in showing that prior entry really exists and is not the mere outcome of a response bias.

Jaśkowski (1993a) tried to avoid response bias by introducing three rather than two possible responses. Besides "S_x first" and "S_y first," their participants could report that the two stimuli were simultaneous. The reasoning behind this approach was that, in having only two responses at their disposal, participants would have followed any hint as to the possible order of the stimuli, such as experimenter instructions or peripheral or central cues. This would have led to response bias. This tendency should have disappeared if they could respond “simultaneous” or simply “don’t know.” Indeed, Jaśkowski (1993a) showed that while for the binary response paradigm a shift of the psychometric function occurred, it disappeared once the participants were allowed to use the third response. This result was, however, inconsistent with that obtained by Stelmach and Herdman (1991), who showed a 40-ms shift of the psychometric functions using the ternary response paradigm.

Spence et al. (2001) performed a series of experiments addressed to resolve this controversy. Pairs of tactile or visual stimuli, or both, were presented from the left or right at varying SOAs. The participants’ task (experiment 2) was to report the side of the first stimulus. However, the focus of attention was manipulated by changing the probability of occurrence of the stimuli from a given modality. The results showed that the participants more often reported as first the stimulus of the emphasized modality. This finding was successfully replicated by Zampini, Shore, and Spence (2005) for vision and audition and for vision and nociception (Zampini et al. 2007). The shift of psychometric functions was also observed with peripheral cues (Eskes et al., 2007; Santangelo & Spence, 2009; Van Damme et al., 2009; for a review, see Spence & Parise, 2010).

It should be noted, however, that response bias could remarkably contribute to the effects observed in experiments where attentional focus was manipulated. Indeed, Shore, Spence, and Klein (2001) compared psychometric functions obtained when participants had to report which stimulus was first or which was last. The authors reasoned that any response bias in reporting “which first?” would be equal and opposite to the response bias in reporting “which second?” Therefore, they expected to obtain the “pure” prior-entry effect from averaging of the performance in the two tasks. Based on these assumptions, they calculated that response bias, being half the difference between the “which first?” and “which second?” was equal to 13 ms.

These results strongly suggest that it is possible by instructions (i.e., a spatial or symbolic cue) to force a shift of attention during judgments of temporal order. Can this phenomenon somehow contribute to the TOJ/RT dissociations? Sternberg and Knoll (1973) had suggested earlier the possibility that participants might spontaneously focus their attention on one of the two stimuli, thereby shortening the latency of one stimulus while lengthening the latency of the other. In experiments involving the manipulation of stimulus intensity, it is reasonable to assume that participants attend to less intense stimuli to avoid overlooking them. Similarly, one can explain the modality dissociation assuming that participants tend to focus their attention primarily on visual stimuli due to the phenomenon called “visual dominance,” thereby shortening latency of the visual stimuli in respect to the (nonattended) auditory ones (Colavita, 1974; Pick, Warren & Hay, 1969; Shapiro, Egerman & Klein, 1984).

Sanford (1974) and more recently Jaśkowski and Verleger (2000) showed, however, that it is impossible to eliminate the intensity dissociation by better experimental control of attentional allocations. In their experiment 3, Jaśkowski and Verleger (2000) compared PSS for visual stimuli of different intensities under block-wise and random presentation (i.e., either a stimulus of a given intensity was assigned to a given location—block-wise presentation—or not, in a random presentation). Of course, under random conditions it was impossible for participants to allocate attention preferentially to low-intensity stimuli. The results showed that spontaneous shift of attention had negligible effects on the relationships between PSS and stimulus intensity.

19.7.2 Channel Coactivation

The attentional shift account focuses on a very fundamental difference between the TOJ and RT tasks, namely the number of stimuli presented in each trial, which is assumed to affect the attentional distribution. The same difference is taken under consideration by the channel coactivation hypothesis (Jaśkowski, 1999).

It is well known that RT to two simultaneously presented stimuli (or stimuli in close temporal proximity) is always shorter than RT to the stimuli presented separately (e.g., Miller, 1982; Raab, 1962). This result holds both for within- and between-modality stimulus pairs (Miller, 1982).

Raab (1962) provided the first account of this phenomenon. He assumed that independent channels processed the stimuli, and that the response is triggered by the stimulus that is processed faster. On average, therefore, RT to the redundant stimulus (i.e., two stimuli in close temporal proximity) is always shorter than RT to each of the stimuli. Miller (1982), however, showed that the redundant stimulus effect is larger than predicted by Raab's model. Since Miller's study, a scientific debate has developed regarding the location of the coactivation phenomenon. One idea shared by several of these models was that the coactivation could occur in the motor component (Diederich & Colonius, 1987; Giray & Ulrich, 1993). However, in more recent studies this locus was excluded (Hackley & Valle-Inclán, 1998; Miller, Ulrich & Lamarre, 2001; Mordkoff, Miller & Roch, 1996). In these studies, it was shown that R-LRP was not affected by redundancy, suggesting that motor processes had the same duration with redundant stimuli as with single stimuli.

There is some evidence for a perceptual locus of coactivation. For example, Miniussi, Girelli & Marzi (1998; see also Murray et al., 2001) presented visual stimuli to the left or to the right visual field or to both fields while recording EEG. They showed that the P1 and N1 components of visually evoked potentials, both of which are generated most probably in extrastriate visual areas, had shorter latencies for redundant signals than for summed responses evoked by stimuli presented separately.

These findings led Jaśkowski (1999) to propose a new hypothesis explaining the RT/TOJ dissociation. He assumed that in the TOJ task, one channel might speed the processing time of the second stimulus, and vice versa, thereby reducing the effects of stimulus manipulations relative to those observed in RT tasks. More specifically, he supposed that a strong stimulus reduces the sensory latency for a weak stimulus more than the reverse. Therefore, the latency difference obtained in the TOJ task is reduced in comparison with the RT situation, where only one stimulus is presented and therefore its latency remains intact.

Recently, Miller, Kühlwein, and Ulrich (2004) provided evidence to the contrary. They examined the effect of signal redundancy on RT and TOJ. In each trial, participants were presented with a tone and either single visual stimulus or two redundant visual stimuli. No evidence of redundancy on TOJ was found.

19.7.3 Dual Routes

So far we have considered the hypotheses explaining the TOJ/RT dissociations as simple modifications of the canonical model, in the sense that they still assume that PSS represents changes of perceptual latency/detection time, the same that is a part of RT, but this latency is modified somewhat by prior knowledge (simultaneity constancy), attentional distribution (spontaneous shift of attention) or mutual influence of sensory channels (channel coactivation). In the other group of hypotheses accounting for the TOJ/RT dissociations, it is assumed that RT and TOJ are admittedly based on the same input information, but processed completely differently by the cognitive system to perform the tasks.

One example of such a model is Neumann's dual route hypothesis (Neumann, 1990; Neumann & Müsseler, 1990). He emphasized a fundamental difference between judgment and reactions: only judgment requires conscious perception, while response can be directly specified by stimulation parameters. According to the most recent version of the direct parameter specification theory (Ansorge & Neumann, 2005; Kiesel, Kunde & Hoffmann, 2007), participants' sensory systems search the environment for stimuli that help to perform the task. Features of these searched-for stimuli are determined off-line by the demands of a task (experimenter instructions or participants' current intentions). Once such a stimulus appears, it is enough to specify some action parameters from the information conveyed by the stimulus. For example, in the case of choice responses with left and right hands, the response hand is the information to be specified after stimulus presentation. Other parameters could already be specified before the stimulus was presented. This model gained remarkable support from studies of the so-called subliminal priming, where unconsciously processed information was shown to affect the speed and accuracy of participants' responses (for reviews, see Kiesel et al., 2007; Kouider & Dehaene, 2007; Sumner & Husain, 2008).

According to Neumann, such a direct specification is impossible for the TOJ task. This creates a fundamental difference between the two tasks, implying completely different processes involved, in separate brain systems or pathways. Due to different processing of the stimuli, the different input-output relations in the two tasks seem to be quite plausible. This account of the dissociation has never been subjected to any experimental tests. A main reason seems to be the very high level of generality of this approach, which precludes inferring any testable predictions. Moreover, some objections against this model have been raised (Jaśkowski, 1999; Miller & Schwarz, 2006).

First, although Neumann assumed otherwise, it seems conceivable that in TOJ the order of messages arriving a suitable structure in the central nervous system can directly specify the action that has to be taken to choose the suitable response (Jaśkowski, 1999).

Second, although some perceptual tasks seem to indeed use different neuronal routes, resulting in different stimulus-related effects (cf. Jaśkowski & Sobieralska, 2004), the reason why the changes of RT were usually smaller than the changes of PSS is not obvious.

Neumann was not specific about the neuronal pathways implied by his account. However, it was sometimes suggested (Neumann & Niepel, 2004; Steglich & Neumann, 2000) that TOJ predominantly activates the ventral pathway, while RT is processed along the dorsal pathway (e.g., Goodale, Króliczak & Westwood, 2005). The differences between the neuronal properties of the pathways determine the RT/TOJ dissociations. Is there any neuroanatomical evidence supporting this view?

Neuropsychological studies with patients shows the potential role of the right posterior parietal cortex (rPPC) in TOJ. It is known that damage to the rPPC evokes clinical symptoms such as neglect; that is, a failure to explore and attend to stimuli in the left hemispace. It has been commonly shown that TOJ is severely impaired in neglect patients (Dove et al., 2007; Rorden et al., 1997; Sinnett et al., 2007). Usually patients reported as being first a stimulus presented ipsilesionally, even if a contralesional event had a substantial physical lead. These neuropsychological findings recently gained some support from a TMS study (Woo, Kim & Lee, 2009) in which the right or left posterior parietal cortices were stimulated while participants judged the order of two visual stimuli presented in the left and right hemispace. They found, in keeping with the neglect patients' studies, that TMS over rPPC delayed the detection of a visual target in the left hemispace by about 20 ms. In contrast, TMS on the left posterior parietal cortex was not effective.

More recently, Davis, Christie, and Rorden (2009) attempted to find the brain locus of TOJ by means of fMRI. They compared brain activity while their participants performed one of the two tasks. In one task, they were asked to tell the order of two stimuli. In the other, they recognized the shapes of the same stimuli. Interestingly, they found that the left rather than right posterior parietal cortex seemed to be crucial for order perception. Commenting on Woo et al.'s (2009) study, the authors pointed to two issues. First, they suggested that Woo et al. stimulated a more dorsal area of the left posterior parietal cortex than Davis et al. did, thereby missing the crucial region, and concluded that the left posterior parietal cortex was not involved in order perception. Second, Davis et al. argued that magnetic stimulation of the rPPC modulated attention rather than the TOJ/SJ center. To support their claim, they pointed to the fact that TMS merely evoked a shift of the psychometric functions by a number of milliseconds, having not affected the temporal-order resolution (as measured by the slope of the TOJ psychometric function). This claim is supported by Sinnett et al. (2007), who found their neglect patients could distinguish the order of the stimuli as precisely as normals although their psychometric functions were shifted, thus revealing their inattention to the contralesional hemispace. However, this argument seems to be weakened by two previous studies of neglect patients in which in addition to shifts of the psychometric functions, the patients' temporal sensitivity was lower as measured by the slope of their psychometric functions. Although those studies did not focus on temporal resolution, however, from the figures presented it seems evident that slopes of patients' psychometric functions were approximately twice as large as those for controls (Karnath, Zimmer & Lewald, 2002; Rorden et al., 1997).

Although substantial progress in research into the neuronal substrates of order judgment is visible in recent years, we still know relatively little about the neuronal underpinnings of this phenomenon. Nevertheless, the above-cited findings do not point to the ventral pathway as being involved in TOJ. Moreover, the general picture of the properties of the ventral and dorsal pathway become more and more complicated (e.g., Goodale et al., 2005), hence making any testable predictions of the two routes hypothesis practically impossible.

In sum, it seems quite obvious that different processes are involved in the two tasks and, thus, different neuronal systems. Yet to make the hypothesis falsifiable, further specifications are needed.

19.7.4 Parallel Grains

Miller and Ulrich (2003) proposed recently an elegant model of simple RT. In this model, a stimulus can activate *N* perceptual grains processed in parallel. Stimulus parameters like intensity affect *N*. After a grain is activated, some variable time is needed for this activation to spread to a decision center. The stimulus is detected if a criterion number of activated grains reach the decision center. Detection time is therefore the sum of activation time and transmission time. Even though this model was devoted to simple RT, the TOJ/RT dissociation was also addressed. Miller and Ulrich assumed that the difference in perceptual latency of the two stimuli determines their subjective order. However, the decision center for a motor response was assumed to be further from the sensory apparatus than that for stimulus detection. Therefore, even with the same decision criterion, transmission time is longer and more variable for RT than TOJ. With this assumption, it was possible to show that stimulus intensity affects more RT than sensory latency. Note that in this model motor time is assumed to be constant.

This model has never been tested empirically.

19.7.5 Diffusion Differencing Model

Many models of simple RTs rely on the idea of accumulation. It is assumed that the presentation of a stimulus triggers a stream of neural impulses that accumulate in a counter (see figure 19.3A). Once the counter content reaches a criterion, a motor response is triggered (e.g., Grice 1972; Grice, Nullmeyer & Spiker, 1982; Ractliff & Rouder, 1998; Smith, 1995).

Such a cumulative process underlies the model of RT and TOJ proposed by Ulrich (1988) and rediscovered recently by Schwarz (2006). According to this model (see figure 19.3A), each stimulus generates a series of neuronal impulses in its sensory channel described by a Poisson process—that is, a stochastic process in which the probability of an impulse generation at a given moment in time is equal to a constant λ ($0 \leq \lambda \leq 1$). λ depends on stimulus

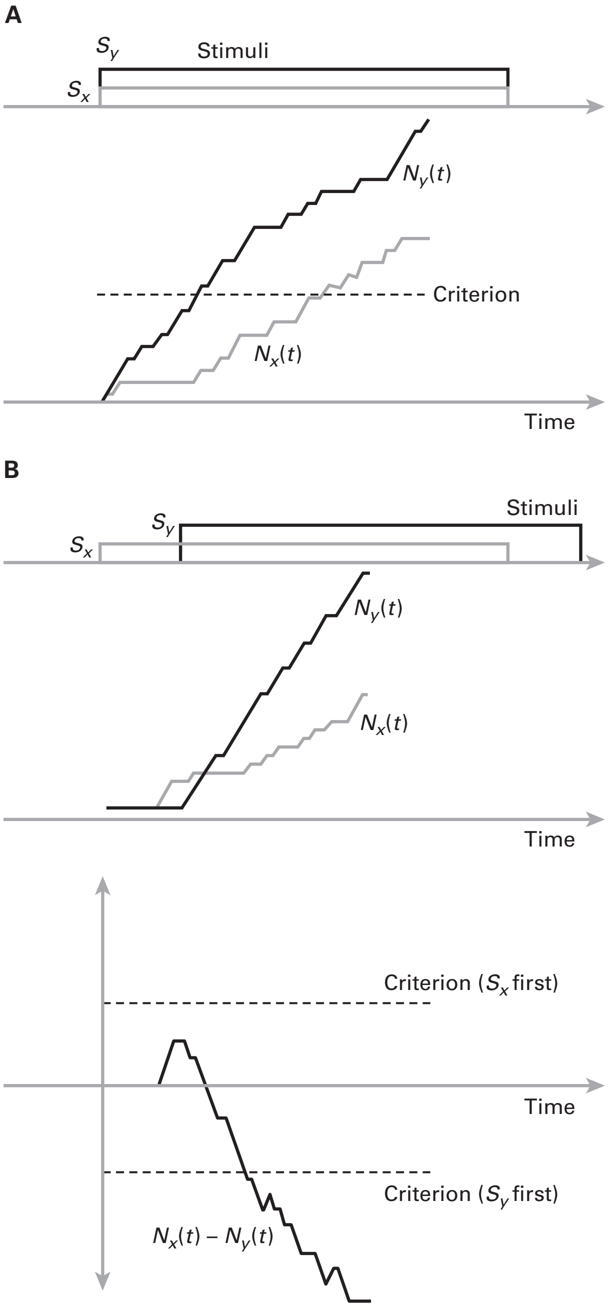

Figure 19.3

(A) Diffusion differencing model to explain RT. Each stimulus evokes a train of neuronal spikes that accumulate in a counter. The rate of spike generation depends on stimulation parameters such as intensity. Once the counter $N_i(t)$ reaches a criterion, the motor response is delivered. (B) Diffusion differencing model to explain TOJ decision. To judge the order of two stimuli, another counter accumulates the difference of the accumulations, $N_x(t)$-$N_y(t)$ in the two sensory channels. A decision is taken if the counter reaches either the upper or the lower criterion.

parameters; in particular, it is assumed to be a nondecreasing function of stimulus intensity. Specialized counters accumulate the impulses from each channel separately. Once the number of the accumulated impulses reaches a criterion, a motor response is delivered. Bearing in mind that λ is larger for high- than low-intensity stimuli, the criterion is reached sooner for more intense stimuli and, thus, RT is an inverse function of stimulus intensity.

In case of the TOJ task, two stimuli, S_x and S_y, are presented in close temporal proximity. Let us denote the number of accumulated impulses in a channel at the moment t by $N_i(t)$, $i = x, y$. The order judgment relies on the difference between the number of impulses accumulated in channel x and y. More specifically, once $N_x(t) - N_y(t) > \alpha$, the response "S_x was first" is triggered, while the response "S_y was first" is reported once $N_x(t) - N_y(t) < -\alpha$ (see figure 19.3B).

A nice feature of this model is that it accounts for the dissociation due to intensity manipulation (Ulrich 1988). Schwarz (2006) provided an additional test of this model. He performed an RT and TOJ experiment where the eccentricity of one stimulus was manipulated. RTs were measured under three conditions randomly intermixed: only to the central signal, only to the peripheral signal or to both with a given SOA. Therefore, stimulation in the last condition was identical to that in the redundant signal paradigm and in the TOJ task. Schwarz could test the predictions of the model for RT changes, PSS, and redundant signal effect. The results obtained were captured by the model both qualitatively and even quantitatively.

19.7.6 Criterion Shift

As I noted above, it is commonly assumed that in RT models stimulus intensity affects the rate of information accumulation, making it faster for more intense stimuli. A simple consequence of this assumption is that the effect of intensity depends on the detection criterion level: the higher the criterion, the larger the intensity effect. Therefore, an attractive and simple solution to the dissociation problem is to assume a higher criterion for a motor decision than for stimulus detection needed for order judgment. Sanford (1974) was the first to propose such a solution. More recently, this idea was suggested by Aschersleben (1999).

Although such a criterion shift can successfully explain most dissociations, it encounters some conceptual problems. The main weakness is that this hypothesis relies on a clearly *post hoc* assumption. Indeed, one can ask why more sensory information is needed to trigger the motor response than for the TOJ decision. As Tappe et al. (1994) pointed out, one can rather expect a lower criterion in the RT task, because this is the task that needs speed, after all, while the higher the criterion, the longer the overall RT.

In spite of this criticism, Miller and Schwarz (2006) argued that this assumption was not as arbitrary as it seems at first sight. They noticed that a lower criterion might optimize the accuracy of the order perception. Let us consider the cumulative sensory activation for two intensities, as presented in figure 19.4. The high-intensity stimulus reaches the higher criterion earlier than the low-intensity stimulus, even though it is presented later. This means

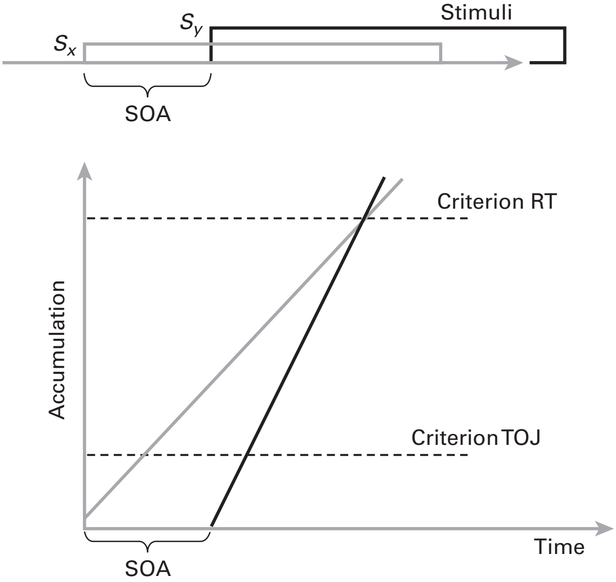

Figure 19.4

Miller and Schwarz's justification of the lower TOJ than RT criterion. If a high-intensity stimulus is presented SOA ms later than a low-intensity one, the observer is still able to properly recognize objective order only if the criterion is set low enough.

that the observer's response would be wrong if his or her decision is based on the order of the moments at which the two stimuli reach this criterion. If, however, the criterion is set lower, the high-intensity stimulus reaches the criterion later than the low-intensity one. Therefore, the response accuracy is better with the lower criterion. Still, the criterion cannot be set at zero, for which the order judgment would be perfect, because of internal noise. Taking this into account, Miller and Schwarz (2006) proposed a criterion-shift model where the sensory input is modeled as a Poisson process, like in Ulrich's differential diffusion model. The criterion for RT was set at a level that ensured a low rate of premature responses, while the criterion for TOJ, lower than for RT, was set to optimize the order judgment.

Besides the intensity dissociation, which was a rather obvious consequence of the assumptions, it was shown that the model is able to predict the shapes of psychometric TOJ functions.

19.7.7 Different Time Markers

Sternberg and Knoll (1973) were the first to note that TOJ and RT differ fundamentally because "the RT task requires speed with low false-alarm rate, whereas the TOJ task requires low variance to maximize precision. Thus, TOJs might depend on the estimated time of

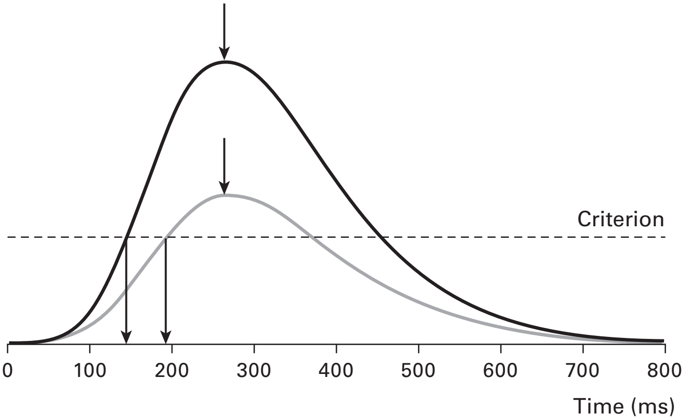

Figure 19.5
Explanation of intensity dissociations based on the hypothesis of different time-markers. This hypothesis assumes that the motor response is started once the internal response crosses a criterion, while in TOJ another time marker (e.g., maximum) is calculated from the internal response. The internal response for high intensity (black line) crosses the criterion much earlier than the internal response for low intensity (gray line), but they reach their maximal values almost simultaneously.

peak response, which might have less sampling variance than the delay before a response first exceeds a criterion level, because the latter, but not the former, varies with trial-to-trial fluctuations in sensitivity" (p. 650). More generally, they suggested that observers might make different use from the same input information depending on the task at hand. If so, the perceptual latency could differ even if the inputs were the same and processed along the same route in both tasks. This hypothesis is referred to as the "different time-markers hypothesis" (Jaśkowski 1996).

Electrophysiological research provides some support for this hypothesis. Indeed, Fourtes and Hodgkin (1964) showed for the *Limilus* eye that the latency of the maximum response can behave differently from the latency of crossing a critical value. Although *Limulus* has rather primitive eyes, similar mathematical description to that used by Fourtes and Hodgkin was also applied to the human eye (see, for example, Roufs, 1972). In figure 19.5, this idea is illustrated for the intensity dissociation. The response crosses the criterion later for a low-intensity stimulus than for a high-intensity stimulus. However, it reaches its maximal value only slightly sooner, if at all. Lennie (1981) has shown such dissociation between differentially defined response latencies for discharges of ganglion cells in the cat retina. When latency was defined from stimulus onset to the moment when the number of impulses generated by a stimulus exceeded a criterion, the latency depended much stronger on intensity than when it was defined as the time at which the averaged discharge reached its maximal value. The dissociation between them strikingly resembles the dissociation found for TOJ and RT.

Two TOJ studies provided some indications in favor of this hypothesis. In one series of experiments, Jaśkowski (1991a) investigated order judgments with stimuli of unequal durations. As in a typical TOJ experiment, two stimuli, located one above the other, were displayed on the screen. Durations of the stimuli were manipulated. The participants' task was to match the onsets of both stimuli to obtain subjective simultaneity. If participants were able to ignore offset asynchrony, PSS should be equal to zero. In fact, the onset of the shorter stimulus had to be shifted toward the end of the longer one to obtain a satisfying impression of simultaneity. Offset asynchrony disturbed the perception of order of onsets. Originally, Jaśkowski (1991a) suggested that participants were not able to distinguish if the perceived asynchrony came from unaligned onsets or offsets, and to achieve satisfying simultaneity tended to maximally reduce both onset and offset asynchrony. Alternatively, observers estimate time position of a stimulus using the peak or center of gravity of its internal response. This idea was explored by Jaśkowski (1993b) in experiments, in which the stimulus luminance profiles were manipulated by means of changing the rise and fall times. In one experiment, the slopes of the luminance rise were identical for all stimuli used, but they differed in terms of the duration of the rising interval, thereby reaching their maxima at different times. Time profiles of the stimuli used are reproduced in figure 19.6. As a reference, a rectangular stimulus was used.

Reaction times did not change with the stimulus rise time. This result was expected based on the predictions resulting from the idea of a criterion that should be crossed by an internal response to start motor activity. Indeed, the temporal location of threshold crossing does not change, assuming that the shapes of internal responses reproduce by and large the shapes of luminance profiles of the stimuli. Conversely, PSS increased systematically with rise time. This result can easily be accounted for by assuming that what is compared in the

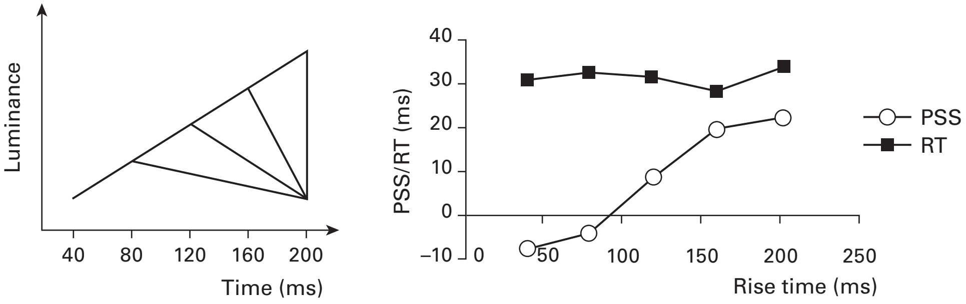

Figure 19.6

Results of Jaśkowski's experiment 2 (Jaśkowski 1993b) with stimuli having different rise times. The luminance profiles are displayed in the left plot. The effect of rise time on RT and PSS (relative to reference stimulus) is shown in the right plot. (Adapted from Jaśkowski, P. (1993). Temporal order judgment and reaction time to stimuli of different rise times. *Perception*, *22*, 963–970 [Pion Ltd, London: www.pion.co.uk and www.envplan.com].)

simultaneityorder center in the brain is the temporal position of the peak or gravity center of the stimuli internal responses. Indeed, due to the manipulation of rise time, peaks and centers of gravity of internal responses shifted toward the end of the stimuli when the rise time increased.

It should be noted that Jaśkowski's (1993b) finding is the only dissociation where the changes of PSS were found to be larger than those of RTs. It seems to be a very important result, bearing in mind that most models accounting for RT/TOJ dissociations predict smaller changes of PSS than RT. Unfortunately, the results obtained by Jaśkowski (1993b) are inconclusive because of some interindividual variance of PSS and the small sample (n=3). It was concluded (Jaśkowski, 1993b) that this high variance might suggest that the participants individually selected features of the internal response, which seems to them most suitable for a particular task. One can speculate that this is also the reason why the between-modality TOJ shows very large interindividual variability (Boenke et al., 2009; Stone et al., 2001). Indeed, one can figure out that finding a satisfactory time marker for TOJ is much harder in the case of the bimodal than unimodal stimulation.

Miller and Schwarz (2006) raised some objections against the different time-markers hypothesis. In my view, these objections are relatively easy to refute.

Miller and Schwarz argue that although it seems obvious that the internal response has a clear maximum, it is not as obvious for long or response-terminated stimuli. Therefore, it is not clear what time marker could be used in the order judgment. Moreover, they referred to Jaśkowski's study (1992), which showed that the effect of intensity on PSS and RT is almost identical for short and response-terminated stimuli.

In my opinion, Miller and Schwarz's argument is valid only if one assumes that the system response is linear. In Figure 19.7 (left graph), the responses of the nonlinear version of the Fourtes-Hodgkin (1964) model mentioned above of responses of the *Limulus* eye are plotted for short and long stimuli. As can be seen, for the longest stimuli a peak is visible, although it is not as distinct as in the case of short stimuli. Moreover, for stimuli longer than 300 ms, the peaks overlap. Note that Jaśkowski's (1993b) short stimuli were only slightly shorter (200 ms). Moreover, the lack of peak coincidence does not necessarily mean that intensity affects these peaks differentially.

In addition, Miller and Schwarz's second argument does not look very convincing either. They argue that the different-time-markers hypothesis cannot explain how people are able to judge offset order (i.e., in a situation where two steady-state stimuli are switched off and the observes' task is to tell which of the two was stopped first). In fact, in our sensory systems there are cells (e.g., ganglion cells) that respond exclusively to stimulus onset, as well as cells that react only to stimulus offset. In responses of both these cell types, initial overshoots forming clear maxima are present. Thus, at least in early stages of processing, such time markers for both onsets and offsets are available.

Miller and Schwarz argued further that some empirical observations give evidence against the hypothesis. First, TOJ should be strongly affected by stimulus duration, because "for

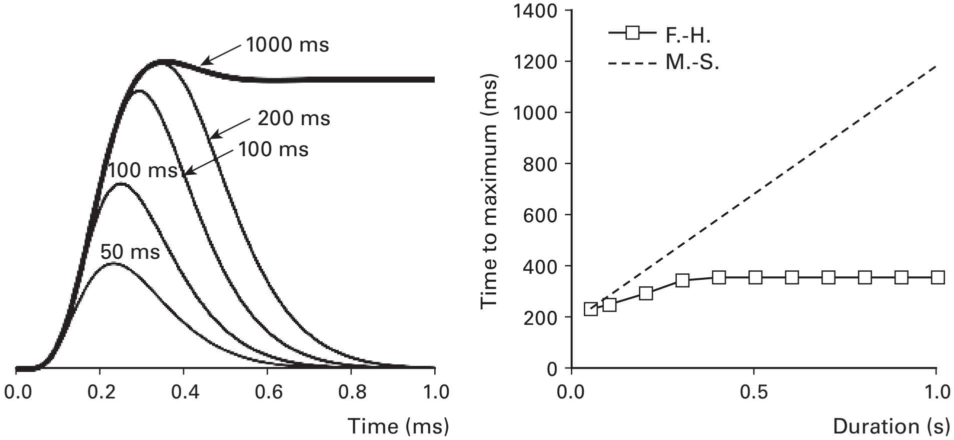

Figure 19.7

(Left) Responses of nonlinear Fourtes-Hodgkin model of *Limulus* eye to stimuli of different durations. The curves represent the solutions of equation 15 therein with the following parameters: $g_0 = 0.4001$, $C = 0.022$, $w = 0.0218$; $\mu = 0.4517$. The stimuli were steps of different durations with the amplitude equal to 1. (Right) Time to maximum of the model responses as a function of stimulus duration. The dashed line represents Miller and Schwarz's prediction (see text).

many plausible types of activation functions, the moment of peak activation should shift by approximately 1 ms for each 1-ms increment in stimulus duration" (2006, 397). In figure 19.7 (right graph), the peak position is plotted as a function of stimulus duration calculated from the nonlinear version of Fourtes-Hodgkin model. As is seen, the peak position increases much slower than in a 1 ms per 1-ms increase of duration (the rate of peak position increase predicted by Miller and Schwarz is showed by the dashed line).

Second, "manipulations of stimulus rise time produce approximately equal effects on RTs and TOJs (Jaśkowski, 1993b)" (2006, 397). This argument is simply not true. Jaśkowski clearly showed (see figure 19.6) that while RT was hardly affected by intensity, PSS systematically increased.

In sum, the time-marker hypothesis still appears to be a valid and powerful account of the TOJ/RT dissociations.

19.8 Concluding Remarks

It seems quite natural that having to judge the order of two stimuli, we report as first the one which was detected first by our cognitive system. Therefore, the most crucial determinant of the order judgment should be detection latency. Similarly obvious seems to be the assumption that motor processes are started once we detect a stimulus in a simple RT task. Building on these assumptions, TOJ and simple RT were some decades ago considered to be useful and reliable methods to measure the changes of perceptual latency. Neither of the two assumptions turned out to be as obvious as it seemed at first sight. Direct comparisons showed that the methods did not provide converging results.

This question, explicitly raised by Neumann et al. (1992) and Jaśkowski (1996), motivated some authors to search for explanations of these dissociations.

These efforts generated worse or better elaborated hypotheses attempting to account for the dissociations. The review of these theories provided in this chapter shows that neither of them may be accepted without hesitation. It is striking that there are more hypotheses than attempts to find decisive empirical evidence. In other words, all existing hypotheses were tested against more or less the same set of empirical results and did not provide predictions that could be tested in new experiments.

The problem of dissociation turned out to be quite complicated. Although perceptual latencies of the stimuli were proven to be crucial determinants of order judgment, the lack of coincidence between RT and PSS results proves that our image of how the stimuli are processed even in these relatively easy tasks is probably wrong. Some recent findings may suggest that the temporal-order judgment is even a more complicated phenomenon. It was shown that longer stimulation with a pair of asynchronously presented visual and auditory stimuli affected their subjective order. More precisely, if for a given SOA participants tended to perceive that, say, auditory stimulus precedes the visual one, after an adaptation phase, where the participants were exposed to a series of visual-before-auditory stimuli, they tended to judge that visual stimulus precedes the auditory one for the same SOA (e.g., Fujisaki et al., 2004; McDonald et al., 2005; Vatakis et al., 2007). This phenomenon seems to prove that there are some other important factors, besides perceptual latency, that determine our temporal order, as it is rather difficult to figure out that adaptation somehow affects the perceptual latency of one stimulus in the pair more than the other. Unfortunately, this situation does not lead us to believe that the problem of dissociations will be solved soon.

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Editors' note: During the final editing of this volume we learned of the death of Piotr Jaśkowski. The current chapter exemplifies the high quality of Professor Jaśkowski's research. Concerning the person behind the research, his colleagues wrote that he "never treated himself as someone who knew everything in his field; he was very humble in this respect and he never stopped deepening his knowledge regarding new methods and content areas. This 'need for knowledge' guided him to always learn more and think of new intriguing research questions. He was not afraid of saying 'I don't know' if he was not aware of some new research findings or to ask in order to learn more. In particular, he was very keen in learning from his young collaborators and generously encouraged and supported their scientific activities (workshops, conferences, and scholarships)."

20 The Research on Audiovisual Perception of Temporal Order and the Processing of Musical Temporal Patterns: Associations, Pitfalls, and Future Directions

Argiro Vatakis and Georgios Papadelis

20.1 Introduction

Almost all everyday acts are governed by time. Acts such as walking and speaking are often taken for granted and are considered easy to execute and understand. These acts, however, are not nearly as easy as they appear to be. They are in fact highly complex acts that unfold over time and require attending and perceiving the temporal order of the individual units of each single act. Temporal perception (in terms of temporal synchrony) is also essential (along with space and semantic congruency) in multisensory integration in determining whether the observer will experience a unified audiovisual event or two separate auditory and visual events (e.g., Calvert, Spence, & Stein, 2004; de Gelder & Bertelson, 2003; Doehrmann & Naumer, 2008; Driver & Spence, 2000; Kallinen & Ravaja, 2007; Sekuler, Sekuler, & Lau, 1997; Slutsky & Recanzone, 2001).

Multisensory integration is indeed enhanced when multiple sensory signals are close in time (e.g., see Calvert et al., 2004; de Gelder & Bertelson, 2003), however precise temporal coincidence is not mandatory for the human perceptual system to create a unified perceptual representation of a multisensory event (e.g., Dixon & Spitz, 1980; Engel & Doherty, 1971; Grant, van Wassenhove, & Poeppel, 2004; Kopinska & Harris, 2004; Morein-Zamir, Soto-Faraco, & Kingstone, 2003; Navarra et al., 2005; Rihs, 1995; Soto-Faraco & Alsius, 2007, 2009; Sugita & Suzuki, 2003; Vatakis & Spence, 2010). Thus, even though information received by our different senses may require different processing times, we still experience the illusion of a synchronous event (Spence & Squire, 2003; Zeki, 1993). In order to estimate sensory latencies and their effects on the integration of a multisensory event, many psychophysical methods have been applied in the laboratory. This chapter will mainly focus on one such method, the temporal-order judgment (TOJ) task (other methods include reaction time, simultaneity judgment, and ternary response tasks; Vatakis & Spence, 2010).

The TOJ task has been central in experimentation on temporal perception for more that a century now (e.g., Exner, 1875; Hamlin, 1893; Jaśkowski, Jaroszyk, & Hojan-Jezierska, 1990; Rutschmann & Link, 1964). The idea of this method is that if a given stimulus is processed faster, then it should also produce a faster reportable sensation in comparison to another stimulus. Consequently, a participant's judgment in regard to the point in time they experienced a sensation should represent the processing time of the stimulus responsible for that sensation (Neumann & Niepel 2004). In a typical TOJ task, therefore, the participants are presented with a pair of stimuli (e.g., an auditory and a visual one) at various stimulus-onset asynchronies and asked to make a judgment about the order of stimulus presentation (i.e., "Which stimulus was presented first?"; e.g., Bald et al., 1942; Hirsh & Sherrick, 1961; Spence, Shore, & Klein, 2001; Sternberg, Knoll, & Gates, 1971; Vatakis & Spence, 2010; or "Which was presented second?"; e.g., Parise & Spence, 2009). The data obtained from a TOJ task allows for the calculation of two measures, the just-noticeable difference (JND) and the point of subjective simultaneity (PSS; see figure 20.1). The JND provides a standardized measure of the sensitivity with which participants can judge the temporal order of the two stimuli that have been presented at a given performance threshold (typically 75 percent correct; see figure 20.1A). The PSS provides an estimate of the time interval by which the stimulus in one sensory modality has to lead or lag the stimulus in the other modality in order for the two to be perceived as having been presented synchronously (see figure 20.1B). These two measures are used for the calculation of the temporal window of multisensory integration using the formula PSS±JND. (Note that the term *temporal window of multisensory integration* does not imply an active process, but rather refers to the interval in which no signal discrepancy is perceived; anything beyond this interval will normally be perceived as being desynchronized.)

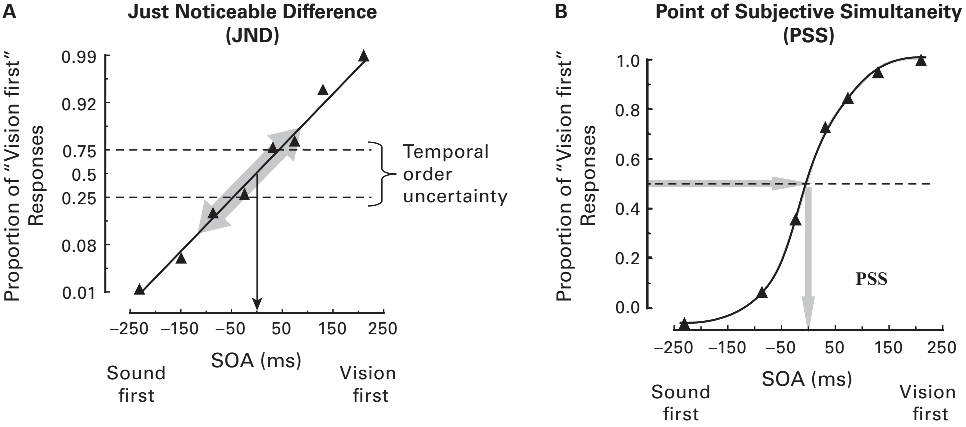

Figure 20.1

Measures of (A) the just-noticeable difference (JND) and (B) the point of subjective simultaneity (PSS) derived from the TOJ task.

20.2 Audiovisual TOJs for Simple Stimuli

The investigation of temporal perception using TOJs was initiated very early using stimuli of low informational content, such as a flashing light, a bursting sound, or a buzzing vibrator. The results of these early studies, however, exhibited great differences in the JND and PSS values reported, thus leading to a long debate regarding the cause of the temporal-order inconsistencies obtained. For example, Exner (1875) presented auditory clicks and light flashes in order to measure the smallest time difference that had to be introduced between a pair of auditory and visual stimuli for participants to report the pair as being asynchronous. The participants' TOJ responses resulted in visual leads of 160 ms and auditory leads of 63 ms before any asynchrony in the audiovisual pair was perceived. Subsequent attempts to replicate these results, however, led to a series of conflicting findings that suggested the possibility that participant sensitivity to audiovisual asynchrony may be quite different from that suggested by Exner's results (e.g., Hamlin, 1893; Smith, 1933). In more recent TOJ studies, it has been shown that the auditory, tactile, and visual stimuli (in audio-visual, visual-tactile, and audio-tactile combinations) need to be separated by a minimum of 20 ms in order for well-trained participants to be able to judge correctly which modality was presented first on 75 percent of the trials (e.g., Hirsh, 1959; Hirsh & Sherrick, 1961).

Subsequent studies have revealed that discrete pairs of auditory and visual stimuli actually need to be separated by approximately 60–70 ms in order for untrained participants to judge accurately which modality was presented first (Zampini, Shore, & Spence, 2003). Larger temporal-order differences were also observed for pairs of auditory and tactile (e.g., JNDs of approximately 80 ms in Zampini et al., 2005) and visual and tactile (JNDs of 35–65 ms in Keetels & Vroomen, 2008; Spence et al., 2001) stimuli. These temporal-order discrepancies have been attributed to factors such as spatial confounds (see Vroomen & Keetels, 2012). Specifically, in Hirsh and Sherrick's (1961) study, the auditory and visual stimuli were presented from different spatial locations. For example, the auditory stimuli were presented over headphones, while the visual stimuli were presented from a screen or from LEDs that were placed directly in front of the participants (also see many of the early TOJ studies; e.g., Bald et al., 1942; Bushara, Grafman, & Hallett, 2001; Jaśkowski et al., 1990; Rutschmann & Link, 1964). It has recently been demonstrated that the use of experimental set-ups that present pairs of stimuli from different spatial locations can introduce possible confounds, since the spatial separation of stimulus sources can often impair multisensory integration (e.g., Soto-Faraco et al., 2002; Spence & Driver, 1997; Spence & Squire, 2003; Zampini et al. 2003; although cf. Fujisaki & Nishida, 2005; Noesselt et al., 2005; Recanzone, 2003; Spence, 2007; Teder-Salejarvi et al., 2005; Vroomen & Keetels, 2006). It is possible, therefore, that participants could have used redundant spatial information to facilitate their TOJ responses (that is, the participants may have judged which location came first rather than which sensory modality came first; see Spence et al., 2001).

20.3 Audiovisual TOJs for Complex Stimuli

Recently, research has been aiming to investigate the temporal constraints on the multisensory perception of synchrony under more realistic conditions by using more ecologically valid and complex stimuli (e.g., speech, musical, or object-action stimuli) rather than stimuli of low informational content (see de Gelder & Bertelson, 2003; Mauk & Buonomano, 2004; McGrath & Summerfield, 1985). Previous studies investigating the temporal constraints on the multisensory perception of synchrony (in other than TOJ tasks) mainly focused on the use of audiovisual speech stimuli and have identified three relatively consistent characteristics of the audiovisual temporal window of multisensory integration. These characteristics were related to the temporal window for synchrony perception for audiovisual stimuli: (a) having a width on the order of several hundred milliseconds; (b) being asymmetrical, with participants exhibiting higher performance decrements in detecting the asynchrony under conditions where the visual signal leads, as compared to conditions where the auditory signal leads; (c) exhibiting great variability across experimental set-ups and stimuli. In this section, we will review the studies that have experimented with complex stimuli and the TOJ task (see Vatakis & Spence, 2010, for a review of studies investigating temporal perception for complex stimuli using various types of temporal tasks). The studies that will be reviewed here verify the characteristics mentioned above and extend these by identifying a number of factors that affect TOJs and consequently the temporal window of multisensory integration.

Investigation of the differences in the sensitivity of temporal-order discrimination for simple versus more complex audiovisual stimuli was initiated using audiovisual speech, musical, and object-action stimuli (Vatakis & Spence, 2006a, 2006b, 2006c, 2007d, 2007e, 2008a). Complex stimuli are defined here as stimuli of higher information content and having a continuously changing audiovisual temporal profile. Initially, an investigation was conducted on whether the type of stimulus presented can affect participant audiovisual temporal-order discrimination (Vatakis & Spence, 2006a, 2006b, 2006c). This question was addressed through a series of experiments utilizing complex speech (i.e., continuous and brief speech tokens such as sentences, words, and syllables) and nonspeech stimuli (i.e., object-actions and musical stimuli that comprised single-impact events, such as the smashing of a block of ice with a hammer or the playing of musical pieces with single and double notes) in a TOJ task. The results from these experiments revealed that participants found it significantly easier to detect the temporal asynchrony present in desynchronized audiovisual object-action events than to detect the asynchrony in speech events (see also Dixon & Spitz, 1980). The results obtained also demonstrated, for the first time, that people are less sensitive to the asynchrony present when viewing audiovisual musical events than when viewing either speech or object-action events. Most importantly, however, the results showed that audiovisual TOJs are modulated by the properties and complexity of a given stimulus as well as by the level of familiarity that a participant has with that particular stimulus (cf. Petrini, Russell, & Pollick, 2009; Schutz & Kubovy, 2009a).

The familiarity effect was investigated by comparing TOJ performance for both familiar and unfamiliar video clips. The familiar stimuli were composed of normally presented video clips of syllables, guitar notes, and object-action events, while the unfamiliar stimuli consisted of the temporally-reversed versions of the same clips (note that the temporal profile of the stimuli may also have been somewhat different for the normal versus reversed presentations). The most important finding to emerge from this experiment was the difference in participants' temporal sensitivity for familiar versus unfamiliar (i.e., reversed) stimuli of the same stimulus type (i.e., lower JNDs for familiar as compared to unfamiliar stimuli; see also Petrini et al., 2009b). Interestingly, however, this reversal effect was only evident for the musical and object-action video clips, not for the speech stimuli.

The results of Vatakis and Spence's (2006a, 2006c) studies also showed that shorter duration stimuli that are less complex (i.e., where the stimulus properties remain relatively constant) lead to a higher sensitivity to temporal order as compared to stimuli that are longer in duration, of higher complexity, or both (e.g., the temporal window for a sentence being larger than that for a syllable). In addition, high variability in modality leads/lags was observed between different speech stimuli, a finding that could have been driven by the fact that the phonetic and physical properties (in terms of articulation) involved in the production of speech sounds vary as a function of the particular speech sound being uttered (e.g., Kent, 1997; van Wassenhove et al., 2005).

The above-mentioned variability in modality leads/lags between different speech stimuli led to a new line of experiments that focused on the perception of speech stimuli and how physical differences present in the articulation of various speech tokens affect people's temporal sensitivity (Vatakis & Spence, 2007e). Specifically, a series of experiments was designed to investigate the possible effects that physical changes occurring during the articulation of different consonants (i.e., varying as a function of the place and manner of articulation and voicing) and vowels (i.e., varying as a function of the height and backness of the tongue and roundedness of the lips; see Kent, 1997) might have on the temporal window of audiovisual integration for speech stimuli (Vatakis et al., 2012). The results of these experiments showed that visual-speech had to lead auditory-speech in order for the PSS to be attained. This, however, was not true for the case of vowels. Specifically, for vowels, larger auditory leads were observed for the highly visible rounded vowels as compared to the less-visible unrounded vowels (see Massaro & Cohen, 1993, for a comparison of /i/ and /u/ vowels and the /ui/ cluster; and Traunmüller & Öhrström, 2007). In addition, the participants showed higher sensitivity to the temporal order of the rounded as compared to the unrounded vowels. These differences in sensitivity to the temporal order of the audiovisual speech stimuli were only found as a function of roundedness/backness of the vowels presented, while no such differences were observed as a function of the height of the tongue positions (i.e., a highly auditory-dominant feature; Vatakis et al., 2012).

Overall, it was observed that visual-speech leads were generally larger for lower-saliency visual-speech signals (e.g., alveolar tokens) as compared to the smaller visual leads observed for speech signals that were higher in visibility (such as bilabial tokens). Vatakis and Spence's (2007e) findings therefore replicated previous research showing that the visual-speech signal typically precedes the onset of the auditory-speech signal in the perception of audiovisual speech (e.g., Munhall et al., 1996). More importantly, this study demonstrated that the precedence of the visual-speech signal changes as a function of the physical characteristics in the articulation of the particular speech signal that is being uttered (Vatakis et al., 2012). These results agree with the "information reliability hypothesis," which supports the notion that perception is dominated by the modality stream that provides the most reliable information (e.g., place versus manner of articulation of consonants; Schwartz, Robert-Ribes, & Escudier, 1998; cf. Wada, Kitagawa, & Noguchi, 2003). Finally, Vatakis and Spence's results also support the idea that the degree of visibility of the visual-speech signal can modulate the visual lead required for two stimuli to be perceived as simultaneous. That is, the more visible (i.e., informative) the visual signal, the smaller the visual lead that is required for the PSS to be reached. These findings accord well with van Wassenhove et al.'s (2005) claim that the higher the saliency and predictability of the visual input, the higher the facilitation of the processing of the auditory input.

Up to this point, therefore, audiovisual temporal perception can be modulated by any inherent differences in the properties of a complex audiovisual stimulus (such as in terms of physical differences attributable to the articulation of a particular speech sound). However, in an otherwise constant (in terms of its properties) stimulus, changes in the orientation of that stimulus (such as shifts in the orientation of a speaker's head during conversation) may also result in changes in sensitivity in the temporal perception of the stimulus. In order to evaluate this possibility, dynamic complex speech and nonspeech stimuli of short duration were presented in an upright or inverted orientation (Vatakis & Spence 2008a). The results of these experiments revealed that the inversion of a dynamic visual-speech stream did not have a significant effect on the sensitivity of participants' TOJs concerning the speech and nonspeech stimuli (i.e., the JNDs were unchanged). The perception of synchrony was, however, affected in terms of a significant PSS shift in the case of inverted speech stimuli. Specifically, inversion of the speech stimulus resulted in the visual stream having to lead the auditory stream by a greater interval in order for the PSS to be attained. These results agree with the findings of previous research on the face inversion effect, wherein the inversion of a visual display has been shown to lead to the loss of configural information (thus leading to slower face processing when compared to faces presented in an upright orientation) and to the recruitment of additional processes for the processing of a face but not for the processing of nonspeech events (cf. Bentin et al., 1996).

The wider temporal windows of audiovisual integration obtained for complex versus simple stimuli suggest that the perception of synchrony may be affected by stimulus complexity. One possible account of how complexity might modulate temporal perception proposes that a high level of stimulus complexity may promote the perception of synchrony (even for objectively slightly asynchronous stimuli), thus leading to wider temporal windows. This could be due to an increased likelihood of binding that may be attributable to the operation of the unity assumption (i.e., the assumption that a perceiver has as to whether he or she is observing a single multisensory event versus multiple separate unimodal events—a decision that is based, at least in part, on the consistency of the information available to each sensory modality; e.g., Spence, 2007; Vatakis & Spence, 2007-c; Welch & Warren, 1980).

In order to investigate the impact of the unity effect on the temporal perception of complex audiovisual stimuli, matching and mismatching auditory and visual speech streams consisting of syllables and words, and nonspeech stimuli consisting of object-action, musical, and monkey call stimuli were presented (Vatakis & Spence, 2007a, 2007b, 2007c, 2008a; Vatakis, Ghazanfar, & Spence, 2008). A total of eleven TOJ experiments were conducted, providing psychophysical evidence in support of the conclusion that the unity effect can modulate the crossmodal binding of multisensory information at a perceptual level of information processing. This modulation was shown to be robust in the case of audiovisual speech events, while no such effect was reported for audiovisual nonspeech or animal call events (but see Petrini et al., 2009a, and Schutz & Kubovy, 2009b, for musicians). Specifically, the results of these experiments on the unity effect (Vatakis & Spence, 2007c) showed that people were significantly more sensitive to the temporal order of the auditory- and visual-speech streams when they were mismatched (e.g., when the female voice was paired with a male face, or vice versa) than when they were matched. No such matching effect was found for audiovisual nonspeech and animal call stimuli. Moreover, it was shown that this modulatory effect was specific either to the integration of the auditory- and visual-speech signals, or perhaps to the presence of the auditory-speech signal itself, with no generalization to all human vocalizations (though see also Parise & Spence, 2009, for a recent demonstration of the unity effect for synaesthetically congruent simple auditory and visual stimuli).

20.4 A Focus on Nonspeech Complex Stimuli: The Case of Music

The gradual move of experimental research on multisensory integration from the use of simple stimuli toward the use of more complex and ecologically valid stimuli has been motivated by the fact that most events that occur in everyday life are highly dynamic in nature. Audiovisual speech, given its important role in human communication, has dominated the investigations of multisensory integration of stimuli of high-informational content. However, speech represents a highly overlearned stimulus for most people, and it has even been argued by some researchers that it may represent a “special” class of sensory event (e.g., Bernstein, Auer, & Moore, 2004; Massaro, 2004; Munhall & Vatikiotis-Bateson, 2004; Tuomainen et al., 2005). As a consequence, the recent studies described in the previous section have directed their attention to the use of both speech and other complex nonspeech stimuli such as music or object-actions. In the sections that follow, we will focus on musical stimuli and the research related to audiovisual perception of music's temporalities.

There are many reasons why music has recently been recognized as a valuable tool for capturing aspects of multisensory processing in real-life situations: (1) music is a kind of human behavior frequently experienced in everyday life and typically present to all historic or contemporary cultures; (2) it shares many common physical and structural properties with spoken language, though musical sound constitutes a subtype of auditory stimuli that is of much higher spectrotemporal complexity compared to speech (e.g., Patel, 2007); (3) numerous neuroimaging studies have shown that a number of important properties of speech and music are processed in a similar manner (e.g., Zatorre, Belin, & Penhune, 2002; though see also Zatorre, 2001); (4) previous temporal perception research has tended to focus on speech events while ignoring other equally complex events, such as music. However, music might serve as a better stimulus than object-actions and simple sound bursts and light flashes for comparison with speech, given its complex time-varying nature. Finally, the multiple ways that visual information can influence and shape our experience of music has been extensively investigated and has been concerned with a considerable range of aspects, extending from low-level (perceptual properties of individual notes) to higher-level characteristics (expressiveness or emotional engagement; see Schutz & Kubovy, 2008, for a detailed review of these studies). Despite the wealth of this field, it is surprising that time-related aspects have not yet attracted serious attention.

20.5 Audiovisual Interactions on Temporal Perception of Single Notes and Musical Temporal Patterns

There is a consensus among recent theories of music that temporal relations in music are organized in a number of different and explicitly specified structural levels that interfere with each other in a hierarchical fashion (Cooper & Meyer, 1960; Lerdahl & Jackendoff, 1983; Yeston, 1976). This approach has also gained considerable empirical support from psychological research on the subject (Clarke, 1999; London, 2004). As a piece of music unfolds, temporal information acquired from the lowest level (i.e., temporal properties of individual events, such as note duration or time interval between the attack points of successive events) is accumulated over time and shapes the perception of temporal relations at the next higher level, where short temporal patterns and rhythmic motives emerge. These two basic temporal levels point directly to two distinct areas within recent research on audiovisual perception of synchrony that have utilized musical stimuli and TOJ or synchrony detection tasks.

One of these areas includes a number of studies examining audiovisual interactions that occur at a local (microtemporal) level of the musical structure and are associated with the perception of temporal properties of individual events (i.e., single or double notes played concurrently). Recent research has shown that visual information of different stroke types on the marimba may influence listeners' auditory perception of note articulation (staccato, legato), even though there were no acoustic differences between the produced tones (Schutz & Lipscomb, 2004). Schutz and Lipscomb (2007) further investigated this issue and extended it into the temporal domain by examining whether visual observation of different stroke types relates to perceived note duration. Interestingly, they demonstrated that gesture length of different stroke types affects auditory-duration judgments of the marimba's notes, despite explicit participant instruction to base responses on hearing alone. The pattern of visual influence, however, remained the same along different pitch ranges of the instrument. In a subsequent experiment, videos of the original long and short marimba strokes paired with notes produced by marimba, piano, French horn, clarinet, and voice were presented, and participants had to rate the perceived duration. These ratings were influenced in the case of percussive instruments (marimba and piano), but not in the case of nonpercussive ones (French horn, clarinet) and voice (Schutz & Kubovy, 2007, 2009b). Visual influence was also observed when the naturalistic video of the marimbist's strokes was replaced by a four-point skeleton, or just a single moving dot that imitated salient properties of impact motion (Schutz & Kubovy, 2009a). Further investigation of the visual cues that mostly affect the perceived duration pointed only at the duration of the post-impact portion of the gesture as a dominant factor, showing also that other aspects of the post-impact motion (such as distance traveled, velocity, acceleration, and the rate of its change) play a minor role, if any (Armontrout, Schutz, & Kubovy, 2009).

Although this line of research does not link directly to the concept of temporal order, it contributes to our understanding of how visual perception of different physical parameters attributable to the movements that produce a sound on a percussion instrument affect the perceived auditory-duration of the tone. Interestingly, among these studies there is one that examines the effect of synchrony and asynchrony between the auditory and visual stimuli on the strength of the perceived illusion (i.e., the effect of the visual input on the perceived auditory-duration of the tone; Schutz & Kubovy, 2009b). The results were surprising in demonstrating that the strength of the visual influence was almost absent in the auditory-lead condition, reached a maximum in the synchrony condition, and had a medium strength in the auditory-lag condition up to a stimulus-onset asynchrony of 700 ms. These values imply a rather large temporal window of cross-modal binding, but most importantly suggest that the degree of causality attributed to temporal proximity between the auditory and visual inputs may constitute a critical factor in cross-modal binding of events. Thus, visual influences seem to play a role in temporal processing of musical stimuli, as was reported in the previous section on speech. However, for the case of music, further work is required to determine whether these parameters might also influence aspects of temporal perception of percussive musical tones other than duration (i.e., audiovisual synchrony perception). Of particular interest, in addition, are questions about the significance of similar cross-modal interactions that may occur beyond the percussion family, along the huge variety of sound-producing movements in musical instruments that do not necessarily imitate impact-like motion.

As noted previously, Vatakis and Spence (2006a, 2006b) were among the first to point out the necessity of using stimuli other than speech, especially musical stimuli, for exploring audiovisual temporal perception. In a series of experiments with audiovisual musical stimuli, they assessed sensitivity to temporal-order discrimination using a variety of musical events under different viewing conditions and durations. The purpose of these experiments was mainly to explore potential differences in audiovisual synchrony perception between speech, object-action, and musical stimuli, or among different categories of musical stimuli, rather than to examine the effect of certain dimensions of the musical events per se. Among the wide range of video clips that were presented in these experiments, the following piano and classical guitar stimuli were included: (a) a male playing the notes A and D on a classical guitar (only the center of the body of the guitar was visible; 1700 ms duration); (b) the same male playing pairs of simultaneously occurring notes (D/B and E/G) on a classical guitar (2200 ms duration); (c) a bird's-eye view of the hands of a female playing the notes A and D on the piano (1700 ms duration); (d) the same female playing pairs of simultaneously occurring notes (C/E and F/D) on the piano (2200 ms duration; Vatakis & Spence 2006c); (e) a close-up view of a person's fingers on a classical guitar playing the note D (800 ms duration); (f) the same video clip played back in reverse (Vatakis & Spence 2006a); (g) upright and inverted bird's-eye views of the fingers of an individual playing the piano notes C and F (both clips were 800 ms in duration; Vatakis & Spence 2008a); (h) close-up views of a person's fingers on a piano playing the notes A and D, and then the same notes on a classical guitar (1650 ms duration); (i) the same close-up views but with the auditory channels swapped over (e.g., the visual image of the piano was paired with the guitar sound, and vice versa; Vatakis & Spence, 2008b). The results obtained from the above studies, though rich in the information they convey, still constitute a sparse image of cross-modal interactions in the perception of synchrony of musical audiovisual events. However, they do provide valuable insights in regard to the relative contribution of factors that influence temporal characteristics of cross-modal binding of musical events.

In general, pronounced variability both in sensitivity to synchrony (JND values) and in modality lead/lag needed to attain perceived synchrony (PSS) was obtained among different combinations of instruments, sounding notes, and viewing conditions. A closer look at all the musical stimuli used in these studies (Vatakis & Spence, 2006a, 2006c, 2008a, 2008b; Vatakis et al., 2008) provides some interesting findings. For instance, results drawn from different viewing conditions of the same instrument (e.g., comparing the guitar body view and the close-up view of the guitarist's fingers) suggest that higher-saliency visual cues of the finger movements lead to higher sensitivity to asynchrony (see figure 20.2). However, inversion of a bird's-eye view of the pianist's hands did not demonstrate any effect, possibly indicating that this kind of configural information of the pianist's hands is not as critical

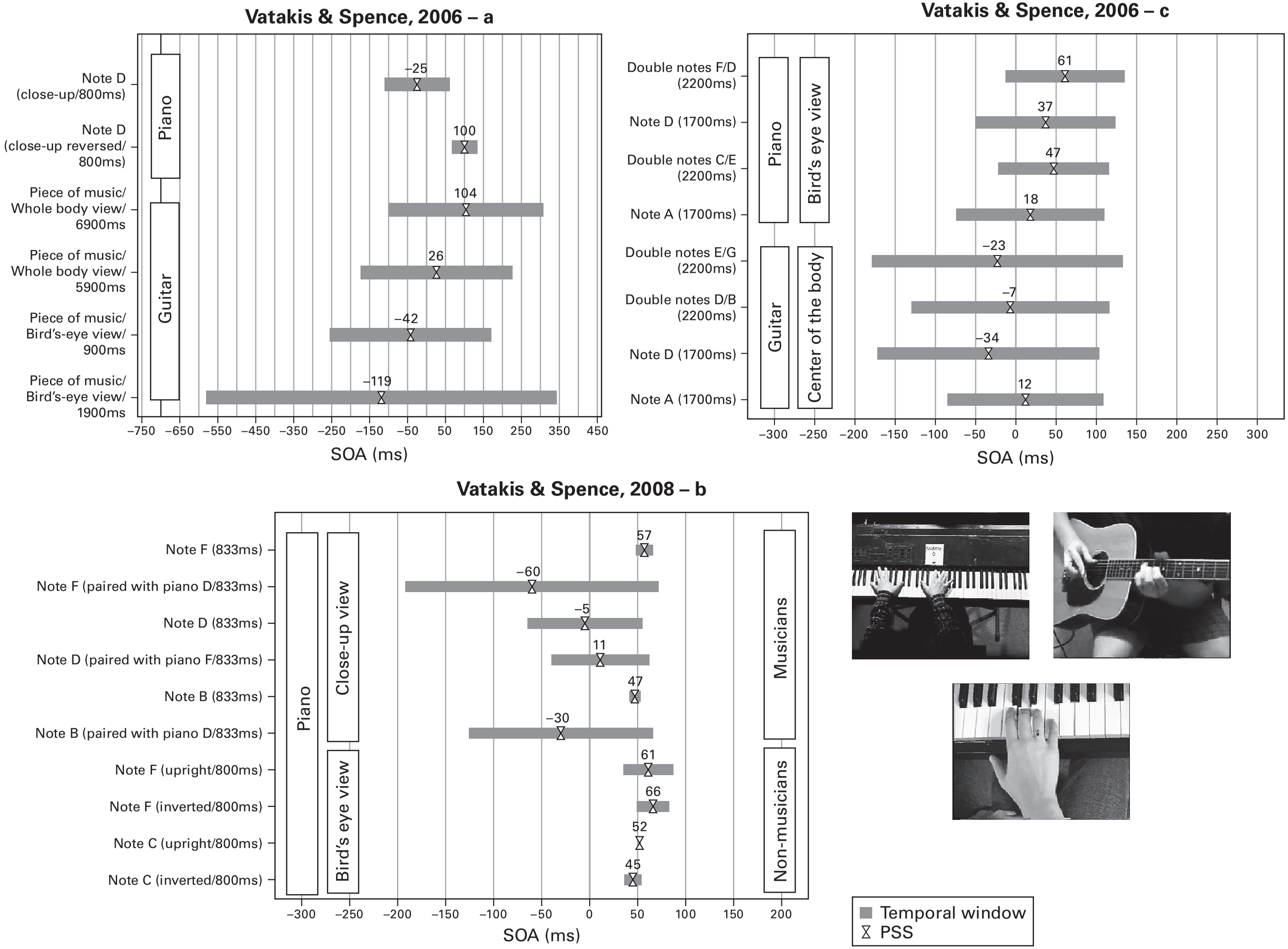

Figure 20.2
Audiovisual temporal windows for the musical stimuli used in some of Vatakis and Spence's studies.

as, for example, in cases of audiovisual speech processing when human faces are inverted (Vatakis & Spence 2008a). Similarly, incongruency of the presented video image with the concurrently heard sound, as for example in cases when the visual image of the piano was paired with the guitar sound, and vice versa (Vatakis & Spence 2008b), has a minimal effect in temporal-order sensitivity. One would have assumed that the absence of a causal relationship between the auditory and visual input may not affect cross-modal binding, but it is also reasonable to think that pairing a visual image of the piano with the guitar sound (or vice versa) may not seriously break the sense of the stimulus congruency, since both the piano and the guitar sounds are produced by strings, and are thus qualitatively similar (also see related findings on the marimba in Schutz & Kubovy, 2009b).

Single or simultaneous-sounding notes demonstrate a temporal window for synchrony that extends from about 50 ms up to 300 ms, and its magnitude appears to be affected mainly by the existence of salient information in the visual input (also see van Wassenhove et al., 2007, for speech). Thus, it is rather insensitive to auditory tone duration, at least for the specific families of instruments used (i.e., stroked or plucked string instruments), where the sound energy of the tone decays exponentially within a couple of seconds. In order to determine whether the relative low weight of this factor constitutes a general characteristic of cross-modal binding in the majority of musical instrument sounds, further work should be done with other musical sound categories, such as electronically generated ones or the sounds made by breath and bow, which generally have longer steady states after the attack that vary as a function of the performer's strike or breath duration. Comparative analysis of participants' responses to the normal and the temporally reversed video clips of the same note on a classical guitar showed a pronounced difference in temporal discrimination accuracy. This difference could be explained as an effect of familiarity with the stimulus, since the reversed playback of the guitar note can be considered an unfamiliar experience to the participants. However, this explanation should be adopted with caution, because the effect may also have been caused by the high contrast in the energy temporal envelope of the sound between the normal and the reversed video clips (see Schutz & Kubovy, 2008, for a demonstration of the importance of sound envelope as an acoustic cue for cross-modal binding). The potential influence of the sound envelope also points directly to a critical question: whether the importance of the attack portion of the sound, which in auditory research has been indicated as a perceptually salient feature (Heil, 2003; Phillips, Hall, & Boehnke, 2002; Scott, 1998), remains a prominent source of temporal information in audiovisual contexts as well.

An interesting finding was the demonstration of a modality lead/lag typicality effect within each instrument category. That is, visual leads are typically required for the perception of synchrony when participants viewed videos of piano, but, in contrast, auditory leads were mostly obtained in the case of the guitar videos. One possible explanation for these differences might be related to the appropriateness or ambiguity of the information provided by the visual or auditory stimulus. For instance, these differences could be driven by the difficulty that participants may have had in dividing their attention between the two different, fast, and spatially separated hand movements (guitar frets and central body movements) involved in playing the guitar. Another possible factor could be the fact that the guitar strings (due to the narrow width of each string and the small distance between them) are not as distinctive (or discriminable) as is, for example, the single action of a soda can being crushed. Additionally, the fact that the fingers in close proximity to the finger plucking a string tend to move and pause together (a phenomenon known as enslaving) may have rendered it harder for people to pinpoint the exact moment in time at which the appropriate finger plucked the string (Baader et al., 2005). Overall, however, these issues need further investigation with the incorporation of kinematics data in order to be in a position to explain the observed effects more accurately.

Although the findings on musical stimuli are intriguing, they merit further investigation, because they raise the important issue of how different spatiotemporal profiles of performers' fine and gross movements are perceptually evaluated, especially in musical instruments beyond the percussion family, given that these movements do not display sharp differences. Additionally, it is important to investigate the extent to which these movements constitute sources of information that have the power to counterbalance the saliency of the auditory cues in the temporal domain.

Moving at the level of the hierarchy of musical temporal structure, where rhythmic properties of music emerge as a result of an interaction between both temporal (durational proportions, tempo, metric hierarchies) and nontemporal properties (contours of pitch, timbre, and dynamics), it would be timely to extend the traditional, purely auditory research on the perception of musical temporal (rhythm) patterns to more ecologically valid, multisensory contexts. Currently, there are only a few published studies on audiovisual perception of synchrony with short streams of music or patterned sequences of events. In an exploratory experiment by Vatakis and Spence (2006a), a series of short musical pieces of durations between 900 and 6900 ms played on a piano and a classical guitar were presented. The results demonstrated a reduced sensitivity to temporal order due to the stimuli's greater length or complexity (see figure 20.2), which was also found for audiovisual speech stimuli.

The role of specific auditory properties (durational patterning, tempo, structure of dynamic accent, timbre) that are significant in the perception of short temporal (rhythmic) patterns in music, together with their interaction with aspects of visual information and participants' characteristics, have been investigated by a very limited number of studies in the field. The observation that the perception of audiovisual synchrony is affected by the tempo of a musical sequence has been reported in a study by Arrighi, Alais, and Burr (2006). In a series of experiments with isochronous patterns played on a conga drum at various tempi and visual stimulus variations (i.e., natural conga performances versus artificial motion profiles of the percussionist's middle finger hitting a bar that represented the conga surface), it was shown that both the size of the auditory delay needed for synchrony to be perceived and the magnitude of the corresponding temporal window were inversely related to the drumming tempo. Specifically, larger auditory lags (PSS of about 80 ms; range of perceived synchrony about 200 ms at an inter-onset interval, or IOI, of 1000 ms) were obtained with natural conga performances, becoming progressively smaller toward faster tempi (PSS of about 40 ms; range of perceived synchrony about 100 ms at an IOI of 250 ms). The same phenomenon was observed with the artificial stimuli, except for the corresponding PSS values and synchrony ranges, which were slightly lower. These values are also in agreement with related findings by Petrini et al. (2009a) for point-light displays of drumming actions in combination with a synthetic sound of a jazz drummer playing swing rhythm patterns. This study further demonstrated that the narrowing of the temporal window with tempo increment associates with an asymmetric lowering of the upper bound of this window. These findings on the effect of tempo are intriguing, because they are consistent with related findings from the classical psychoacoustical research on auditory tempo perception, which demonstrated that sensitivity to tempo changes (i.e., anisochrony) in monotonic isochronous sequences is a fraction of less than 10 percent of the base IOI (at least over a range of IOIs between 300 and 1000 ms; Ehrlé & Samson, 2005; Friberg & Sundberg, 1995; Vos, Assen, & Fraňek, 1997). Although these JND's are considerably smaller in magnitude compared to those for the temporal windows reported in the above studies, this common principle, which appears to underlie both auditory and audiovisual perception of synchrony, provides evidence on the existence of a higher-level timing mechanism that incorporates temporal information provided by multiple modalities (see also Burr et al., 2009, for a detailed review). Another fundamental observation of empirical research on the role of tempo in auditory perception of music is that, besides synchrony perception, other critical aspects of perceived musical time have been also demonstrated to be affected by tempo, such as, for example, expressive timing (Honing, 2006; Repp, Windsor, & Desain, 2002) and perceptual representation of musical rhythm categories (prototype detection, boundary localization, etc.; Papadelis & Papanikolaou 2004).

Apart for the examination of tempo influences, Petrini et al. (2009a,b) went a step further in the issue of participants' familiarity with the experimental stimuli and tested how enhanced levels of expertise can affect sensitivity to asynchrony. They found that experienced drummers exhibited considerably lower PSS values and ranges for the temporal window of perceived synchrony compared to nonmusicians. As regards the variance of sensitivity to synchrony across different tempi, it was found to be relatively low for drummers in contrast to nonmusicians, who showed a gradual decrease in sensitivity toward slow tempi. In a subsequent experiment, where audiovisual congruency/incongruency of the stimuli was manipulated in a manner that the impact velocity of the point-light display matched or mismatched with the paired sound, the influence of audiovisual mismatch was found to affect only the width of synchrony window in nonmusicians. Further evidence on the influence of musical expertise is provided in a study by Hodges, Hairston, and Burdette (2005), where auditory-alone, visual-alone, and audiovisual sensitivity to temporal order was measured in a group of highly-skilled orchestra conductors and a matched group of musically untrained controls. As expected, conductors demonstrated considerably shorter auditory temporal thresholds, but no significant differences in visual ones were observed compared to controls. However, in a subsequent visual TOJ task, where task-irrelevant sounds were also presented together with the visual stimuli at various stimulus-onset asynchronies, conductors' response times in detecting synchrony/asynchrony of the visual stimuli were consistently faster than those of the controls. Thus, these findings render the issue of familiarity in music and temporal perception important for future investigations.

20.6 Conclusions

In the present chapter, we reviewed the literature on temporal perception of simple and complex audiovisual stimuli using a TOJ task. Temporal perception of simple stimuli has been of central interest since the start of experimental psychology (Boring, 1929). Nowadays, the research on the topic continues to be vigorous and advances by slowly moving toward the use of ecologically valid stimuli of high-informational content (e.g., Vatakis & Spence, 2010). This move toward the use of more complex stimuli has opened a series of critical issues associated with stimulus control and experimental set-ups; however, it has also lead to a series of interesting questions related to the audiovisual binding of information and the modality appropriateness of a given event (Welch & Warren, 1980). The studies reviewed here point to a series of new directions for research related to (1) the role of familiarity (and possibly learning) on temporal perception, given the differences reported here between musicians and nonmusicians and between speech and nonspeech stimuli; (2) the exact nature of the visual and auditory influences on the temporal perception of a unified audiovisual event. Investigation in this area will allow us to clarify why, for instance, the playing of the guitar is auditorily shifted, as compared to the visual shift observed for the piano playing; (3) the visual-dominance effects observed in complex stimuli as a factor of the stimulus presented (e.g., bilabial versus alveolar tokens); and 4) the systematic study of object-action and musical stimuli (as opposed to samples of actions and musical notes) in order to better understand audiovisual temporal perception for complex stimuli.

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21 On the Flexibility of Human Temporal Resolution

Agnieszka Wykowska and Valtteri Arstila

Our ability to efficiently interact with the environment is to a large extent dependent on how exact we are in perceiving the world's temporal properties. Imagine a situation in which one is to cross a busy street. Such an environment requires a temporal resolution down to the milliseconds range to be able to estimate the speed of an approaching car and its distance relative to one's position. The same holds for, say, a soccer player, who needs not only to estimate the speed of the to-be-kicked ball but also the speed of the player who is supposed to receive the ball. These and other similar scenarios show that we live in a fast-paced world in which good temporal resolution plays a fundamental role for adaptive behavior.

21.1 What Do We Talk about When We Talk about Human Temporal Resolution?

For artificial systems, one can talk about sampling rates or pixels per square inch. Similarly, one can investigate the resolution of the human information processing system—the ability to perceive (and/or report) two distinct stimuli as separate. By the same token, human *temporal* resolution might be understood as the ability to perceive two events occurring at the same time as simultaneous, and two events occurring with a delay as asynchronous. The *window of simultaneity*—the time range within which two asynchronous stimuli are still perceived as a single event—is how temporal resolution might be operationalized, given the above way of understanding *temporal resolution*. As various research results have shown, the human window of simultaneity is far from being precise. For example, the window of simultaneity for visual stimuli can be in the range of 20–30 ms, depending on circumstances. That is, two distinct visual events occurring with a small delay might be fused and seen as simultaneous (Pöppel, 1988, 1997).

Temporal resolution, understood as the ability to detect two stimuli presented with a delay as asynchronous, has been commonly investigated using so-called simultaneity judgment (SJ) tasks (e.g., Bushara, Grafman, & Hallett, 2001; Raizada & Poldrack, 2001; Santangelo & Spence, 2008; Stone et al., 2001) or temporal-order judgment (TOJ) tasks (e.g., Bald et al., 1942; Hirsh & Sherrick, 1961; Jaśkowski, 1993; McDonald et al., 2005; Shore, Spence & Klein, 2001). In the SJ tasks, two stimuli are presented either simultaneously or with a variable delay, and participants are asked to judge whether the stimuli were presented at the same time or asynchronously. In the TOJ tasks, two stimuli are presented with variable stimulus-onset asynchrony (SOA), and participants are asked to make a judgment concerning which of the stimuli was presented first. According to Ernst Pöppel (e.g., Pöppel, 1988, 1997), the SJ tasks target perceptual processes that are simpler and hierarchically subordinate to those pinpointed by the TOJ task. It is indeed the case that SJ requires observers to perceive two events as separate, whereas TOJ requires something more: first of all, perception of distinct events, and second, perception of their order. In support of such a thesis, Pöppel (1988) described findings indicating that the threshold for simultaneity judgments varies between modalities, being at around 30 ms for the visual modality and around 4 ms for the auditory (when the two clicks are presented to different ears). Still, the time needed for making correct judgments about temporal order is about the same across all modalities: 30 ms (Hirsh & Sherrick, 1961). Therefore, even if auditory events are already perceived as separate and not fused into one, observers might not be able to determine their order of occurrence. This implies not only that different systems might be involved in those two different tasks, but also that the systems involved in the simultaneity judgment are modality-specific, whereas the system involved in temporal-order judgments must be supramodal and, according to Pöppel, central.

It seems that human temporal resolution, as measured by the window of simultaneity, is a bit sluggish. Is human temporal resolution that varies across modalities still constant and fixed for each of the modalities? Or perhaps the window of simultaneity can be narrowed? Several authors have investigated how such factors as attentional focus (e.g., Correa, Lupiáñez & Tudela, 2005; Shore et al., 2001; Santangelo & Spence, 2008; Yeshurun & Levy, 2003; Hein, Rolke, Ulrich, 2006; Rolke, 2008; Rolke et al., 2008); task set (e.g., Zampini, Shore, and Spence, 2003); or expertise (e.g., Petrini et al., 2009) influence temporal resolution.

The aim of this chapter is to describe various factors that might have an impact on the precision with which humans perceive or report temporal relationships between events. This chapter will focus on findings in which temporal resolution has been addressed explicitly in the paradigm, i.e., by asking participants to judge temporal characteristics of stimuli. That is, temporal resolution will be understood in the narrow sense of the ability to determine temporal relationships between events. Hence, we will concentrate on the issue of how temporal resolution—as measured in the SJ and TOJ tasks—can vary depending on "internal" factors such as attentional orienting in space and time, task set, or expertise.[1] Therefore, phenomena like attention-related enhanced sensitivity of the visual system to detection of briefly presented (and possibly masked) stimuli (e.g., Enns & DiLollo, 2000; Sagi & Julesz, 1986) or degraded stimuli (e.g., Marais, 1998) will not be reviewed, as these (and other modulatory effects on sensory-perceptual processing) do not fall into the narrow sense of temporal resolution presented here. We do, however, acknowledge that those effects might also result from modulatory mechanisms operating on the temporal resolution of sensory processing, mechanisms that might increase the sensitivity of a sensory system in general.

21.2 Interactions between Spatial Attention and Temporal Processing

In the following, after specifying how we understand the concept of spatial attention, we will describe the influence of spatial attention on simultaneity and temporal-order judgments, and eventually we will discuss how spatial attention might influence temporal *resolution*. While the focus will be on temporal resolution understood as the ability to perceive two *visually* presented simultaneous events as simultaneous and two *visual* events presented with a delay as asynchronous (and, possibly, being able to determine their order), ability to detect temporal gaps in the stimuli will be discussed, too.

21.2.1 What Do We Talk about When We Talk about Spatial Attention?

Spatial attention will be understood in terms of focus on a part of visual field. It has been investigated since Helmholtz's first experiments in the nineteenth century, in which he pointed out that he could voluntarily shift his attention to identify certain letters on a visual display prior to shifting his gaze (von Helmholtz, 1894). In 1908, Titchener demonstrated that sudden onsets of stimuli attract attention. Subsequently, Posner (1980) introduced a paradigm in which he cued participants to attend to the left or right side of a visual field either by a stimulus that automatically attracted attention in a *reflexive* or *bottom-up* manner through its saliency (e.g., a flash of light, a so-called *exogenous* or *peripheral* cue), or by a symbolic cue that instructed participants where they should direct attention in a *voluntary*, *goal-oriented* or *top-down* manner (a so-called *endogenous* or *central* cue). Posner has reported that stimuli presented subsequently at the cued location are detected (and/or responded to) faster as compared to stimuli that are presented at the uncued location.[2]

Since Posner, the attentional cueing paradigm has often been used with various degrees of modification (see, e.g., Hopfinger & Mangun, 1998; Mangun & Hillyard, 1991; Müller & Rabbitt, 1989). Not only unimodal attentional cueing procedures have been applied, but also cross-modal paradigms (e.g., Santangelo & Spence, 2008; McDonald et al., 2005). When neural mechanisms of spatial attention were described in addition to behavioral effects, attentional enhancement of processing at the attended location has been demystified. For example, Luck et al. (1997) and Luck and Hillyard (1999) have reported single-cell results of attentional modulations—inhibited firing rates for to-be-ignored locations, or "shrinking" of receptive fields at the attended location (Moran & Desimone, 1985). Several authors have described electrophysiological correlates, such as modulations of the early sensory ERP components (Eimer, 1994; Luck, 1994; Luck & Hillyard, 1994; for reviews also see Hillyard, Vogel, and Luck, 1998; Luck, Woodman, & Vogel, 2000); a commonly used indicator of allocation of spatial attention, the N2pc component (Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 2003; Wykowska & Schubö, 2010; 2011); as well as gamma-band responses (e.g., Gruber et al., 1999). Finally, studies using the fMRI technique reported that blood oxygen level–dependent (BOLD) response might be modulated by spatial attention in the extrastriate (Mangun et al., 1997) or even striate cortex (Somers et al., 1999; Gandhi, Heeger, and Boynton 1999; Martinez et al., 1999; Reynolds, Pasternak, & Desimone, 2000).

21.2.2 The Prior-Entry Hypothesis

In the TOJ and SJ tasks, in combination with the attentional cueing procedure, a typical phenomenon occurs: as a result of directing participants' attention to a particular spatial locus, participants respond to stimuli that are presented at the attended locations as occurring earlier than stimuli in unattended locations. To be more precise, what is measured is the shift on the point of subjective simultaneity (PSS), which describes the SOA where a subject perceives the two stimuli as simultaneous.[3] Since Titchener presented his seven principles of attention in 1908, it has been hypothesized that such a phenomenon might be due to *prior entry;* that is, attended stimuli might have faster access to conscious perception.

It is not entirely clear, however, whether it is the early perceptual processing of temporal characteristics that is altered by focus of attention or, rather, that attentional manipulation biases responses. In temporal-order tasks, participants are asked to determine which of the stimuli was presented first. A clear case of a possible response bias confound is when participants need to indicate whether it was the left or the right stimulus that was presented first. If attention is directed to the left or to the right side, this manipulation might bias responses to the attended side. Researchers have attempted to circumvent this problem by making the response dimension orthogonal to the spatial manipulation of attention directing. For example, some researchers have asked participants to respond to the color of the stimulus that was presented first (e.g., McDonald et al., 2005) or to whether visual or tactile stimulus was presented first (Shore et al., 2001; Spence, Shore, and Klein 2001). Still, Schneider and Bavelier (2003) argue that even in such paradigms response biases might come into play: when participants are uncertain with regard to which stimulus was presented first, they might adopt a strategy of favoring the attended stimulus.

Even though it is difficult to decide which stage of processing is affected by attentional manipulation in TOJ tasks, some authors have provided support for the idea that perception is influenced by spatial attention. For example, Santangelo and Spence (2008) used an SJ task, arguing that such a task is immune to possible response biases that might constitute a confounding factor in temporal-order judgment tasks. In SJ tasks it seems unlikely that cueing a side of a visual field should in any way bias participants to respond more frequently with a "simultaneous" response than with an "asynchronous" response. In the study of Santangelo and Spence, two stimuli were visually presented either simultaneously or with a delay; one of the stimuli was cued by a lateralized auditory tone. The results showed that the PSS was equal to -17.4 ms—that is, the stimulus presented at the uncued location must have preceded the stimulus in the cued location by 17.4 ms, on average, to be judged as simultaneous. Since it was a non-speeded SJ task, the effect is likely not to be attributed to response biases. As such, this result supports the prior-entry hypothesis (Titchener, 1908) and therefore, the authors concluded that focal attention speeds up information transmission through sensory pathways. A similar conclusion was also drawn by Lew Stelmach and Chris Herdman (1991) based on their results, obtained by using only visual stimuli.

It thus seems that attended stimuli might become prioritized not only thanks to signal enhancement (e.g., Eimer, 1994; Eimer, 1996; Hillyard, Vogel, & Luck, 1998; Hawkins et al., 1990; Lu & Dosher, 1998; Treue & Martinez-Trujillo, 1999) or noise reduction (Yeshurun & Carrasco 1998; Luck & Hillyard, 1994), but also thanks to accelerated processing. A similar claim has been made by Carasco and McElree (2001), who examined whether spatial attention increases sensitivity to signal or influences speed of information processing. Because their method of analysis allowed for disentangling those two possible ways attention might affect processing, the authors were able to show that spatial attention both increases sensitivity through enhancing signal and, additionally, accelerates speed of processing of the signal. Not everyone agrees, though. Indeed, the results of a recent study by McDonald et al. (2005) that used event-related potentials methodology (ERP)[4] speak against the idea of prior entry, as focus of attention has been shown to influence amplitude rather than latency of the P1 ERP component. On the other hand, it is also possible that their ERP results mirror only an attentional cueing effect (as in, e.g., Eimer, 1994; Luck et al., 2000; Hillyard, Vogel, and Luck, 1998; Wykowska & Schubö, 2010; 2011) and are not related to the behavioral PSS. The behavioral effect might be independent of the P1 effect and might still be a result of a response bias to the spatially cued location.[5]

Even if the prior-entry hypothesis holds, it is not clear that it has any consequences for temporal resolution *in general,* because results only show the shift in the PSS. Accordingly, when two stimuli are presented in asynchrony, and the location of the first stimulus is attended, subjects can determine their temporal order with shorter SOA than without being attended. On the other hand, if the location of the latter stimulus is attended, a longer SOA is required for subjects to reliably determine the order of stimuli. Finally, when stimuli are presented simultaneously, then if attention accelerates processing of one of them, they might end up being (erroneously) perceived as asynchronous.[6]

21.2.3 Spatial Attention and Temporal Resolution

In the studies concerning prior entry, the location of *one* of the stimuli is attended. Although prior entry does not appear to have consequences for the temporal resolution of perception in general, this does not rule out the possibility of there being some effects when all relevant stimuli are attended. That is, it could be that focused attention has a beneficial or detrimental effect on temporal resolution of perception when compared to dispersed attention.

This issue of the relationship between spatial attention and temporal resolution was recently addressed by Yeshurun and Levy (2003) with the use of a temporal-gap detection task. In this task, participants observed two flashes of light presented at the same location.

The interval between the offset of the first flash and the onset of the second flash was varied. The authors measured the minimal interval in which participants still perceived the two flashes as separate events and below which the flashes were fused and perceived as one event. Additionally, the authors manipulated attentional focus via an exogenous visual spatial cue that preceded the onset of the first flash by about 100 ms. The participants' task was to indicate whether they perceived one flash of light or two separate flashes. The results showed that participants' sensitivity (measured by d') to detecting the temporal gap between two flashes was impaired in the condition of focused attention (cued location) as compared to dispersed attention (neutral cue). That is, in the focused-attention condition, a longer gap was needed for participants to notice it. The authors concluded that spatial attention degrades temporal resolution. According to Yeshurun and Levy, this may be because attention enhances activity of the parvocellular neurons, which, in turn, might inhibit activity of the magnocellular neurons. As parvocellular cells have longer response duration compared to magnocellular cells, the temporal resolution might be impaired as a cost of enhancement of spatial resolution. Another similar possible explanation for such results would be related to the finding that attention prolongs the visual persistence of the stimuli (Enns, Brehaut, & Shore, 1999; Rolke, Ulrich, & Bausenhart, 2006; Visser & Enns, 2001). Then, if the first stimulus has a longer visual persistence when attended, the temporal gap between two stimuli is shorter and hence more difficult to perceive. Accordingly, for attended stimuli a longer temporal gap is required so that the gap will be noticed.

Hein and colleagues (2006) investigated whether Yeshurun and Levy's (2003) conclusion also holds with respect to other tasks, and whether the detrimental effect of spatial attention on temporal resolution can also be found when attention is oriented to a particular location in an endogenous manner. Hein and colleagues found effects similar to those in Yeshurun and Levy (2003), although they used a standard temporal-order judgment task with unimodal (visual) cueing procedure and measured error rates. However, the authors found that when exogenous cues were substituted by predictive endogenous cues (75 percent validity), a reverse effect was obtained. The authors concluded that exogenously and endogenously cued attentional shifts influence different stages of the processing stream and, as such, have a different impact on temporal processing.

In contrast to the conclusions of Yeshurun and Levy, Wykowska, Arstila, and Busch (unpublished) observed that sensitivity to simultaneity detection might actually not be impaired at the attended location. The authors used an SJ task in which participants were presented with two stimuli simultaneously, with a 30 ms SOA, or with a 60 ms SOA. The first stimulus was a visual search display. The second stimulus was a simple quadratic dot probe that was presented either at the position of the search target or elsewhere. Since the visual search display was task-relevant (in addition to the SJ task, participants were asked to detect the target of the search display), and since the target feature was kept constant for the whole experiment, the target location of the probe could be treated as an endogenously "cued" (attended) location, whereas other locations could be treated as neutral (uncued) locations.[7] The authors found that sensitivity in the simultaneity judgment tasks, as measured by d', decreased when the probe stimulus was presented at neutral locations as compared to the target location or blank trials, especially in the more difficult condition of short SOA (30 ms). This result shows that when focal attention is directed *away* from the stimulus, temporal resolution is impaired, at least in terms of sensitivity to detecting asynchrony. Therefore, attention does not necessarily impair sensitivity to asynchrony.

Carver and Brown (1997) also found that attentional focus modulated simultaneity judgments. In particular, validly cued locations yielded a decreased proportion of "simultaneous" responses in an SJ task, independent of SOA. That is, when participants' attention was directed to the location of the stimuli, they were less likely to respond "simultaneous" to simultaneously presented stimuli. Importantly, in the validly cued condition, participants were also less likely to respond "simultaneous" to asynchronously presented stimuli. Although at first glance it might seem that attentional focus improved temporal resolution in the asynchronous condition and impaired temporal resolution in the simultaneous condition, Carver and Brown offer a more consistent interpretation of their data. The authors propose a model for simultaneity judgments. In line with the predictions of that model, attentional focus reduced the size of a critical interval during which two stimuli were judged as simultaneous, which resulted in reduction of the proportion of "simultaneous responses" in general. In that sense, attention enhanced temporal resolution. It might also be argued, in this case, that the improvement of temporal resolution might be due to attention being directed to a location in a top-down manner (the validity of the cue was 80 percent).

To sum up, the above-described findings illustrate that the relationship between spatial attention and temporal resolution is not as straightforward as Yeshurun and Levy's (2003) study suggested. In particular, their claim that spatial attention degrades temporal resolution in general is unwarranted. To begin with, Hein et al.'s (2006) results showed that while exogenous attentional cueing may worsen the performance in an SJ task, spatial attention actually seems to improve the performance when valid or endogenous cues are used. Given that Yeshurun and Levy's study only used exogenous cues, it is possible that subjects' performance in detecting short temporal gaps could improve with endogenous cues. This in fact appears to be the case; Poggel et al. (2006) have shown that sustained attention facilitates the detection of short temporal gaps, thereby improving the temporal resolution.

However, depending on what one means by temporal resolution of perception, one can also give two different interpretations of Yeshurun and Levy's result. On the one hand, if it is defined as an ability to detect temporal gaps in the physical stimuli, then exogenous attention to the location of stimuli indeed impairs temporal resolution. On the other hand, temporal resolution can also be defined by the temporal thresholds at which sensory or perceptual mechanisms function (Holcombe 2009). In this case, it could be that the mechanism providing us with the ability to detect temporal gaps in stimuli is a higher-level mechanism and hence subject to the output of lower-level mechanisms (such as temporal integration). This is not entirely implausible, because it could be that the detection of temporal gaps is dependent on what kind of sensations we have. Thus, if exogenous attention prolongs the duration of perception of a stimulus, which in effect shortens the temporal gap (based on which the mechanism functions), it could be that the temporal resolution of the mechanism that provides us with the ability to detect temporal gaps in stimuli remains the same while the sensory signals they work with are modulated by attentional cues. Regardless of how this particular issue will eventually turn out, it appears unlikely, however, that the conclusions based on the results of Yeshurun and Levy (2003) can be expanded to the issue of influence of spatial attention on temporal resolution in general.[8]

21.2.4 Temporal Resolution is Penetrable to Attentional Modulation

Taken together, this collection of results shows that the question of whether the focus of attention impairs or facilitates temporal resolution is far from having a simple answer. It is very difficult to pinpoint what processes are modulated by attentional focus. The influences of attention on speed of processing might be confounded with response biases in behavioral results. In addition, ERPs might not be sensitive enough to exhibit the attentional impact on temporal processing per se. This situation might be due to the fact that researchers do not yet have a clear view on where and how time is processed in the brain. Moreover, the answer to the question of how temporal resolution is influenced by spatial attention depends on how temporal resolution is defined and measured, and what attention manipulations are employed in the experimental paradigms. However, although one cannot draw a direct conclusion concerning the influence of focal attention on temporal resolution, it becomes evident that *the window of simultaneity can be affected by attentional processes*.

21.3 Interactions between Temporal Attention and Temporal Processing

Anticipating *when* something occurs is as important for successful behavior as anticipating *where* it occurs. Accordingly, it is unsurprising that our temporal expectancies—predictions on when an event is about to occur—also enhance our performance in various tasks. This happens by means of temporal attention, which is a temporal analog to spatial attention. That is, it has been suggested that just as we can attend to particular locations, we can also attend to certain moments in time. In this section, we discuss two cases where temporal attention has an effect on temporal resolution.

The first case is the foreperiod paradigm. The foreperiod is the duration between the warning signal, which indicates that something is about to happen, and the target. An everyday example of such an event is a traffic light: when the light turns red to others (the signal), we know that it is about to turn green to us (the target). The *foreperiod effect* refers to the fact that the duration of the foreperiod influences reaction times to the target—as already observed by Herbert Woodrow (1914).

There are two types of foreperiod effects. In fixed foreperiod tasks (also known as blocked foreperiod tasks), the duration between the signal and the target is kept constant between the trials and is changed only between the blocks. Experiments employing such tasks have revealed that the responses to the target are faster with a short foreperiod than with a longer foreperiod. In the variable foreperiod tasks, however, the duration of the foreperiod varies within a block, and the effect is opposite: the reaction time to the target is longer with the shorter foreperiod (see Niemi & Näätänen, 1981 for a review). That is, when the foreperiod is predictable, the reaction time increases with the duration of the foreperiod, and when the foreperiod is unpredictable, the reaction time decreases with the duration of the foreperiod.

Most of the studies on the foreperiod effect have focused on the latter result, obtained by using a variable foreperiod. The traditional way to explain the results is with reference to hazard functions: the preparatory reaction state is enhanced with an increased probability for the event to occur, which in turn results in faster reaction times (Näätänen, 1970).[9] Although this explanation accounts for the results, and the foreperiod effects have been replicated countless times and in various conditions (for different foreperiod ranges, for various response-time tasks, with different modalities, and so forth), the underlying neural and cognitive processes remain a matter of disagreement (for discussion, see Los, 2010).

Another case of temporal attention concerns the temporal orientation paradigm. Here the temporal expectancies on whether a forthcoming event is likely to occur after a short or long interval are induced by giving subjects explicit (and mostly valid) cues or instructions. This can be done, for example, by showing the words “early” or “late,” which in turn orients subjects’ attention to a right moment in time. In this paradigm, the temporal expectancies vary from one trial to another (unlike in a constant foreperiod paradigm), but subjects get informative cues when an event is about to occur (unlike in a variable foreperiod paradigm). A further difference is that in a temporal orientation paradigm, the cues in question are explicit, and hence the temporal orienting of attention happens voluntarily, whereas in the foreperiod paradigm the cues for orienting attention are implicit.[10]

In the first studies on temporal orientation, the subjects’ task was to respond to the presence of the target as quickly as possible. The results showed that reaction times were shorter when the cues were valid, thus suggesting that subjects were able to attend to a specific moment in time and that this enhanced their performance in the experiments. The initial evidence suggested that the performance effects in the temporal orienting tasks are due to enhanced preparation of motor responses. It has since been shown, however, that when the task is perceptually demanding, participants modulate the perceptual processes themselves, independently of motor responses. One of the first studies to show this was by Correa et al. (2005), who used rapid serial visual presentation (RSVP), where a target letter was shown in the successive stream of letters (14 ms per item). All letters were shown in the same spatial position, and thus masked each other. The results showed that subjects were better at detecting the targets when the targets were presented at the time indicated by the cues as compared to unexpected times of appearance. Accordingly, although temporal orientation influences reaction times, and could be thus considered only a preparatory, behavioral effect, it has thus been shown that it also influences perceptual processes. Behavioral results suggesting that temporal orientation can improve perceptual processes are also supported by ERP studies (Correa et al. 2006a; Lange, Krämer & Röder, 2006).

Improved perceptual detection related to temporal orientation raises the question whether there could also be perceptual effects in foreperiod paradigms. After all, they both involve temporal attention and have similar effects on speeding responses. After Correa et al.'s (2005) results, such a possibility was investigated by Bettina Rolke and her colleagues. In the first study, they (Rolke & Hofmann, 2007) showed that temporal preparation related to the occurrence of the target influences perceptual processing by degrading ability to detect small spatial gaps in briefly presented stimuli (masked afterwards). Later, Rolke (2008) showed that an identification of briefly shown and then masked letter is better with a shorter foreperiod (in a fixed-foreperiod experiment), thus illustrating that the foreperiod effect has an influence similar to that of temporal orientation on RSVP tasks where the target is also masked. In short, the consequences of fixed foreperiod and temporal orientation are alike in this sense too.

Importantly for the topic of this chapter, temporal orienting, however, not only influences the perceptual accuracy in spatial discrimination tasks, but it also influences temporal resolution of our visual perception, as defined in the present chapter. Correa et al. (2006b) investigated the effect of temporal orientation on temporal-order judgments by showing subjects two visual stimuli in small asynchrony (10–110 ms). The subjects' task was to tell which one of them occurred first. Unlike in the "usual" TOJ experiments, here subjects were first cued whether the stimuli would occur after a short or long interval (400 ms versus 1400 ms after the cue). The results showed that the TOJ threshold was lower for valid cues than it was for invalid cues (41 ms versus 46 ms). This means that subjects were able to attend to a particular point in time, and when two stimuli were shown at that time, their threshold for determining the temporal order of the stimuli improved.[11]

Since temporal orienting and foreperiod paradigms have similar effects on perceptual detection tasks, one could also expect similar effects on temporal resolution. Even though Rolke did not measure foreperiod effects on temporal resolution in the narrow sense of the term, as used in this chapter, one possible explanation for the improved target discrimination in the rapid successive stream of stimuli is that it is a consequence of improved temporal resolution in general. In this case, the similarity of temporal orientation and foreperiod effects would mean that the latter also improves our temporal resolution. Whether this is indeed the case remains an open empirical question.

Altogether, temporal attention appears to exert very similar effects as spatial attention. First, regardless of whether attentional orienting is due to exogenous or endogenous cues, subjects' reaction times are decreased. Moreover, both spatial attention and temporal attention improve the performance in spatial discrimination tasks, and temporal resolution appears to improve, too, though it is dependent on a given experimental manipulation. While SJ/TOJ tasks have been used in cases of both temporal and spatial attention, the temporal gap paradigm has only been used in relation to spatial attention, whereas the RSVP paradigm has been used in relation to temporal attention.

21.4 Task Set and Temporal Resolution

Task set is a psychological concept that describes a set of rules that humans use in order to complete a given assignment. In everyday situations, it refers to cases in which humans need to maintain simple rules such as "in order to turn on the computer, one needs to press a certain button," or more complex rules such as "in order to cook a soup, one needs to boil water and add particular ingredients." In laboratory settings, the maintenance and application of such rules has been investigated with paradigms like task cueing or task switching (for a review, see Sakai, 2008). In psychological experiments, in which participants are given instructions specifying their experimental task, task set refers to the representation of simple rules such as, for example, stimulus-response mappings: "if you see a red square, press the right key, or if you see a blue square, press the left key."

Zampini et al. (2003) investigated the question of whether a task set for participants would have an influence on temporal resolution in a TOJ task. In one experiment, they manipulated the location of two successively presented visual and auditory stimuli, but the response-defining dimension was modality (e.g., was the visual or the auditory stimulus presented first?). The authors found that if the stimuli were presented in the same location (e.g., left-left), participants' performance sensitivity to temporal order was impaired as compared to a different location condition (e.g., left-right), although the response dimension was orthogonal to the spatial manipulation. In the second experiment, the authors presented either unimodal (e.g., visual-visual) or crossmodal (e.g., visual-auditory) stimuli. This time, however, participants were to respond with respect to the *spatial* characteristics of stimuli, indicating whether the left or the right stimulus was presented first. The authors did not find that significant differences in sensitivity to temporal order depended on whether the modality was the same or different. A cross-experimental comparison revealed that the response-defining dimension had a significant influence on accuracy in the TOJ tasks: the *modality* discrimination task yielded better precision than the *spatial* discrimination task. Importantly, this analysis was carried out on the same type of trial: bimodal trials that were present in both experiments. The authors concluded that factors such as spatial configuration (stimuli presented in the same versus a different location) might influence temporal resolution in TOJ tasks. Importantly for the purposes of this chapter, the study of Zampini and colleagues (1993) also showed that temporal resolution can be influenced by the response-defining dimension, or, in other words, a top-down factor of task set.

21.5 Expertise and Temporal Resolution

Another important factor that may influence sensitivity to the temporal order of events is expertise. For example, Petrini et al. (2009) conducted a study in which they examined expert drummers and novices in a synchrony detection task. The authors used complex audiovisual stimuli (i.e., videos) with point-light displays generated from 3D motion capture data obtained while professional drummers were playing music samples. The videos presented to participants combined the aforementioned point-light displays and synthetic sounds, with varying delays between the visual and the auditory stream. The task of participants was to judge whether the drummer's movements were in synchrony with the sounds. The authors found that not only were experts more sensitive to asynchrony detection, as measured by a narrower temporal integration window[12] and smaller PSS, but they were also less sensitive to such factors like tempo of the music samples or incongruency between auditory and visual stimuli. In other words, experts showed a better temporal resolution that was more stable with respect to physical properties of the stimuli. Similar results were obtained by Hodges, Hairston, and Burdette (2005), who showed that orchestra conductors' TOJ threshold for auditory stimuli was less than half the threshold of musically untrained subjects (33.7 ms vs. 76.7 ms). Interestingly, these two groups did not differ in their TOJ threshold for visual stimuli. This suggests that it is either expertise that influences temporal resolution, or that people who have better temporal resolution become experts in the areas where good temporal resolution is necessary (this possibility applies equally to Petrini et al.'s [2009] results).

Given the nature of their profession, and the fact that Hodges et al.'s (2005) results also showed orchestra conductors to be better at localizing sounds and discriminating pitches, one could argue, however, that conductors were more familiar with the stimuli than musically untrained subjects. In this case, the interpretation according to which expertise does improve temporal resolution would receive support from the study by Vatakis and Spence (2006), who found an effect of familiarity on sensitivity to asynchrony for musical and object action events. In accordance with this, Powers, Hillock, and Wallace (2009) found that extensive training with feedback improved temporal resolution in a simultaneity judgment task of audiovisual stimuli. Moreover, Fujisaki et al. (2004), for example, showed how adaptation to a particular temporal lag between two audiovisual stimuli shifts the PSS in the direction of the adapted lag.[13]

These results indicate that expertise, training, and adaptation have a high influence on timing of events in perception. Once again, temporal resolution seems to be flexible and modifiable. An interesting question concerning expertise arises: does the sensitivity of, for example, expert musicians to musical asynchrony generalize to other tasks? That is, do experts in one domain have better timing in general?

21.6 Theoretical Implications

In the above, we have described various factors influencing human temporal resolution. If focal attention, task set, expertise, and probably many more internal factors influence temporal resolution, then what follows is that there is no clear absolute value that could be an estimate of human precision in processing the temporal characteristics of the world. Such a conclusion is in line with the view put forward by, for example, Holcombe (2009), who claims that the human visual system has multiple temporal resolutions. According to Holcombe, various temporal scales fall into two broad categories of fast and slow limits on visual perception. The first group consists of fast peripheral early processing, whereas the second group comprises slower, later central processing that involves attentional resources and higher-level cognition.

Is such variability adaptive, or rather a by-product of other adaptive mechanisms? It might be the case that in general, the speed of motor responses might put a limit on how fast humans can act in the world and, therefore, a very high temporal resolution is not necessary in natural settings after all (for a similar view concerning selection-for-action mechanisms, see Allport, 1987 or the premotor theory of attention by Rizzolatti, Riggio, & Sheliga, 1994). However, since the human brain exhibits plasticity and flexibility to a large extent, in situations in which higher temporal resolution plays a crucial role—such as in the case of the fine discrimination of rhythm and timing necessary for good musical performance or the extremely precise estimate of movement trajectory in, for example, a tennis competition—temporal resolution might be enhanced. Therefore, as with many other mechanisms of the human brain, temporal resolution also might be adjusted to particular task requirements and limits. As such, the variability in temporal resolution might prove to be a highly adaptive strategy of the brain.

A different case might hold for attentional influences on processing of temporal characteristics. Attention plays the role of an adaptive mechanism that allows for fast and selective interaction with relevant (or potentially relevant) events of the world. Therefore, what might actually happen is that while attention accelerates processing of relevant information (provided that the prior-entry hypothesis holds) for the sake of more efficient interaction with the world, as a consequence, performance in some tasks involving processing of temporal characteristics might be impaired.

It is also important to note that the window of simultaneity has been so far described as a measure of temporal resolution, which tacitly implies that "the narrower, the better." However, it might be that a relatively broad window of simultaneity is actually beneficial. The human brain needs to exhibit some degree of tolerance to asynchronous stimuli in order to be able to bind different sensory inputs into one event. The window of simultaneity can be seen as an *integration window* for stimuli and, as such, is a necessary mechanism for binding signals from different pathways into one single object or event. Various sensory systems have a different transduction speed (i.e., speed of data transmission). For example, the auditory system transforms acoustic input to neural activity faster than the visual system transforms visual stimulation (e.g., Hirsh & Sherrick, 1961; Pöppel, 1988; Pöppel, Schill & Steinbüchel, 1990). Hence, information might arrive to various sensory areas of the brain with different sorts of delays. As Ernst Pöppel put it in his book *Mindworks. Time and Conscious Experience* (1988, 29): "Our visual interpretation of the world around us lags always a split second behind our auditory interpretation." On the other hand, physical properties also have different temporal characteristics (light travels roughly a million times faster than sound). The brain must have developed means to tolerate those different rates at which signals from the same event but different senses arrive. The “window of tolerance” is how the brain might be able to code, say, the auditory and visual characteristics of events as belonging to same event. Therefore, the window of simultaneity that somewhat imprecisely corresponds to the timing of events in the physical world is, most probably, a beneficial and adaptive outcome of evolutionary mechanisms and not a deficit of humans’ processing system. That is, given variable transduction times for different modalities, if the brain represented information in a manner that describes the time when the neural signals arrive to the cortex, events would often be falsely temporally integrated (and often not integrated).

Finally, the studies reviewed above cast light on inter- and intraindividual differences in temporal resolution. If temporal resolution depends on attentional focus or expertise, then the way we perceive the world in time is not constant and depends on particular circumstances. Moreover, individuals do differ in their sensitivity to time perception (e.g., Petrini et al., 2009). Hence, in situations where human-world interaction requires high temporal resolution—such as, for example, tennis playing or social interaction—humans might need to “learn to adjust” to other people’s level of temporal sensitivity for the interaction to be successful. Thus, if one takes into account such variability in the window of simultaneity, it is almost miraculous that we do find common “temporal worlds” with other people. How that is achieved remains to be answered.

21.7 Conclusion

Imagine an expert in robotics planning to design an artificial system that will perceive the temporal characteristics of the world analogously to humans. Being able to equip an artificial system with human temporal resolution would be very convenient—it would mean that such a system could bind stimuli to events in the same way humans do. It would be able to follow social cues such as gaze direction or emotional interaction in facial expressions with appropriate temporal precision, it could precisely comprehend speech, it would be able to train musicians and sportsmen, and its *now* would be the same as humans’ *now*, or—to put it in simple words—it would perceive the world’s temporal dimension the way humans do.

What is the temporal resolution of humans? So the expert in robotics might ask a cognitive psychologist.

It depends … the psychologist must reply.

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Notes

1. Note that "external" factors or physical properties such as stimulus intensity (Boenke, Deliano, and Ohl, 2009; Jaśkowski, 1996; Neumann & Niepel, 2004; Smith, 1933), stimulus duration (Boenke et al., 2009), or spatial arrangement (Zampini et al., 2003) can also have an impact on temporal processing. The "external" factors, however, will not fall within the scope of this chapter.

2. The facilitative effect of cueing depends at large on the time between the cue and the subsequent stimulus and on the validity of cue. If the cue is invalid and exogenous, and the time is relatively long, a phenomenon called inhibition of return might occur—performance related to stimuli at cued locations might be deteriorated as compared to the uncued locations. This phenomenon is interpreted as a means to prevent revisiting locations that are task-irrelevant (as in the case of invalid cues).

3. PSS is the amount of time with which one stimulus needs to precede another in order for participants to respond to the temporal-order judgment with 50 percent accuracy (such an error rate indicates that participants were equally likely to indicate either of the stimuli as occurring earlier). When an SJ task is used, PSS is the SOA that produces the most simultaneity responses, i.e., usually close to 0 ms when unimodal stimuli are used (Efron, 1963), whereas it varies considerably when crossmodal stimuli are used (Stone et al., 2001).

4. ERPs are waveforms extracted from continuous EEG signals that are related to a particular event, i.e., stimulus presentation or response execution. ERPs are calculated by averaging EEG activity across many trials of a particular condition. This allows for extracting EEG activity related to a particular type of event.

5. That is, even when first-order response bias can be circumvented by designing a task in which response dimension is orthogonal to the cueing dimension, second-order response bias might still take place in temporal-order judgment tasks (see, e.g., Schneider & Bavelier, 2003).

6. For example, in McDonald et al. (2005), the likelihood that a stimulus was reported as occurring first rose from 50 percent (chance level) to 79 percent when it was cued in simultaneously presented trials.

7. The authors assumed that participants set their attention for a particular feature. Therefore, attention was not "captured" to a salient location in a bottom-up manner, but rather, guided to a target location with the influence of a top-down "attentional set" component (Folk, Remington, & Johnston, 1992).

8. It should be further noticed that Yeshurun and Levy's (2003) study was rather concerned with temporal characteristics of a particular perceptual mechanism (gap detection) and, as such, does not target temporal characteristics of stimulus itself, unlike in the case of simultaneity and temporal-order judgments, as well as duration judgments discussed in other chapters. Therefore, the results of Yeshurun and Levy as well as Rolke et al. (2008) do not necessarily imply that mechanisms of *temporal* perception in general deteriorate at the locus of focal attention.

9. Let us assume, for example, that the foreperiod can be 500 ms, 750 ms, or 1000 ms, and that the target appears equally likely in each of these time windows. Hence the probability for it to appear 500 ms after the signal is 33.3 percent. If it does not appear at that time, however, the probability of it

appearing 750 ms or 1000 ms after the signal has increased to 50 percent, and after 750 ms it is already 100 percent for the 1000 ms target. Hence, the probability for the target to occur increases as time passes. Thus, if the reaction time is inversely correlated with the probability of occurrence, then it should be shorter for a target presented at 1000 ms than it is for a target presented at 750 ms, which in turn is shorter than for a target presented at 500 ms. indeed, this is what the results show. This explanation is also in accordance with the results showing that if in some trial no targets are presented, so that the probability of a target to occur in each SOA remains the same, the foreperiod effect disappears (Näätänen, 1970).

10. Two other forms of temporal expectations are rhythmic expectations (temporal regularity) and sequential effects. In the first case, the temporal pattern generates temporal expectancies, which has been shown to improve the performance when the task to be conducted coincides with the temporal pattern. In the second case, reaction times are faster in a trial for a short foreperiod if this trial has been preceded by a trial with short foreperiod. Because both of these involve implicit cues to direct attention, as does the foreperiod as well, only the foreperiod effect is discussed here.

11. It is worth noting that the temporal orienting effects are not restricted solely to visual perceptual processing. On the contrary, similar enhancements have been demonstrated in early perceptual stages of auditory and tactile processing (e.g., Lange & Röder, 2006; Lange, Rösler & Röder, 2003).

12. The temporal integration window is understood as the time range within which two asynchronously presented complex stimuli are still fused into one event. This concept is used to denote the brain's tolerance to delays between multimodal complex information without a detrimental effect on quality of multimodal experience.

13. For similar effects of adaptation on temporal judgments, see Takahashi, Saiki, and Watanabe (2008); Vroomen et al. (2004); Vatakis et al. (2007).

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IX Action and Passion

"Here" and "now" are fantastically elastic concepts. Here I am, in our local arm of the Milky Way. But I'm just as much here in front of the computer. My Now can be broadly construed as the current geological epoch (as opposed to Then, the Age of Dinosaurs), or zoomed to the instantaneous Now of approximately 10:13:24 a.m. "I" sit comfortably in heres of all sizes, from the cosmic to the intimate, and the zoom from the cosmic here to the local is a smooth one. Except at close quarters, where we might ask, Where, exactly, is my personal "here"? Is it a mathematical point, perhaps my center of gravity, or the midpoint of eyes and ears, or the fovea of a dominant eye? Or is it a region of points in different places, from head to toe and in between? These questions don't need precise answers, because it is clear where the issue arises: namely, at the edge of my body. My body, the "material me" (as Marc Wittmann puts it), defines an event horizon within which I partake in a different world of relations and concerns. I can move my hand by a simple act of will, while moving my chair this way would be magic. I can know there's a tingling in my foot without doing any research. I care about what happens to my body with special intensity.

These observations are obvious, but sustain a new emphasis in philosophy and psychology on embodiment. For Descartes and much of the historical tradition, the body was an accident and incidental to the rational mind in its pursuit of knowledge. The Cartesian self, a bare "thinking thing," was bodiless, without extension or location. That has changed, as the body takes its place (here) as a particular constraint and constituent of everything that can be known, or done.

The boundaries of the body create a special region in space. Is there a similar special horizon for time? The papers in this section collectively imply that just as the body creates a unique and fluid spatial field, a personal here and a material me, so also the body innervates a temporal window. When the self is in play, "now" is not merely an abstract point on a constructed timeline. Rather, the embodied Now is a personal temporal window in which subjective time warps in response to the urgent priorities of the material, biological self.

Under this theme, however, the three chapters ahead develop different dimensions of the interaction of bodies and time. Kielan Yarrow and Sukhvinder Obhi (chapter 22) consider the time of action. A moment ago, you turned the page of this book. If you had been watching a clock as you moved, you could determine when you acted to within a fraction of a second. But strung within this subsecond window are the sequential components of the action: you form the intention to act, you initiate the action, your arm moves, and the act achieves its intended consequences. Determining when each of these events occurs is a subtle and controversial matter. Moreover, the same event will shift its apparent timing in different circumstances, which can be manipulated experimentally.

Subjective time also alters in the presence of strong emotion, as reviewed by Sylvie Droit-Volet (chapter 23). Fear and anger speed up the (virtual) clock, so one second in the presence of a live spider will seem longer (if you happen to fear such things). But not every emotion has this effect. Disgust, for example, leaves the clock rate untouched. Why? Droit-Volet conjectures that fear and anger are both linked to the need for immediate defensive action. Thus, these emotions are “grounded” (to use her term) in a fast fight or flight system; emotion joins action as an embodied field of distortion for the perception of time.

Action, emotion, and time all meet in the body, leading to the conjecture by Marc Wittmann (chapter 24) that the awareness of the body just is the awareness of passing time. Moreover, the center of that dual awareness might be the insula, where metabolic activity ramps up as time passes during a duration-estimation task. It looks like an accumulator, but, likewise, it’s the region where overall bodily homeostasis is registered.

As Wittmann points out, these experimental effects occur within the 2–3 second window of the immediate present, which likewise frames the emotional effects and action-based distortions of the other chapters of this section. This window has made repeated appearances in this volume, most prominently in part V. Empirically, it does seem that temporal processing at intervals shorter than 100 milliseconds and longer than 3 seconds follow different rules. We might expect that the mechanisms of subjective time at these short, medium, and longer intervals are different.

The chapters both before and after this point underscore one general observation: although humans and other animals make poor stopwatches, they are not simply randomly inaccurate. We can offer a few conjectures about the constraints on timing in the natural world. To begin, we note that exact or accurate timing is essential in some situations, but not in all. In many cases, something other than timing may be more important. For example, often speed matters more than anything else. The speeding virtual clock may be a side effect of heightened arousal that has its primary purpose in launching urgent and immediate action. When rapid response is needed, a distortion in time estimation may be incidental. The time warp may even alter the perception of the time at which the consequences of action occur (as Yarrow and Obhi describe), but this may not matter if the point is just to ascertain that an action did (or did not) have the intended effects. Similarly, chronostasis may be the price of a smoothly experienced visual world. By the clock, these are chronic failures. In their biologically embodied contexts, however, successful behavior may outweigh distortions of subjective time.

22 Temporal Perception in the Context of Action

Kielan Yarrow and Sukhvinder S. Obhi

We do not usually experience the world as passive recipients of sensory information. Instead, we explore our environment through action. For senses like sight and touch, a framework exists to explain how we can interpret and predict the consequences of our own actions. In order to accurately distinguish sensory events arising in the environment from the sensations we ourselves generate, we make use of an efferent copy of our motor command(s) to generate predictions (Sperry, 1950; von Holst & Mittelstaedt, 1950). In this chapter, we will offer a selective review of studies investigating how our sense of *time* is affected by our own actions. These studies address how we determine the time of an action (section 22.1), and also how both the sensory consequences of action (section 22.2) and externally generated stimuli occurring around the time of actions (section 22.3) are processed by the brain in order to determine a subjective temporal narrative of events.

22.1 The Perceived Moment of an Action

22.1.1 Actions as Complexes of Events

Actions unfold over time. For brief motor acts, the physical movement of the body is just the tip of the iceberg. Whereas *movements* can be reflexive, such as the extension of a knee in response to a physician's tap, *actions* comprise both an observable movement component and a series of hidden, mental components. Thus, in action, overt movement is preceded by a sequence of preparatory internal events. These have been inferred from the behavioral assays of cognitive psychologists (e.g., Rosenbaum, 1980; Sternberg et al., 1978) and also observed directly in neural measurements (e.g., for the development of readiness potentials in EEGs, see Kornhuber & Deecke, 1965; for changes in premovement motor cortical excitability indexed by motor-evoked potentials elicited with transcranial magnetic stimulation, see Chen et al., 1998).

Indeed, every action generates a *complex* of internal events, reflecting for example the decision to move; the creation of a motor plan; the transmission of that plan to the muscles of the body; the re-afferent feedback that results from the body's movement; and the (iterative) use of this re-afference in correcting the movement. This simple fact implies that any experimental attempt to retrieve a subjective report about the time of an action should be scrutinized very carefully. For one thing, the extent to which a subjective report can accurately separate the internal events that collectively define an action is a matter of debate (although this has certainly not prevented researchers from asking questions of this kind). In the rest of section 22.1, we describe some attempts to grapple with these kinds of issues and thus determine the subjective time of actions.

22.1.2 Watching the Clock

Although by no means the first attempt to investigate the perceived time of action, a good (and oft-cited) starting point can be found in the classic study of Libet et al. (1983). These authors made use of the "complication" experiment (Dunlap 1910a) in which a visual clock (in Libet et al.'s case, a spot of light rotating around a clock face with a period of 2560 ms) is used to estimate the time of an event. The relevant events that Libet et al. (1983) investigated were the moment at which an action was 1) intended, and 2) physically initiated (as well as the time of an auditory tone, used as a control). The most famous result from this study relates to the time at which participants reported they first *intended* to act. Naturally enough, this time preceded the moment of action initiation. However, it was itself preceded by the onset of the readiness potential, an event-related potential (ERP) that can be recorded in the EEG in the lead-up to an action. This result led the authors to conclude that the conscious decision to move does not in fact initiate action, but rather follows on from unconscious mental activity that is itself causal in nature.

This interpretation has given rise to considerable controversy. We might, for example, question whether the first-deflection method used to estimate the onset of an ERP, which will reflect the left-tail of the distribution of activity across trials, provides a fair comparison with the mean average of clock estimates (Trevena & Miller, 2002). Commentators have also questioned whether equating the readiness potential with the intention to move is reasonable in the first place (with the lateralized readiness potential offered as one preferable alternative; e.g., Haggard & Eimer, 1999). Given the issues outlined above in section 22.1.1, we should also wonder whether it is even possible to accurately estimate the moment of intention without considering other components of the motor complex. Indeed, recent data suggest that delays applied to the sensory consequences of action generate almost equivalent delays in estimates of the time of intention, suggesting that time of intention is in part estimated based upon the events that are observed subsequently (Banks & Isham, 2009; see also Lau et al., 2007; Strother & Obhi, 2009).

Leaving aside vexing questions about the nature of free will, a second result from the Libet et al. (1983) study was that the time at which the physical action was judged to occur also preceded the moment of action initiation by around 80 ms (as measured by onset of electromyographic [EMG] activity in the muscles of the wrist). This anticipatory awareness of action suggests that efferent activity relating to the planning or execution of action influences the perceived time of action. This interpretation is bolstered by an interesting follow-up study described by Haggard, Newman, and Magno (1999), who reported an anticipatory awareness of movement initiation that scaled with the complexity of the movement pattern. They used the Libet clock paradigm, but also made use of a classic result from experimental psychology: the time to initiate a fully prepared movement sequence increases with the number of submovements in that sequence (Henry & Rogers, 1960; Sternberg et al., 1978). This result, which is typically interpreted as evidence that the whole sequence is planned in advance, also suggests that motor planning may begin earlier for longer sequences. The perceptual reports about action onset mirrored this interpretation: actions were judged to have begun earlier when movement sequences were more complex, as though efferent (or at least "pre-movement") processing components were influencing the percept.

One recent study has extended this approach further by requiring clock judgments about both active and passive movements made with either the hand or the foot (Obhi, Planetta, & Scantlebury, 2009; see also Obhi, 2007). There was a greater anticipatory awareness of active movements, which provide both efferent and re-afferent cues to timing, compared to passive movements, which provided only re-afferent cues. This again implies a role for efferent cues in judgments about the time of an action. However, anticipatory awareness was less pronounced for foot movements, where the motor command would be expected to come *earlier* relative to the time of physical movement (due to the longer neural pathway to the foot) than for hand movements (see figure 22.1). This finding suggests that re-afferent cues (which would be expected to reach the brain *later* for foot movements) also influence the perceived time of action. Hence, awareness of action appears to be based on a combination of predictive and re-afferent cues.

Results emphasizing the role of re-afference in action awareness also bring up other interesting issues. For example, if judgments of action really are anticipatory, and don't just appear anticipatory due to problems with the measurement of subjective time (see below), then how does sensory re-afference, which arises after movement onset, inform the judgment? The mechanism by which "after the fact" information is used to construct a "before the fact" judgment remains to be elucidated (although see Libet, 2004 for discussion of a backward referral mechanism that might have some explanatory power).

22.1.3 The Order of Events

The clock method brings with it a range of problems. Firstly, interpreting clock estimates in any absolute sense is complicated by the unknown time taken to register clock position by the visual system. Relative differences in clock estimates between conditions are therefore preferable, and have generally been employed. Secondly, the requirement to monitor the clock alongside an action is problematic, because the degree to which an event is being attended influences judgments about its time of occurrence ("prior entry"; e.g., Spence et al., 2001). There are no easy fixes for these kinds of problems.

Temporal-order judgments (TOJs) provide one alternative means of estimating the time of an action. Here, the clock is replaced by a brief sensory event such as a tap or a beep,

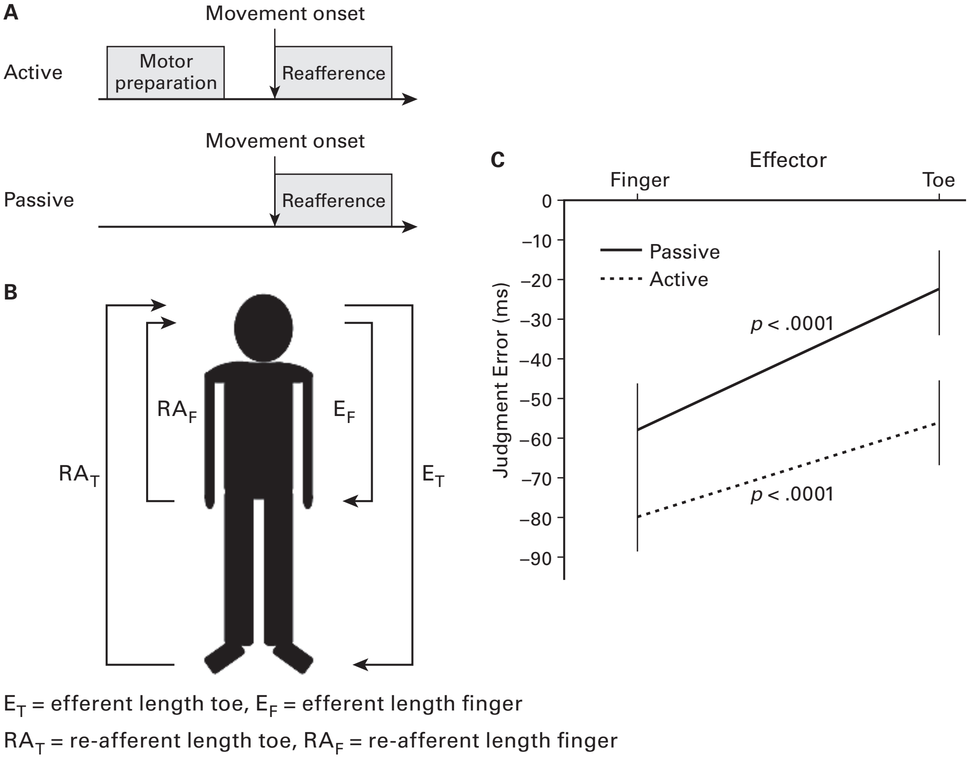

Figure 22.1

(A) Signals available in active and passive movements, respectively. The perceived time of action could be based on efferent information, re-afferent information, or both for active movements, but only on re-afferent information for passive movements. (B) If awareness of action is based on efferent information, this predicts that toe movements should be judged as occurring earlier than finger movements, because $E_T > E_F$. If awareness of action is instead based on re-afferent information, the prediction is that toe movements will be judged to occur later than finger movements, because $RA_T > RA_F$. (C) Judgment errors (difference between actual action onset and judged onset). Active movements produce earlier judgments than passive movements, which supports a role for efferent information. However, toe movements are judged later than finger movements, which supports a role for re-afferent information. Hence, both efferent and re-afferent signals contribute to judgments of action onset.

and observers judge whether this event preceded or followed the movement. Plotting a psychometric function reveals the point of subjective simultaneity (PSS), where "before" and "after" judgments are equally likely. Of course, these judgments too suffer from problems akin to the clock method. One could argue, though, that the motion of the clock exacerbates the problems of interpreting instantaneous time from a perceptual judgment (cf. Nijhawan, 1994) and that a tactile event *may* be less problematic when divisions of attention are considered.

One example of the TOJ approach, which parallels the work of Libet et al. (1983), comes from McCloskey et al. (1983). They used brief tactile electrical stimulation to the ankle presented around the time subjects made a voluntary movement. Individual participants made contractions primarily involving a single muscle, but a range of movements were studied across subjects, including those of the foot and jaw. Participants judged the onset of a movement to be synchronous with the shock when EMG activity actually preceded the shock by 40–320 ms. They were, however, capable of differentially judging the moment of their internal instruction to begin movement (their conscious intention). This was judged to precede the onset of EMG by up to 100 ms. While the finding that a conscious decision to move is judged to have arisen before actual movement concurs approximately with studies using the clock method (e.g., Haggard & Eimer, 1999), the movement onset result is essentially opposite.

Another example, this time using a ternary ("before," "during," "after") TOJ approach, is provided by Dassonville (1995) who required subjects to judge when a tactile stimulus delivered to the index finger occurred relative to a horizontal (left to right) arm movement. Here, anticipatory awareness was reported, at least for the time of movement onset. Hence there is no simple division between the TOJ and clock approaches in terms of whether an anticipatory or delayed awareness of action results.

Aside from discrete and continuous movements of the limbs, a number of early studies also investigated observers' temporal perception of visual stimuli around the time of saccades. For example, when subjects were asked to judge whether a test grating was presented before, during, or after an eye movement, a complex pattern of results emerged (Volkmann & Moore, 1978). For stimuli presented after the onset of the saccade, observers showed a strong bias toward judging the stimulus to have arrived during the saccade (i.e., delayed awareness of action; see also Dassonville, 1995). For the single observer tested with stimuli also occurring prior to the saccade (and additionally given the "before" response option), these stimuli were also judged to have occurred during the saccade more often than would be expected (i.e., anticipatory awareness of action). Stimuli that arrived during the saccade were typically judged to have arrived before it, so times of occurrence for all stimuli were not simply drawn inwards toward the saccadic event.

However, more recent work has demonstrated that brief visual events undergo temporal distortions in the peri-saccadic interval even when judged without reference to the saccade itself (Morrone, Ross & Burr, 2005, reviewed below in section 22.3). This may help to explain the inconsistencies in Volkmann and Moore's (1978) results, because their visual reference was itself subject to distortion. When an auditory marker was used instead, and observers reported whether the tone came before or after the *end* of a saccade, a bias consistent with anticipatory awareness was obtained (Yarrow et al., 2006a). Of course, it seems likely that estimating the beginning or end of a saccadic eye movement will spontaneously evoke strategies that make use of correlated visual information (i.e., the offset and onset of fixations). These sensory cues are subject to their own substantial biases, discussed in section 22.2.2 below.

22.1.4 Tapping to the Beat

Another approach to determining the perceived time of a sensory event is to use synchronization tapping tasks (e.g., Dunlap, 1910b). Participants listen to a sequence of regular beats (like a metronome) and tap along. The time of their button presses relative to the time of each stimulus provides a measure of the perceived time of action, because participants are presumably trying to align their actions with the stimuli.

In fact, it seems that participants behave as though they were aligning the sensory consequences of their actions with the external beat, in a delayed awareness of action (if considered relative to the onset of EMG). For example, taps consistently precede an auditory beat (at least when the taps do not make a distinct noise at contact), which is consistent with a shorter sensory latency for auditory compared to somatosensory events. Furthermore, this anticipatory tendency grows larger when tapping with the foot compared to tapping with the hand, in line with a longer neural pathway (Fraisse, 1980; Paillard, 1949). Hence in this task, re-afferent feedback appears to be the dominant cue used to determine the time of action, with little heed paid to efferent internal events. Of course, synchronization tapping brings its own interpretational difficulties, but it is a valuable complement to purely sensory judgments. For a more nuanced and complete review of work using this task, see Aschersleben (2002).

22.1.5 Adapting to Delays

One of the most intriguing results in recent years regarding the perceived time of action comes from Stetson et al. (2006). These experiments build upon earlier work suggesting that participants can adapt to the timing relations experienced during repetitive sequences of paired visual and auditory stimuli. If visual stimuli are consistently presented after auditory stimuli, or vice versa, small audiovisual asynchronies in the same direction (which were previously judged asynchronous) now begin to seem synchronous (Fujisaki et al., 2004; Vroomen et al., 2004). Stetson et al. (2006) applied this notion to actions by varying the interval between a key press and the flash of light that the key press evoked (i.e., a source of artificial sensory feedback; see also Cunningham, Billock & Tsou, 2001; Pesavento & Schlag, 2006). In their first experiment, delays were fixed on 60 percent of trials and varied randomly on the remaining 40 percent. Participants judged whether the flash came before or after their key press on every trial (a TOJ). Comparing two different contexts where the typical delay was either small (35 ms) or large (135 ms), the point of subject equality between action and flash shifted forward by around 40 ms, such that large delays seemed more synchronous in the context of other regular large delays.

This result has now been replicated and extended in other labs. Both Heron, Hanson, and Whitaker (2009) and Sugano, Keetels, and Vroomen (2010) have demonstrated shifts in the PSS following delayed sensory feedback (but see Winter et al., 2008 for an exception). Both groups also extended another finding from Stetson et al.'s (2006) experiments. Stetson et al. had found that adapting to LED flashes of three different colors generalized to cause PSS shifts in test trials using a fourth LED color. Heron et al. (2009) and Sugano et al. (2010) showed that generalization also occurred when test TOJs were made in a different sensory modality (e.g., adapt to delayed flashes, test with beeps). Although it is possible that delayed feedback in one modality brings about a realignment of event time across all sensory modalities, the most straightforward interpretation of this result would be that the perceived time of the action is shifting forward toward its delayed sensory consequence. This would explain why testing with any sensory event yields an equivalent shift.

Considering sections 22.1.1 through 22.1.5 together, what can we conclude from this brief overview relating to the perceived time of action? Different experimenters have come to quite different conclusions regarding anticipatory versus delayed awareness of action. Undoubtedly, the following factors are important in contributing to these differences: the various kinds of questions that have been asked; the uneven (and generally unknown) allocation of attention to different streams of events; the definition of action onset (e.g., key depression versus EMG); the history of recent action-dependent feedback; and the sensory delays inherent in the clocks and markers used for comparison with motor acts. However, it seems most reasonable to conclude that all of the internal events that constitute the "movement complex" can probably influence judgments about the time of an action, and that the particular blend of cues taking precedence varies in a context-dependent manner. Such an account might suggest that the recalibration found by Stetson et al. (2006) represents a shift from early toward late cues brought about by motor-sensory delays, but this hypothesis is currently untested.

22.2 Timing Actions and their Sensory Consequences

22.2.1 Intentional Binding

Actions yield results: that is generally why we act in the first place. Are the consequences of action perceived as temporally veridical, and does the outcome of an action affect when the action is perceived to occur? In a series of experiments only one step removed from the complication experiment described in section 22.1.2, Haggard, Clark, and Kalogeras (2002) asked participants to judge a clock's position at the moment when they made an action (either voluntary or involuntary) or heard a brief tone. The innovation in these experiments was that the authors varied systematically the context in which the events occurred. The actions were a voluntary key press, or an involuntary muscular contraction of the hand (evoked by applying a transcranial magnetic pulse to the primary motor cortex). In baseline blocks, either one of the actions or the brief tone were presented in isolation. In operant blocks, an action (be it voluntary or involuntary) was followed consistently after 250 ms by the tone, and participants judged when one or the other of these events had occurred (in separate blocks).

The main finding, termed "intentional binding," was that when an intended action caused the tone, the action was perceived to occur later, and the tone was perceived to occur earlier, than when these events were presented in isolation. What's more, when an involuntary action caused the tone, the reverse pattern emerged, with the action seeming earlier compared to baseline and the tone appearing to come later. It seems as though actions cause their delayed sensory consequences to appear earlier in time, while the perceived time of the action is also drawn toward the contingent sensory event. This result may suggest a binding process that can help support conscious inferences of causality (although such an account seems a little tautological, given that the brain must register causality to implement binding in the first place). Many have begun to think of intentional binding as an implicit measure of agency for self-produced action (but see below).

Taken alone, the experimental findings presented so far might suggest partial explanations in terms of other mechanisms. For example, the apparent backward shift of the tone toward its generative action might represent a case of attentional prior entry, given that the voluntary-causal condition permitted better temporal prediction about the time of the tone compared to the tone-alone baseline condition. A quite comparable situation arises in recent demonstrations of the flash-lag illusion (the tendency of a moving object to appear ahead of a coincident flashed object; Nijhawan 1994): the perception of the forward shift for the moving object (cf. Haggard et al.'s clock) is strongly modulated (reduced) when the flash is caused by an action (Lopez-Moliner & Linares, 2006). The other component of intentional binding, the forward shift in the perceived time of the action, might have resulted from the motor-sensory temporal adaptation described in section 22.1.5 (which was discovered only subsequently, and thus not discussed in Haggard et al.'s 2002 paper). This possibility might be discernable by analyzing later trials in operant conditions versus early trials. Presumably, adaptation is more likely at the later stage of blocks, compared to earlier stages. To our knowledge, such an analysis has not been carried out.

However, other details of the original result, and other experiments reported in the same and subsequent papers, support the proposed mechanism. For example, a second experiment from Haggard et al. (2002) varied the interval between the action and the tone (250, 450, or 650 ms) and found that the magnitude of the shift of the tone fell off very dramatically across this range. The precision of temporal expectation would deteriorate to some extent across this range (Weber's law for time; e.g., Wearden & Lejeune, 2008), but it is doubtful whether this could explain such a rapid decay of effect size.

Of the various papers that have followed from the original demonstration of intentional binding, we will describe only a few intriguing results. First, the effect appears to consist of two components, one predictive and one postdictive (i.e., resulting from interpretation of the episode after the event). Moore and Haggard (2008) investigated blocks of trials in which an action produced a tone with varying consistency. When actions often produced tones, the perceived time of action shifted forward, even when the tone never actually materialized. This suggests the involvement of a predictive process that operates even when the tone never arrives. The predictive effect disappeared when the contingency (and thus the prediction) weakened. However, even with a weak contingency, a forward shift occurred on trials when the tone did arrive, suggesting an additional postdictive mechanism.

To avoid conceptual confusion, it is important to separate "predictive" effects into those based on the processing of efference copy by an internal forward model (i.e., those that operate immediately before an action is produced) and those that arise out of a longer history of experienced contingencies, such as those in the experiment just described. These types of predictive effects may be more accurately described as top-down expectation effects. The key point emerging from a range of experiments, however, is that both types of predictive signal seem to be important in producing our temporal perception of various events in an action-effect sequence.

A second intriguing result from recent temporal binding experiments is that the overall effect is enhanced in schizophrenic patients (Haggard et al., 2003), consistent with their abnormalities in assigning causal relationships between agents and actions (i.e., delusions of control). Moreover, referring back to the study by Moore and Haggard (2008), the predictive component of the binding effect is actually reduced in schizophrenia, while the postdictive component is exaggerated (Voss et al., 2010). Some authors have argued that intentional binding may arise for causal relationships in general, rather than depending specifically on intentional action and thus relating mostly to the sense of agency (Buehner & Humphreys, 2009). It is interesting to note that the effect is reduced by repetitive transcranial magnetic stimulation to the presupplementary motor area, a site known to be important in the generation of voluntary actions (Moore et al., 2010).

A very new line of work, which certainly falls into the intriguing category, considers intentional binding in scenarios where multiple individuals act together. This work also attempts to determine the relationship, if any, between intentional binding and subjective feelings of agency. Strother, House, and Obhi (2010) required participants to sit together with right index fingers on a single long button. Both were instructed to intend to press the button at a time of their own choosing, but not to press actively if the other person initiated the action. As in the original experiment, participants judged the position of a rotating clock hand at the onset of various (action and sensory) events. Participants were also required to indicate after every trial whether they felt responsible for the key press or not (subjective agency rating). When temporal compression of an interval was used as a measure of intentional binding, both participants showed significant binding, even when one of them felt *no subjective agency*. If intentional binding was defined not as an interval, but as perceived shifts of action and effect times, then neither participant showed binding, despite one person feeling subjectively responsible for the key press and resultant tone. Hence, no matter how intentional binding is calculated, it appears not to be tied to subjective feelings of agency. This however, does not preclude the possibility that it is an implicit measure of agency, as has been suggested by Moore, Wegner, and Haggard (2009).

A potentially fruitful area for future research is to add an affective component to the sensory effect produced by an action, as previous studies have included affectively neutral effects only. Most real-life actions are associated with some type of positive or negative outcome, and it is plausible that this might alter the perceived time of actions and effects. Experiments examining this issue are underway, but final data is not available at this time. The take home is that, despite the impressive results gathered thus far, the full nature of the intentional binding effect remains to be clarified, as does the full nature of the mechanisms that underlie it.

Finally, it is noteworthy that, while intentional binding has generally been demonstrated using the clock-comparison approach outlined at the beginning of this section, recent reports have changed emphasis, making use of time estimation or reproduction tasks that assess the interval between the action and the tone (e.g., Humphreys & Buehner, 2009, 2010). The duration that is perceived to accrue between the action and its delayed sensory consequence is measured directly, in this approach, and is found to be shorter than in control conditions. However, in contrast to the original finding, the effect is found to remain strong (and even grow) for sensory delays exceeding a second in duration. This leads us neatly on to what some have considered a related phenomenon: chronostasis.

22.2.2 Chronostasis

If you have ever owned a watch with a silently advancing second counter, you may have experienced chronostasis (although you probably didn't realize it had such a catchy name). Sometimes, when glancing down at your watch, you may have had the momentary impression that the watch had stopped. The watch soon ticked on, of course, and you probably forgot all about it. What is strange about this phenomenon is that it occurs exclusively when we make a saccadic eye movement toward the counter just as the counter advances (Brown & Rothwell, 1997). It is as though a little bit of time were being added on to the duration of the newly fixated image, so that a saccade right at the beginning of a new one-second interval gives the impression of an interval that exceeds one second in duration.

To test and develop this idea, we can employ the following method (first described by Yarrow et al., 2001, and developed in subsequent publications; for a more complete review, see Yarrow, Haggard & Rothwell, 2010). In saccade conditions, the participant fixates at one location, and then makes a saccade to a target at a different location. The target changes form or color during the saccade, so that it is first visible in its new state at the end of the saccade. It is presented for a short (usually variable) time, and then replaced by a sequence of one or more reference stimuli. When more than one reference is presented (a rather superfluous feature of earlier experiments), they are all identical in duration. The task is to decide whether the post-saccadic target stimulus was present for more or less time than the reference stimulus. This permits the calculation of a point of subjective equality (PSE), or the duration for which we must present the post-saccadic stimulus for it to appear equal to a given reference stimulus.

The PSE for a post-saccadic target compared to a reference of 1000 ms is in the region of 800–900 ms (Yarrow et al., 2001). However, this piece of information is not very informative, because when two intervals of time are compared it is common to have a bias which leads to a nonveridical PSE (known as the time-order error; e.g., Hellstroem, 1985). Hence it is essential to include a control condition, in which a similar judgment is made but without any saccade. The simplest control conditions match only post-saccadic stimulation precisely; better ones match pre- and post-saccadic stimulation; and the best yet employed match pre-, post- and peri-saccadic stimulation, at least for the fovea (e.g., by initially displaying a peripheral stimulus that jumps to fixation with a saccadic time course; Georg & Lappe, 2007; Yarrow, Haggard & Rothwell, 2004a; Yarrow et al., 2001). However, the fine details of the control conditions don't actually seem to matter all that much (Yarrow et al., 2004a). Nor do technical issues regarding when the post-saccadic stimulus is assumed to become objectively visible (i.e., whether it is timed from the moment it appears on screen, or, as is more typical, from the moment it is first fixated; Yarrow et al., 2006a; Yarrow, 2010). The key point is that the PSE is substantially and significantly reduced in saccade conditions *compared to control conditions*, suggesting that a newly fixated object or scene has a subjectively expanded duration.

An expanded duration might imply changes at the onset or offset of an image, or indeed an altered rate of time accrual between these events. In fact, it seems very much as if the point in time at which the newly fixated object or scene is first perceived gets moved backward, or *antedated*, to reflect the moment when the eyes first left the previous fixation point. The evidence is as follows. First, in experiments where participants make either a small or a large saccade, the size of the saccadic chronostasis effect changes: it grows larger following a large saccade, and the amount by which it grows conforms quite well to the additional time taken to complete the saccade (Yarrow et al., 2006a; Yarrow et al., 2001). This suggests that the post-saccadic image is being antedated to a moment that remains constant with respect to saccade initiation.

Second, the exact duration of the post-saccadic interval doesn't affect the magnitude of saccadic chronostasis (Yarrow et al., 2004a). This suggests that time is being distorted by a shift in an event marker, rather than a change in the rate of some putative internal clock (which might be caused by mechanisms such as arousal or attention). Rate change accounts predict that experimental effects should scale with duration (because subjective time equals objective time multiplied by clock rate), but no scaling is evident in chronostasis experiments. Indeed, saccadic chronostasis is clearly evident when the post-saccadic target is presented for only 100 ms.

The third (and most direct) line of evidence for the antedating account comes from experiments where the interval comparison task is replaced by a temporal-order judgment task (Yarrow et al., 2006a). Here, participants must compare the time of onset of the post-saccadic image with the time of a brief tone. In control conditions, the tone must be presented after the visual onset to yield perceived simultaneity, but in saccadic conditions the PSS occurs when the tone is presented much earlier, near the time of saccade onset. The difference between saccade and control conditions for this task once again grows for larger saccades, emphasizing antedating toward a pre-saccadic reference.

Taken collectively, the data from saccadic chronostasis experiments seem to provide the missing link in a broader story relating to our peri-saccadic perception. Think about a bad home video, where the camera leaps from person to person. Pretty unsettling, right? But a situation like this arises whenever we move our own personal cameras, our eyes. However, when we make a saccade, vision, specifically magnocellular vision, is actively suppressed (and masked), presumably in order to prevent activation of low-level motion sensors that would otherwise signal movement of the entire visual scene (Burr & Morrone, 1996; Ross et al., 2001; Campbell & Wurtz, 1978). This process operates alongside other mechanisms designed to maintain the perceived stability of the visual world (Bridgeman, Van der Hejiden & Velichkovsky, 1994). Why, then, is our vision not interrupted with a brief period of nothingness every time we move our eyes, rather like someone flicking the lights off and on around three times every second? Saccadic chronostasis may reflect the process that stitches individual fixations together in order to generate the illusion of continuous vision (Yarrow et al., 2001).

This story is supplemented by the existence of a plausible physiological mechanism to support saccadic chronostasis. As traditionally defined, the receptive field of neurones in the visual system reflects the position at which a stimulus will modulate the cell's response, measured with respect to fixation (i.e., in a retinotopic frame of reference). However, it is now clear that many cells in the brain have receptive fields that are best defined with respect to the position of the head or body, regardless of eye position. Most critically, some cells (originally described in the lateral intraparietal area, but now found quite widely) have receptive fields that shift suddenly before an eye movement, so that they will respond predictively to stimuli presented at a location their retinotopic receptive fields would usually incorporate only after the saccade (Duhamel, Colby & Goldberg, 1992; Umeno & Goldberg, 1997; Walker, Fitzgibbon & Goldberg, 1995). This predictive response, occurring around the time of saccade onset, might be the signal that is used to begin timing of the post-saccadic scene.

A few other interesting results from saccadic chronostasis experiments are outlined in figure 22.2. They are generally in accordance with the antedating account outlined above.

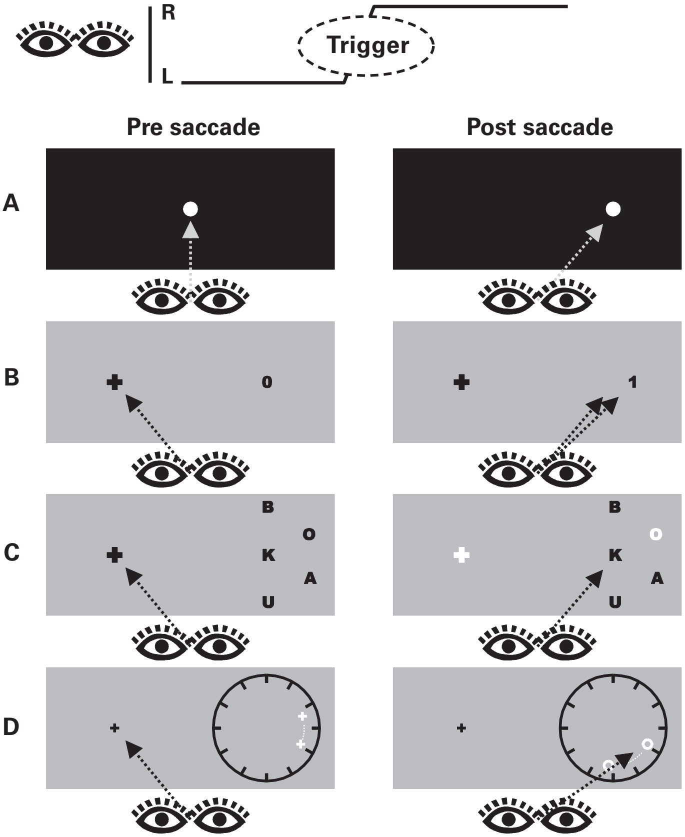

Figure 22.2
Some additional saccadic chronostasis results not described in the main text. (A) Saccadic chronostasis is found for extremely rapid and highly automatic classes of saccade, such as express saccades elicited in complete darkness (Yarrow et al., 2004b). This suggests that a subcortical efferent trigger may be important. (B) Saccadic chronostasis is reduced when the saccade target shifts suddenly but imperceptibly during the saccade, and eliminated when this shift is actually perceived (Yarrow et al., 2001). This suggests that expectations about cross-saccadic continuity must be fulfilled before the illusion is implemented. (C) When objects other than the saccade target are judged, the chronostasis effect is still found (Yarrow, 2010), suggesting that the illusion extends to large parts of the visual scene (but see Georg & Lappe, 2007, for an opposite result). (D) Saccades made towards a moving object give rise to chronostasis, and also to spatial misperceptions that suggest spatiotemporal coherence is maintained in the brain, but in a highly postdictive manner (Yarrow et al., 2006b; see also Hunt & Cavanagh, 2009).

As noted above, one of the reasons that the antedating account is tempting is that it fits elegantly into the broader story of peri-saccadic vision. Unfortunately, this neat and tidy picture is undermined somewhat by the existence of potentially analogous effects for movements of other parts of the body.

The most directly analogous experiments have been described by Yarrow and Rothwell (2003) and Jackson et al. (2005). When observers reach to touch a vibrating tactile target, that target undergoes subjective temporal dilation, just as in the saccadic case. This effect does not scale with reach extent, which implies some differences from the saccadic situation (Yarrow & Rothwell, 2003). The observation does, however, suggest that a more general account than the one outlined above (involving receptive field shifts in visual neurones) should be considered. A slightly different situation was explored by Jackson et al. (2005), who failed to detect a significant chronostasis effect in a patient who makes saccadic head movements in place of saccadic eye movements. In this case, an explanation of saccadic chronostasis in terms of saccade-specific mechanisms garners some support.

These experiments are directly analogous to the saccadic situations described above because the judged stimulus is the natural sensory consequence of the action, and its state is unclear until the action has been completed. These features differentiate the chronostasis situation from typical intentional binding experiments, which ask a question about an artificial and delayed sensory re-afferent. Other experiments have blurred this distinction, with mixed results.

Yarrow and Rothwell (2003) describe two experiments in which participants pressed a button to initiate a visually defined interval. No temporal dilation was detected, despite good experimental power. However, Park, Schlag-Rey, and Schlag (2003) have reported experiments in which temporal dilation of a visually defined interval *was* observed, following either a button press or a verbal utterance. Some time later, Hunt, Chapman, and Kingstone (2008) presented a series of experiments using button presses and judgments about visual intervals and obtained temporal dilation in some, but not all, cases. Meanwhile, Verstynen, Oliver, and Ivry (2010) describe a study in which a right-hand button press initiated a vibrotactile interval applied to the left hand. They found a small but reliable temporal expansion. Interestingly, the size of their effect grew when the onset of the vibrotactile interval was delayed slightly (by 50 ms), consistent with antedating toward an efferent signal. Finally, the observant reader will note that we segued to this section with a discussion of some intentional binding experiments that used an interval duration estimate about the time between a button press and a subsequent beep. In these experiments, the significant effects were actually in the opposite direction to the scenarios described above; that is, the interval was perceived as shorter in action-initiated conditions. Of course, there are some potentially important differences for this final example, since the judgment was about empty rather than filled intervals and the markers were auditory, not visual. Overall, then, it appears that more work is necessary to reconcile the confusing pattern of results regarding the perceived time of visual, tactile, and auditory intervals following a button press.

22.3 Contextual Effects of Action on Sensation

To complete our survey of experiments investigating how temporal perception changes in the context of movement, we will consider briefly the situation where ex-afferent sensory events that have no causal relationship to a movement are nonetheless presented around the time of movement, and judged without reference to the movement itself. These experiments have generally been conducted using saccades.

An experiment that falls midway between the experiments we described in section 22.1 (judging the time of an action relative to a sensory referent) and the situation we wish to focus upon in this section (judging sensory events relative to one another) was conducted by Deubel, Irwin, and Schneider (1999). Participants made saccades from a central position to a peripheral target. An open circle appeared onscreen for 20 ms, at a time ranging from 450 ms before the saccade to 250 ms after it. The circle was located at one of three locations: the initial fixation point, the saccade target point, or the opposite point (i.e., the alternative saccade target). Participants judged whether their gaze had been on the central fixation point or the saccade target point when the circle appeared. They often incorrectly felt that they were already looking at the saccade target even when the circle appeared well before their saccade. The effect was less marked when the circle appeared opposite the target, and nearly absent when it appeared at the initial fixation point. An important issue here is what exactly the subjects were attempting to do in these experiments. The question about the direction of gaze might be answered with reference to the perceived time of the movement (cf. section 22.1.3), the perceived time of onset of the post-saccadic image (cf. section 22.2.2) or the perceived time of offset of the pre-saccadic image (a judgment that has not yet been investigated in detail).

Subsequent attempts to look at the timing of visual events around the time of saccadic eye movements have used questions that are rather less ambiguous. This approach is exemplified by results from two high-profile papers from the same group (Binda et al., 2009; Morrone et al., 2005). The key findings are as follows:

1. When participants are asked to judge the duration between two peri-saccadic visual events (flashed lines), the time between them can appear compressed. This effect is strongest when the two lines are flashed around 75 ms before and 25 ms after saccade onset.
2. When time is compressed in this manner, the precision of time perception actually improves, in line with Weber's law.
3. Compression does not occur between two auditory events presented with a similar time course, suggesting that auditory time remains veridical.

4. Judging two visual events can also result in an apparent reversal of order. When the lines are flashed specifically so that the later one arrives around 50 ms before the saccade onset, they are perceived in the wrong order.
5. Finally, when a single visual event is presented for peri-saccadic temporal comparison with an auditory event (TOJ) or two successive auditory events (bisection), the relative time to perception for the visual event changes depending on when exactly it flashed. Flashed lines are perceived faster if presented around 50 ms before the saccade, and slower if presented slightly later (i.e., immediately before or during the saccade). The speeding observed at around –50 ms is substantial enough to explain the order reversals described in point 4. The slowing from around the time of saccade onset may explain the compression noted in point 1.

These data provide a reasonably consistent story about the timing of transient visual events around the time of a saccade, one that like the account of saccadic chronostasis outlined in section 22.2.2 appeals to the receptive field shifts described in neurophysiological experiments (e.g., Duhamel et al., 1992). However, some puzzles and outstanding issues remain. For example, if the changes observed in the timing of brief intervals are driven by changes in event times, why is only compression found? Expansions should also be evident, for example when the first stimulus is presented 50 ms before the saccade and the second comes around 50 ms after saccade onset. Furthermore, while neural recordings do show changes in the latency of response for a population of dorsal medial superior temporal neurones when stimuli are presented either near to the time of a saccade or during steady fixation, sensory acceleration is evident just *after* a saccade, not before it (Ibbotson et al., 2008). Terao et al. (2008) have also complicated the interpretation of the initial interval timing experiments by showing that similar effects arise when stimuli are reduced in contrast. Such contrast reductions would be expected to occur in the saccadic conditions of Morrone et al. (2005), in line with known properties of saccadic suppression, suggesting a rather simpler explanation for the observed temporal compression.

In concluding this section and the chapter as a whole, we can briefly consider the relationship between biases in the timing of peri-saccadic visual transients, and biases in the timing of the post-saccadic visual information revealed by the saccade. There is a clear overlap in the physiological mechanisms that have been used to explain both situations. Both Yarrow et al. (2001) and Morrone et al. (2005) have invoked shifting receptive fields found in the lateral intraparietal cortex and other regions known to be involved in saccadic control, and Binda et al. (2009) have presented a detailed quantitative model based on the available physiological data that explains many of their temporal distortions (and indeed some related spatial ones). However, at this point it is not quite clear whether a single mechanism can explain all the current results pertaining to the shifts in visual timing that occur for both ex-afferent stimuli presented near a saccade and the natural (post-saccadic/re-afferent) stimulus that is revealed by a saccade. What *is* clear, however, when considering this chapter as a whole, is that representing time in the context of action is an extremely complex mental activity. The oddities of temporal perception that occur before, during, and after an action will certainly need to be taken into account in order to generate a complete account of human temporal perception.

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23 What Emotions Tell Us about Time

Sylvie Droit-Volet

> What really proves that we measure time in terms of the number of our sensations ... is the way we estimate the approximate length of a dream. There we have no artificial measure of time, no tick-tack of a clock to tell us the hour ... in this estimate in which the only element is our consciousness ... which leads to the strangest mistakes. A dream may seem to have lasted several hours when in reality it lasted only a few seconds.
>
> —Jean-Marie Guyau, *La génèse de l'idée de temps*

When we compare the episodes of our everyday lives experienced in different emotional states, we have the strange impression that time is either sped up or slowed down. While time seems like an eternity when waiting for someone we love, it suddenly seems to fly when the loved one arrives. Time no longer exists! Initially, the study of our feeling of time was the preserve of writers and philosophers. Based in part on anecdotal reports, some philosophers have considered that time does not exist independently of our internal representations. Kant (1787) claimed that time is an a priori representation that we impose on our external world. For the young philosopher Guyau (1890), it is grounded in our experience. As he writes, "we evaluate durations *a posteriori* based on the number and the variety of our sensations" (53). Bergson (1968) takes up this idea by arguing that real duration is a pure and simple fact of experience.

When psychologists started to address the question of time, they were profoundly influenced by these philosophers' ideas, especially in Europe. Fraisse (1967) considered that time has no existence in itself and that its evaluation depends on the quantity and the quality of the changes that determine it. Piaget (1946), famous for his works on developmental psychology and genetic epistemology, devoted a whole book to explaining how the perception of time is derived from the perception of movements in space. However, the twentieth century produced a growing number of empirical demonstrations of the ability of animals and humans to estimate durations accurately. Several decades have therefore been spent elaborating and testing models of a putative mechanism—an internal clock—that is thought to be responsible for this accurate measurement of time. Meanwhile, the last ten years have witnessed a remarkable resurgence of interest in time distortions and the effect of emotions as a major cause of these distortions.

We are therefore witnessing an explosion in the number of new studies that are taking a fresh look at time estimation and showing how time is highly dependent on both external and internal contexts (for a recent review see Droit-Volet et al., 2013). However, one major risk lies in the temptation to rewrite the history of psychology of time, although new neuroscientific brain-imaging techniques will probably enable researchers to avoid this trap. The problem therefore lies in gaining a further understanding of how time is judged and how it is instantiated in our biology by expanding our knowledge beyond what we already know in order to challenge the dominant models of the internal clock. Within this perspective, what do the emotions tell us about time?

23.1 The Mechanisms Involved in the Perception of Time

> The start of modern science dates from the time when general questions were replaced by limited questions; when instead of asking "How was the universe created?" "What is matter made of?" … we started to ask "How does a stone fall?" "How does water flow in a pipe?" … This change had a surprising result. Whereas the general questions had only produced limited answers, the limited questions were to lead to increasingly general answers.
>
> —François Jacob, *Le jeu des possibles: Essai sur la diversité du vivant*

Psychological time is complex. Time seems to exist as a reality independent of us, as a physical feature of an objective world that we are able to measure. However, numerous studies have also shown how easily our time estimates can be distorted by our emotions. Under the influence of emotion, time seems shorter or longer than it really is. It therefore seems that time is also a pure product of our emotions and of the upheavals they produce in our bodies and minds. This is the paradox identified by Droit-Volet and Gil (2009): why are our time estimates so variable if we possess a sophisticated mechanism for measuring time? What clockmaker would keep such a clock? Do the time distortions observed in humans cast doubt on the existence in our brains of a dedicated mechanism for the measurement of time?

Many of the theoretical conceptions concerning time perception are based on empirical demonstrations of the ability of animals (rats, pigeons) to estimate time accurately. When animals are presented with a series of stimuli of a given duration, their average temporal estimates are equal to this duration. The variability (standard deviation) of their estimates also increases linearly with duration in conformity with Weber's law. Based on these two fundamental properties of time perception, which are referred to as the scalar properties of time, the idea has emerged that animals possess, in their brains, a specialized physiological mechanism for the measurement of external time. A number of scientists spanning a long period had already imagined that such mechanisms might exist as components in the biological functioning of neural structures (e.g., François, 1927; Hoagland, 1933). For example, Hoagland (1933) thought there might be a biological clock that affects the perception of time in response to metabolic changes. However, in the absence of sophisticated brain study techniques, this idea was rapidly abandoned in favor of simpler conceptions. Since then, Gibbon has proposed a theory (the scalar expectancy theory) derived from Treisman's (1963) internal clock model, that was to become, and still remains, the dominant theory of time perception (Gibbon, 1977; Gibbon, Church & Meck, 1984). According to this theory and the associated models, the raw material for the representation of time comes from an internal clock. This consists of a pacemaker, a switch, and an accumulator. At the onset of the stimulus to be timed, the switch connecting the pacemaker to the accumulator closes, thus allowing the pulses emitted by the pacemaker to flow into the accumulator. At the offset of the stimulus, the switch reopens and stops the flow of pulses. The time estimate thus depends on the number of pulses accumulated during the elapsed time: the more pulses that are accumulated, the longer the duration is judged to be.

The using in human adults of temporal procedures analogous to those employed in animals have allowed to reveal the existence in human adults of the same fundamental properties of time perception (mean accuracy, scalar properties of variance) than those observed in animals (Allan & Gibbon, 1991; Wearden, 1991, 1992). When the experimental conditions are perfectly controlled and the same stimulus is repeatedly presented, these temporal properties are also observed in children as young as three years of age (Droit-Volet, Clément & Wearden, 2001; Droit-Volet & Wearden, 2001). Recently, babies of four to six months have also been shown to be able to discriminate time (Brannon et al., 2008; Provasi, Rattat, & Droit-Volet, 2011; vanMarle & Wynn, 2006). In the face of this remarkable ability to measure time observed at different levels of the phylogenic and ontogenetic scales, researchers have logically concluded that human beings and animals share in common the same clock mechanism dedicated to time measurement, and that it is probably located in early-maturing subcortical structures of the brain (Droit-Volet, 2013a).

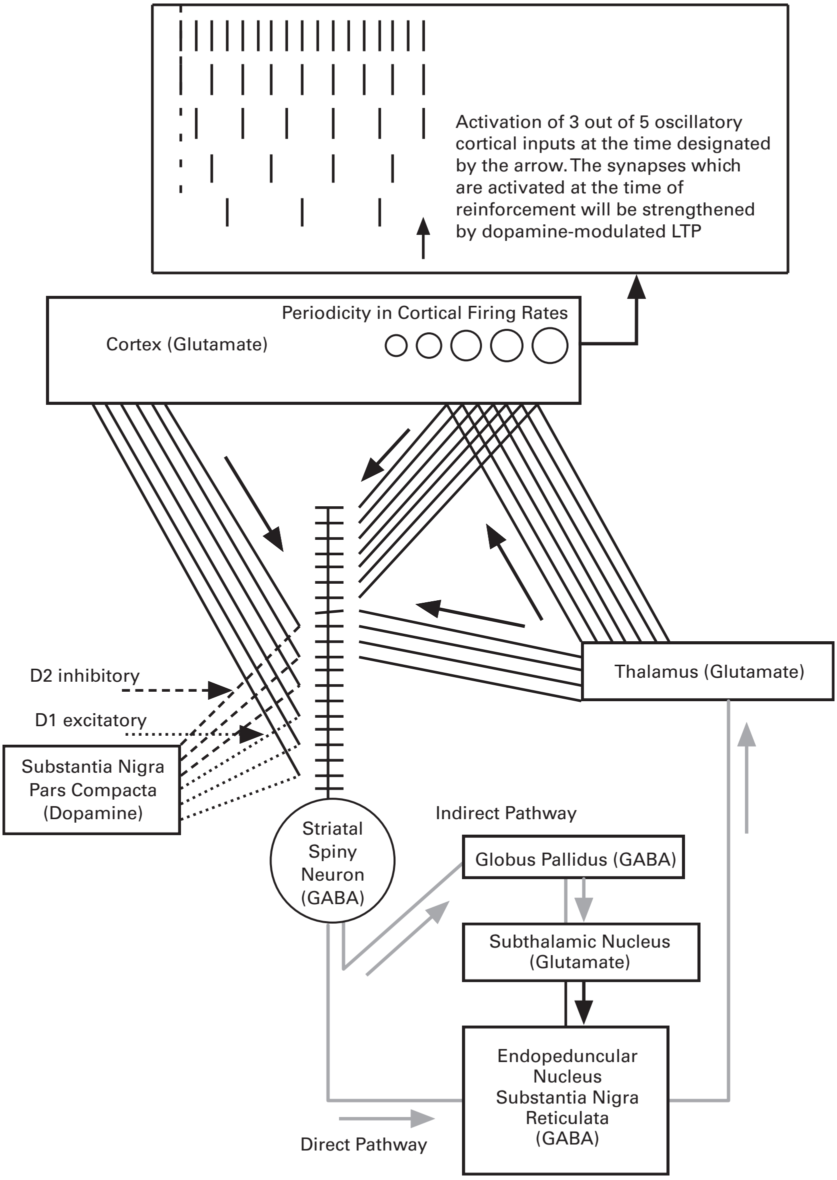
In parallel with these studies designed to demonstrate how humans and animals are able to estimate time accurately, a number of researchers have observed that temporal behavior does not always conform to the scalar properties of time (for a review, see Wearden & Lejeune, 2008). Other researchers went on to point out fluctuations in the time judgments made by humans. Based on a long-standing conviction that a simple clock mechanism cannot account for fluctuations in temporal judgments, some psychologists have also proposed alternative models (e.g., Machado, 1997; Mauk & Buonomano, 2004; Staddon & Higa, 1999). However, the citation levels in time perception studies show that their proposals have made little impact. One main reason for this lies in the fact that the internal clock model (scalar expectancy theory) also takes account of time distortions, as we will see below. Finally, despite the considerable doubts concerning the existence of a central mechanism dedicated to the processing of time, most researchers continue to consider the idea of an internal clock as both epistemologically useful and one that permits the formulation of predictions that can be tested and validated at the behavioral level. As Grondin recently reminded us, “There could be a multiplicity of timing mechanisms, but one fundamental principle in science is simplicity” (2010, 574).

However, it appears to be clear that the debate concerning the mechanisms underlying time perception is currently particularly fierce and that the balance is shifting in favor of the proponents of a nondedicated time mechanism (see Wittman & van Wassenhove, 2009). This theoretical reversal may be due to a number of factors. One of these is the decline in interest in pursuing the study of how accurately humans are able to process time, so well has this phenomenon become established. Another resides in the widespread agreement that the traditional pacemaker-accumulator model does not possess sufficient physiological plausibility. Finally, as we will see below, the most convincing argument probably derives from the results of recent imaging studies in human adults that have not succeed to identify a simple neural structure responsible for the processing of time (for a review, see Coull, Cheng, & Meck, 2011; Ivry & Schlerf, 2008; Meck, Penney & Pouthas, 2008; Weiner, Turbeltaub & Coslette, 2010).

Indeed, the greatest advance in the understanding of the mechanisms underpinning time perception comes from the failure of the neurosciences to find a simple structure in the brain responsible for the processing of time. Livesey, Wall, and Smith observed that when the cognitive task demands are controlled for, most brain activations that are thought to be involved in time processing disappear. Only three regions survive as potential candidates: (1) “a small region at the confluence of the inferior frontal gyrus and the anterior insula, (2) a small portion of the left supramarginal gyrus, and (3) the putamen in the basal ganglia” (321). Matell and Meck (2000, 2004) have therefore proposed a model they consider to be more biologically feasible and in which the basal ganglia plays a critical role. This is known as the “striatal beat frequency” model (SBF) (figure 23.1).

Figure 23.1

The major components of the striatal beat-frequency (SBF) model. Activity in the cortex is synchronized by onset of a relevant stimulus, after which the cortical activity resumes with a variety of oscillatory periods. The coincident activity of a subset of these cortical neurons is detected by striatal spiny neurons that are trained via long-term potentiation/depotentiation (LTP/LTD) mechanisms and signify the end of the trained duration. The output of these neurons is integrated by the basal ganglia output nuclei (globus pallidus, subthalamic nucleus, entopeduncular nucleus, substantia nigra pars reticulata) and relayed to the thalamus for behavioral expression. The thalamic activity can also dynamically modulate cortical and striatal activity via multiple open and closed loops, increasing the model’s flexibility to neurological insult. The excitatory and inhibitory neurotransmitters associated with each pathway (e.g., dopamine, GABA, and glutamate) are indicated in the diagram (adapted by Meck from Matell & Meck, 2000. Also appeared in Meck, W. H., & N’Diaye, K., 2005, Un modèle neurobiologique de la perception et de l’estimation du temps. *Psychologie française, 50,* 47–63; copyright © 2004 Société française de psychologie. Published by Elsevier Masson SAS. All rights reserved.)


Activation of 3 out of 5 oscillatory cortical inputs at the time designated by the arrow. The synapses which are activated at the time of reinforcement will be strengthened by dopamine-modulated LTP
Periodicity in Cortical Firing Rates
Cortex (Glutamate)
Thalamus (Glutamate)
D2 inhibitory
D1 excitatory
Substantia Nigra Pars Compacta (Dopamine)
Striatal Spiny Neuron (GABA)
Indirect Pathway
Globus Pallidus (GABA)
Subthalamic Nucleus (Glutamate)
Endopeduncular Nucleus Substantia Nigra Reticulata (GABA)
Direct Pathway

In this model, the neural inputs that constitute the time code arise from the oscillatory activity of large areas of the cortex (see also Miall, 1989, 1996). At the onset and the offset of the stimulus to be timed, there is a synchronization of oscillatory activity of a subset of these cortical neurons. The striatal spiny neurons that receive inputs from the cortex detect patterns of oscillatory firing (or beats) that match other patterns stored in memory. They then fire to indicate that the interval has elapsed. In other words, the striatum reads the temporal code provided by oscillating neurons in the cortex (Buhusi & Meck, 2005; Meck et al., 2008; Jin, Fujii, & Graybiel, 2009).

Whereas the SBF model conserves the fundamental principles of the internal clock models, other recent models have completely done away with the idea of a specialized brain system for representing time in favor of a general system distributed throughout the brain. The theoretical basis for this approach is that time is inherent to the neural dynamic of our brains. It is thus an emergent property of brain functioning. As summarized by Marchetti, "the working of brain mechanisms (neurons, cell-assemblies, neural networks, etc.) is inherently and essentially based on time. Time is not simply a product, an outcome of such mechanisms and of their working: it is inherent in them" (2009, 26). According to the climbing models (Durstewitz, 2004, Reutimann et al., 2004), the firing activity of certain cortical neurons would indeed linearly encode time. More precisely, it would make it possible to predict the time of occurrence of an expected event. However, this model accounts for the timing of expected motor responses or rapid sensory stimuli rather than for the general processing of time. In the state-dependent networks model, Karmarkar and Buonomano (2007) and Mauk and Buonomano (2004) also suggest that the neural circuits are inherently capable of processing temporal information as a result of state-dependent changes in network dynamics. The way the network evolves over time can therefore itself code the time interval. However, the state-dependent networks model provides an account of time processing only at short durations of tens or hundreds of milliseconds (<500 ms), at which time processing is automatic and requires few higher-level cognitive processes. There is now growing evidence that the mechanisms responsible for processing short and long durations are different. The processing of the latter is thought to activate the prefrontal cortex, especially the right hemisphere, which is involved in maintaining information in working memory (Ivry & Spencer, 2004; Lewis & Miall, 2006, 2009). Beyond 1 or 2 seconds, time effectively consists of a long continuous flow of information whose tracking requires working memory capacities (Baudouin et al., 2006; Droit-Volet & Zélanti, 2013; Fink & Neubauer, 2005; Zélanti & Droit-Volet, 2011). Finally, Eagleman concluded that "the neural basis of time perception remains shrouded in mystery" (2005). Furthermore, whatever the brain system providing the raw material for time representation, temporal judgment in human beings cannot be reduced to the "percept" of time produced by a basic internal clock system. The time judgments and their fluctuations result from complex interactions between different processes. The challenge is to successfully identify the context in which a time distortion occurred and the components able to explain this temporal distortion.

23.2 Explanations of Time Distortions

Let us leave aside the question of uniform time. What we want to establish is that it is not possible to talk of an enduring reality without introducing consciousness into it.

—Henri Bergson, *Durée et simultanéité*

The internal clock models identified two main causes of time distortions at the level of the pacemaker-accumulator system. The first cause relates to the speed of the pacemaker, which may vary depending on arousal level (Treisman, 1963, 1993). According to the scalar expectancy theory model, when the level of arousal increases, the rate of the pacemaker increases, more pulses are accumulated, and the duration is judged to last longer. In addition, when real durations are involved, this effect should be a slope effect and not an absolute effect (additive effect). Indeed, the effect of the speeding up of the internal clock appears to be greater for long than for short durations. The most convincing demonstrations of the speeding up of the internal clock have been provided by pharmacological studies involving the administration of drugs. The administration of indirect dopamine agonists (DA) such as a methamphetamine or cocaine, which increase the level of dopamine in the brain, has been shown to speed up subjective time (e.g., Maricq, Roberts & Church, 1981; Meck, 1983; Rammsayer & Vogel, 1992). By contrast, decreasing the level of dopamine in the brain using a DA-receptor blocker (haloperidol) leads to a slowing down of subjective time (e.g., Drew et al., 2003; Meck, 1996). Whatever clock system is proposed (pulses, oscillators, neural networks), there is now a genuine consensus that the DA system plays an essential role in time perception and that this affects the frequency of the internal clock-like system (Meck et al., 2008). Furthermore, the variations in the speed of the internal clock have been observed not only under the effect of drugs but also in specific environmental contexts. For instance, in the presence of rapid periodic events (repetitive click, flicker), internal clock rates have been seen to increase, thus resulting in accelerated time judgments (e.g., Droit-Volet & Wearden, 2002; Ortega & López, 2008; Penton-Voak et al., 1996; Treisman, Faulkner, & Naish, 1992; Treisman et al., 1990; Wearden et al., 2009). As Wearden et al. (2009) recently concluded, the click train effect on the perception of time due to a speeding up of the internal clock is one of the most robust effects observed in time psychology. To summarize, the speed of the internal clock system is highly dependent on changes in internal states in response to the effects of drugs or external stimuli. In addition, we shall see that emotions constitute another factor affecting the rhythm of the internal clock.

The second robust effect accounting for time distortions relates to attentional processes. Indeed, attention has been extensively investigated in studies of time perception (Nobre & Coull, 2010). Studies using dual-task or attention-distraction paradigms have systematically shown that when participants allocate less attention to time, this results in shorter perceived durations (e.g., Brown, 1997; Coull et al., 2004; Zakay & Block, 1996). The internal clock model explains this temporal shortening effect in terms of the delay in the closure of the switch that connects the pacemaker to the accumulator when attention is distracted away from the processing of time. As the switch closure latency increases, some pulses are lost, and the duration is estimated shorter. In addition, this shortening effect should be absolute. In other words, it should be independent of the duration of the stimulus, since the same number of pulses are lost at the beginning of the stimulus regardless of its length. However, attention can also be thought of as successive phases, during which attention alternates between the processing of temporal and nontemporal information. This would produce the rapid opening of the switch (flickering) across the duration, with the result that more pulses would be lost during longer rather than shorter durations (for a discussion, see Lejeune, 1998; Penney, Gibbon, & Meck, 2000). That is consistent with a slope rather than an absolute effect. However, whatever the mechanism involved, diverting attention away from the processing of time systematically produces a shortening of time estimates.

To summarize, two main mechanisms, one related to the internal clock speed (lengthening effect) and the other to attention (shortening effect), can account for many observed time distortions. A we will see, the effects of emotions on cognition are often explained in terms of these two mechanisms (Bradeley & Lang, 2007; Ekman, 1999). However, the time distortions that occur in emotional contexts cannot be reduced to these two mechanisms alone. Temporal judgment is based on complex information processing that also involves memory and decisional processes. However, very few studies have investigated the role of decisional processes in time perception (Droit-Volet & Izaute, 2009). Furthermore, it is of crucial importance to consider the conditions in which temporal judgments are made. A fundamental distinction must be drawn between the implicit and explicit processing of time (Coull & Nobre, 2011; Lewis & Miall, 2006; Rattat & Droit-Volet, 2007). The former is involved in the processing of short durations (>1 s), in motor timing as in the case of finger tapping, in time conditioning, and in implicit temporal learning involving a long series of sessions, such as those used in studies of animals. The latter is involved in the processing of longer durations, in the judgment of new and unpredictable events, and in temporal tasks involving smaller numbers of trials. Most of the experiments conducted on emotions in human adults have used conditions of explicit temporal judgment with a small number of trials, specifically because it is difficult to guarantee the ecological efficiency of emotional events over a long session (e.g., Hancock & Weaver, 2005; Stetson, Fiesta & Eagleman, 2007). Furthermore, in real-life conditions where time distortions are often observed, explicit judgments are frequent. This results in the fact that temporal accuracy is perhaps the exception in the every-day life, rather than the rule or, more precisely, is specific to certain temporal conditions when the individuals have the opportunity to repeatedly experience the duration of the same event. Indeed, human adults use counting strategies because they are well aware of the inaccurate nature of their temporal estimates. Finally, because humans are often placed in conditions in which they make explicit judgments of time, their time judgments cannot be reduced to a "percept" of time produced by a basic clock system in response to the incoming "sensory" data alone. Their knowledge of the passage of time as well as their awareness of their own emotional states may also affect their time judgments. To investigate the effects of emotions on humans' temporal judgments, it is therefore necessary to be able to analyze the specificity of emotional contexts and their meaning for human adults in order to identify the main causes of time distortions.

23.3 Experiencing a Time Distortion in Response to Fear

Fear lends wings.
—Virgil, *Aeneid*

Without doubt, the emotional situations that have been the most intensively studied are those involving a threat. It is particularly interesting to study these situations in cases of event memory or autobiographic memory when individuals have a traumatic experience, for example when they are the victims of aggression or an accident. Victims of car accidents often report that time seemed to move more slowly during the event (e.g., Loftus et al., 1987; Anderson, Reis-Costa, & Misanin, 2007). The question is why? Recently, Anderson et al. (2007) investigated the effect of the September 11 terrorist attack on time estimates. The participants watched two video clips of three minutes each: one neutral (from the *Wizard of Oz*) and another with the footage of the planes crashing into the towers. After each clip, the participants were asked to estimate the duration of the video and rate the stress they experienced while viewing these films. The results showed that the clip of the event which was considered to be more stressful was systematically estimated as lasting longer than the control clip. However, one methodological problem relates to the absence of any control of the level of familiarity, given that the September 11 clip had been shown often on the television (Pezdek, 2003). Nevertheless, this temporal overestimation of stressful films has been replicated for less familiar scenes (bank robbery, free-fall; Loftus et al., 1987; Stetson et al., 2007). In a recent study, Campbell and Bryant (2007) tested novice skydivers who were making their first jump. As can be imagined, this is a particularly arousing experience. After jumping, they were asked how long they thought their experience had lasted. The results showed that the time estimates were correlated with the level of fear they experienced. Another problem in these studies, as in most studies investigating the effect of emotion on time, is that they are based on a retrospective judgment of time, with the participants being aware of the necessity to estimate the duration only after the temporal episode has ended (Hicks, Miller, & Kinsbourne, 1976). In these conditions, it is difficult to control the level of attention paid to temporal information. Furthermore, the studies involving retrospective time estimates have generally argued that time judgments are based on memory processes, such as the space occupied in memory by the processing of nontemporal information or the structure of event recall (for a review see Block, 1992), rather than on the processing of temporal information per se. In order to understand the mechanism that makes it possible to measure time, psychologists therefore prefer to use a prospective time paradigm in which participants are told that they will have to estimate time; that is, when their attention is focused on time (explicit judgment).

We are currently witnessing an explosion in the number of studies investigating the role of emotions in time judgments within a prospective time paradigm. However, interest in this topic is not new. As early as the 1950s and 60s, researchers were already conducting a series of studies in which they attempted to create stressful conditions in order to investigate the effect of fear on time estimation. And their imagination knew no limits. For example, Langer, Wapner, and Werner (1961) blindfolded participants who were standing up on a treadmill. These then pressed a button that caused the treadmill to move toward or away from the edge of a precipice and were instructed to release it when they considered that 5 s had passed. As one might well expect, the participants produced shorter durations in the danger (3.52) than in the no-danger (4.11) condition. Watts and Sharrock (1984) presented a live spider for 45 s to participants who were or were not arachnophobic and reported longer estimates of the spider presentation duration in the phobic participants. Falk and Bindra (1954) placed electrodes on their participants' fingers and asked them to respond after a 15-s interval, with a signal warning them whether or not they would receive an electric shock at the end of the interval. The results showed that the participants in the experimental group tended to overestimate the length of the interval more than the participants in a control group in which none of the intervals were followed by a shock. However, in the experimental group, there was no significant difference in estimates between the trials that were or were not followed by an electric shock. To reduce the level of anxiety that may have persisted throughout all the trials, including the neutral ones, Hare (1963) decided to remove the electrode during neutral trials in a series of four trials in which the neutral and experimental shock trials alternated with 5-s and 20-s intervals. In these new conditions, the participants clearly estimated the intervals followed by shocks to be longer than the neutral intervals. To summarize, these pioneering studies already showed that time is overestimated in stressful conditions. However, these studies, which used a small number of trials and target durations, could provide only an incomplete description of the characteristics of time perception in threatening situations.

Recently, in order to find out whether the scalar properties of time hold in threatening conditions, Droit-Volet et al. (2010b) observed a temporal discrimination task in human adults close to that previously used in animals by Meck (1983). In this study, the participants performed a temporal bisection task in which they were initially presented with a short and a long standard duration. They were then presented with comparison durations equal to the standard duration or of intermediate values, and had to judge whether these comparison durations were more similar to the short or to the long standard duration. The participants were told that, at the end of some stimulus durations, they would hear, via their headphones, a short noise that would either be pleasant or very unpleasant and that a signal would warn them of the type of stimulus that they were to hear: aversive stimulus, nonaversive stimulus, no stimulus. The threatening stimulus was a 50 ms burst of 95 dB white

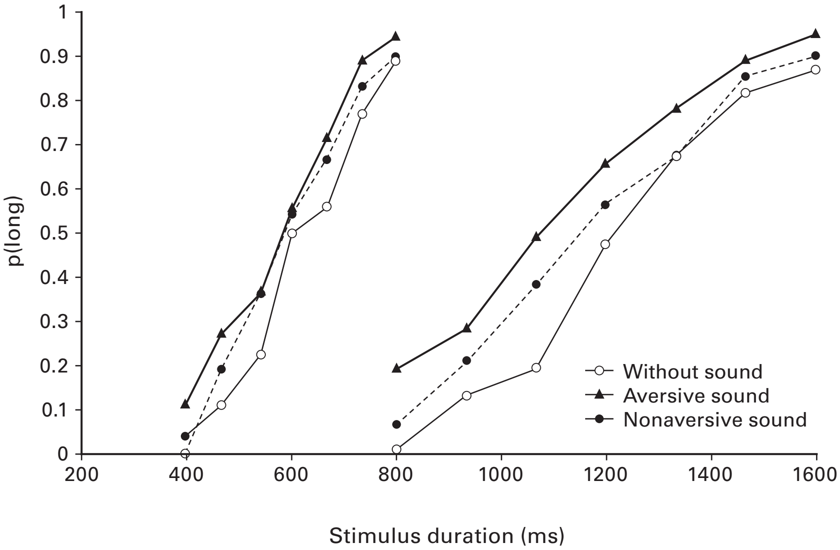


Figure 23.2

Proportion of long responses plotted against probe durations for the trials without sound, and with an aversive and a nonaversive sound in the 400/800 ms and the 800/1600 ms anchor duration condition in temporal bisection. (Reprinted with permission from Droit-Volet et al., 2010b.)

noise with instantaneous rise time of the sort that is associated with the startle reflex produced by primitive defensive reactions (Hillman, Hsiao-Weckslerb, & Rosengren, 2005). The nonaversive stimulus was a simple 50-ms beep. Recordings of skin conductance responses coupled with subjective evaluations of the stimuli in terms of valence, arousal, and emotion confirmed that the aversive sound was effectively high-arousing and produced the emotion of fear compared to the nonaversive sound. Figure 23.2 presents the psychophysical functions obtained in this way for the two duration ranges (400/800 ms vs. 800/1600 ms) by plotting the proportion of long responses (comparison durations judged as more similar to the long standard duration) against the stimulus durations.

The results showed that the psychophysical function was shifted toward the left, thus significantly lowering the point of subjective equality, also called the bisection point, when the participants expected an aversive sound compared to when they expected a nonaversive sound or nothing at all. The expectation of a nonaversive stimulus also shifted the psychophysical function toward the left compared to the absence of any expectation, but to a lesser extent than was the case with the aversive stimulus. When the participants expected a forthcoming threatening event, they therefore overestimated perceived time.

In addition, the magnitude of the leftward shift was greater for the long duration range than for the shorter one, a finding that is consistent with a multiplicative effect (slope effect) due to the acceleration of the internal clock. This suggests that the increase of arousal in the stressful condition sped up the internal clock system. The results also showed that the scalar properties of time perception hold even in the case of fear-related time distortion: that is, the discrimination of the different duration values remained good, and the variability in temporal discrimination increased with the duration values, with the Weber Ratio remaining constant for the different duration ranges.

To summarize, a forthcoming threatening event produces a time distortion, with time being judged longer than normal, but without disrupting sensitivity to time. This demonstrates that the emotion of fear did not disorganize the perception of time. On the contrary, these distortions of time enable the organism to adapt efficiently to forthcoming events. As Darwin (1872/1998) explains, when an organism experiences fear, emotional reactions are organized by motivational states of defense that ensure survival. When a subject is confronted with an imminent danger, the pupils dilate, the heart accelerates, the blood pressure increases, the muscles contract. The whole body is mobilized to be ready to react (i.e., to escape or to attack) as quickly as possible. Consequently, without disturbing the processing of time, the internal clock runs faster, thus ensuring that the individual is prepared to act earlier. The overestimation of time in a fearful situation would therefore be associated with the automatic preparation of the organism to act or to move.

This type of temporal overestimation has also been observed in a social context when individuals are confronted with angry people who may become aggressive. Thayer and Schiff (1975) reported that their participants judged a period of time (12 and 36 s) spent looking at an angry face to be longer than when they saw a happy person. In a bisection task involving short durations (400–1600 ms), Droit-Volet, Brunot, and Niedenthal (2004) used pictures of emotional facial expressions taken from standardized and validated emotional materials. They also observed an overestimation of the presentation duration of angry faces compared to that of neutral faces. In addition, consistently with a slope effect, the magnitude of this temporal overestimation was larger for the longest stimulus durations, thus suggesting that the fact of being confronted by an angry person increases the level of arousal, which in turn speeds up the internal clock system. This overestimation of the presentation duration of angry faces has also been observed in children as young as three years, thus demonstrating that it is an automatic reaction that occurs early in ontogenesis (Droit-Volet & Meck, 2007; Gil, Niedenthal & Droit-Volet, 2007). As reported by Darwin (1877) in "A Biographical Sketch of an Infant," "this feeling of fear is probably one of the earliest which is experienced by infants." Recently, Tipples (2008) and Doi and Shinohara (2009) replicated these results in a temporal bisection task. Doi and Shinohara (2009) also showed that this temporal overestimation of angry faces occurred with a straight gaze but not an averted gaze. Eye contact is thus a condition that clearly signals the presence of a danger and triggers fear in other people.

In threatening situations (expectation of an aversive stimulus, sight of an angry person), time is therefore overestimated, certainly due to the increased level of arousal that speeds up the internal clock system. Recently, in a bisection task with two short durations (250–1000 ms, 400–1600 ms), Grommet et al. (2011) used pictures from the International Affective Picture System (IAPS) that evoked isolated feelings of fear (snake, shark) and had the highest reported normative ratings for arousal (see Lang, Bradley, & Cuthbert, 2008; Mikels et al. 2005). In line with the results described above, these authors found that the psychophysical function was shifted toward the left by the fear-inducing pictures compared to the neutral pictures without modifying sensitivity to time. However, this temporal overestimation was constant whatever the real duration (additive effect), and no larger for the longer than for the shorter durations (multiplicative/slope effect).

Within the framework of the pacemaker-accumulator clock model, this additive effect suggests that the perception of fear-related pictures triggered the earlier closure of the switch connecting the pulses to the accumulator rather than a speeding-up of the pacemaker rate (for a review, see Lejeune, 1998). The problem in using external emotional stimuli lies in successfully controlling the temporal dynamic of emotions, since the level of arousal elicited by these stimuli is usually short-lived. It is nevertheless important to emphasize that each type of emotional stimulus has a particular meaning for adaptive behavior. The perception of unpleasant pictures from the IAPS, the perception of angry faces or the presentation of aversive stimuli (i.e. electric shock, aversive sound) cannot be considered as equivalent, even if all these stimuli are judged to be high-arousing and fear-related.

There is now a large corpus of compelling evidence suggesting that the amygdala plays a critical role in the inducement of fear (fear conditioning) in response to threatening cues such as facial signs of fear (e.g., Adolphs, 2002; Adolphs et al., 1994; Ledoux, 1996). The primary role of this subcortical structure seems to be to enable organisms to rapidly detect potentially dangerous stimuli (Ledoux, 1996; Phelps et al., 2001; Mermillod et al., 2010). Recently, Meck and MacDonald's study (2007) revealed the function of the amygdala in selective attention to temporal information in an emotional context. When rats have to simultaneously time a 50-ms visual stimulus and a 10-ms auditory stimulus paired with a foot shock, they are unable to divide their attention and time both signals simultaneously. By contrast, when lesions in the amygdala blocked this fear-related impairment, they were able to time the signals simultaneously. In line with Meck and MacDonald (2007), we can thus assume that an oriented-attention process is also involved in the effect of fear-inducing cues on time perception.

It is now widely accepted that fear is highly dependent on the dopaminergic system (Phelps & Ledoux, 2005). Within the framework of the SBF model, Meck et al. (2008) recently reported two types of DA release: phasic and tonic. The role of the phasic DA release would be to serve as a start gun by indicating the onset of a relevant signal for the synchronization of the cortical oscillations and the resetting of the membrane properties of the striatal spiny neurons. Another DA release coincides with the delivery of the reward, thus indicating the end of the interval. By contrast, the role of the tonic DA release is to modulate the frequency of the cortical oscillation (i.e., the speed of the internal clock). The results indicating temporal overestimations in fearful conditions are thus consistent with the idea that time processing is highly sensitive to the activity of the dopaminergic system, and that this temporal overestimation may be due either to the selective attention processes, or to the speeding of the internal clocklike system, or both, since it is not always possible to dissociate between the two systems at the behavioral level. The fundamental problem is thus to successfully identify the conditions that do or do not produce overestimations and determine why this is so (Hancock & Weaver, 2005).

23.4 The Factors Involved in the Effect of Nonthreatening Emotional Stimuli on Time Perception

Our feeling of time harmonizes with different mental moods.
—William James, *The Principles of Psychology*

Emotional stimuli are often described on the basis of only two major dimensions, their level of arousal (from relaxed to excited) and their affective valence (from pleasant to unpleasant). Recent studies using nonthreatening emotional stimuli characterized on these two dimensions have also revealed the essential role of arousal in time judgments. Noulhiane et al. (2007) used sounds from the International Affective Digital Sounds collection (IADS; Bradley & Lang, 1999) and found that the negative sounds were judged longer than the positive ones. They concluded that the physiological activation induced by emotion is the "predominant aspect of influence of emotions on time perception" (703). Previously, Angrilli et al. (1997) had also reported the determining role of arousal in the effect of emotions on time judgments on the basis of pictures from the IAPS. In the high-arousing conditions, the presentation duration of the unpleasant pictures was overestimated and that of the pleasant pictures underestimated. Conversely, in low-arousal conditions, unpleasant pictures were underestimated and pleasant pictures overestimated. Angrilli et al. (1997) thus posit that the fundamental factor explaining time distortions is arousal level, which can trigger different mechanisms: an attention-driven mechanism in the case of low arousal and an emotion-driven mechanism in response to high-arousal stimuli. However, what triggers the increase in the arousal level is the motivational relevance (meaning) of the emotional stimulus to individuals, and the necessity for immediate action. As suggested above, in the case of high-arousing unpleasant pictures, the emotional cues automatically activate the autonomic system in order to prepare the organism for defensive behavior. In low-arousal situations where the body is not "on alert," the priority is not the need for immediate action, and a more thorough processing of the information is therefore likely. Rather than the level of arousal per se, the critical factor affecting our temporal judgments would seem to be the type of emotion and its associated reactions, which serve different functions (Frijda, 2007).

In an increasing number of studies, researchers are now trying to avoid reducing the understanding of emotional effects on time perception to two-dimensional space (arousal, valence) by investigating a greater variety of emotions (e.g., disgust, sadness, shame, joy). It appears that each type of emotion has different effects on temporal judgments depending on their meaning for human beings. For example, using a temporal bisection task, Droit-Volet and Meck (2007) and Gil and Droit-Volet (2011a) tested the discrimination of the presentation duration of facial expressions of disgust. The authors found that disgusted facial expressions were typically rated as arousing, and specifically more arousing than happy faces, but less so than fearful and angry faces. However, they did not find any effect of the disgusted faces on temporal performance, whereas the other faces systematically resulted in a temporal overestimation.

As far as facial expressions are concerned, this result confirms that the level of arousal per se is not sufficient to explain the complex effect of emotions on temporal behaviors. It should not be forgotten that emotional facial expressions are a means by which humans not only communicate their emotions and intentions to others but also communicate information (Ekman, 1982; Keltner & Ekman, 2000). Seeing individuals expressing anger or fear triggers defensive behaviors. Seeing other persons expressing happiness triggers affiliation behaviors (Mehu, Grammer, & Dunbar, 2007). However, seeing a disgusted person does not activate any intention to act. The fundamental function of disgust is not the urgency of action to defend oneself against a dangerous event but to prevent oneself from consuming food that would be bad for health. It is important to appraise this bad food in order to decide whether or not to eat it. More precisely, when participants were presented with food pictures in a temporal bisection task, the presentation duration of these pictures was not overestimated but underestimated compared to neutral pictures, and to a greater extent for the disliked than for the liked food (Gil, Rousset, & Droit-Volet, 2009). This is consistent with the idea that disgusted faces are not significant enough to alter the functioning of the internal clock, and that disgusting food generates a cognitive appraisal that distracts attention from the processing of time.

In a similar vein, the perception of ashamed faces has been found to produce not an overestimation but rather an underestimation of time beginning at the age of eight years, at which children recognize this emotion (Droit-Volet & Gil, 2009; Gil & Droit-Volet, 2011b). Shame is, unlike the other emotions, not a basic but a secondary emotion, and is referred to as a "moral" or "self-conscious" emotion (Tracy, Robins, & Tangney, 2007). Lewis (2007) has claimed that these secondary emotions require introspection and self-awareness. They result from "a comparison of our action against a set of standards, rules and goals that are inventions of culture and transmitted to the child" (137). Consequently, perceiving an ashamed face should produce an introspective activity focusing on the self and the causes of the shame, thus distracting attention away from the processing of time and shortening its perceived duration.

Other researchers have begun to investigate the effect on time perception of emotional stimuli that induce sadness. Although further studies are required on this topic, the initial results on the sadness again reveal different patterns of time judgments depending on the type of emotional stimulus: seeing a sad person, listening to sad music, or feeling sad, as in the case of depression (for a recent review see Droit-Volet, 2013b). In a temporal bisection task with short durations, the presentation duration of sad faces has been shown to be systematically overestimated, although to a lesser extent than for happy or angry faces (Droit-Volet & Meck, 2007; Droit-Volet & Gil, 2009). Furthermore, the magnitude of the temporal overestimation was greater in younger five-year-old children, as if they overreacted to the distress exhibited by adult faces. By contrast, when subjects listen to music universally acknowledged as sad (minor mode; Peretz, Gagnon & Bouchard, 1998), as shown in figure 23.3, the presentation duration of the music is not overestimated but underestimated compared to neutral music matched with the sad music in terms of tempo or melodic contour (Droit-Volet et al., 2010a). This is entirely consistent with the findings of numerous studies showing that time seems to fly when we listen to music.

In addition, the time judgment of the sad music (minor key) did not differ from that of happy music presented in a major key. In sum, the factor "type of emotion" (i.e., sad, happy) is therefore also insufficient to permit a correct prediction of the direction of the time distortion, since everything depends on the meaning (motivational relevance) of the emotional stimulus used and the necessity of the clock to run faster for action readiness. Indeed, in the presence of a sad person, it is important to be prepared to act to help someone in distress (Russell & Fernandez-Dols, 1997). In contrast, although related to the mood of sadness, listening to music is not often followed by any immediate goal-oriented action (Zentner, Grandjean, & Scherer, 2008). In addition, it is well known that subjects spontaneously listen to music for pleasure and well-being irrespective of the modality of the music, i.e., whether it is sad or happy. Overall, these results demonstrate that time judgments result from the specific way in which our brains process information in an emotional context. This interpretation is also emphasized by studies of the role of interindividual differences in the regulation of emotional effects on the perception of time. To date, very few studies have been conducted in this field, which remains largely unexplored. Nevertheless, Tipples (2008) and Mondillon et al. (2007) have shown that the temporal overestimation bias in the presence of angry faces is greater in individuals showing negative emotionality as well as in those who are more empathic toward others. More recently, Bar-Haim et al. (2009) showed that high-anxiety participants reproduced longer durations than low-anxiety subjects in response to fearful compared to neutral faces. To summarize, then, time judgments are grounded in our individual experiences.

23.5 Grounded Time: Examples from Social Psychology

> It is through effort and desire that we got to know time. We still have the habit of estimating time on the basis of our desires, our efforts, our own wills.
>
> —Jean-Marie Guyau, *La genèse de l'idée de temps*

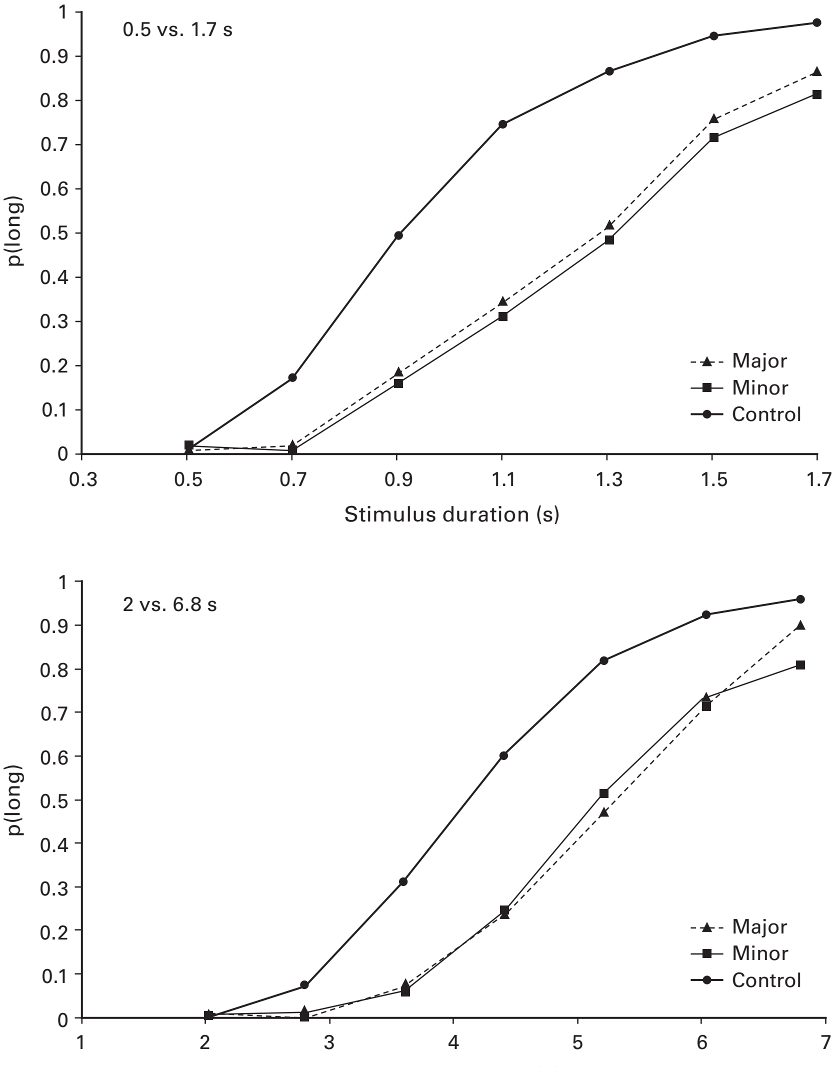


Figure 23.3

Proportion of long responses plotted against stimulus durations for the major (happy), minor (sad), and the sine wave (control) music in the 0.5/1.7 s and the 2 s/6.8 s anchor duration conditions in temporal bisection. (From Droit-Volet et al. 2010a.)

Overall, the findings reported above on the effects of emotion on subjective time demonstrate how our judgments of time vary depending on the context. As Gibbon puts it, there is no sensory receptor for time, as there is for sound or light. The internal clock is thus a pure metaphor, but a metaphor that is nevertheless useful, since “before knowing, one must begin to represent” (Aristotle).

A certain consensus, according to which time is inherent to the functioning of our brains (oscillators, neural networks), is now emerging. The “clock” system that supplies the raw material for the representation of time is thus implemented by a distributed and multimodal system rather than by a dedicated, amodal, and localized time system. Within the theoretical framework of grounded cognition, we assume that time is “grounded” in mechanisms that evolved for interaction with the environment; that is to say, mechanisms for sensory processing and, more particularly, for the motor control of action. The judgment of time thus results from changes in bodily states and in sensory-motor states experienced or reactivated during interaction with the environment (Droit-Volet & Gil, 2009).

The theory of grounded time is directly derived from theories of grounded cognition, sometimes also called embodied cognition (Barsalou, 1999, 2008; Niedenthal, 2007). These theories suggest that cognition is grounded in multiple ways, including modal simulations, situated action, and bodily states. The sensory-motor states acquired during experience therefore provide the material for certain judgments of time, and at least for explicit judgments of time or human awareness of time. Several findings reported in the literature, like those described above, support this conception of grounded time.

First of all, we want to emphasize that many metaphors of time are based on space and the dynamics of movement in space (Engberg-Pedersen, 1999). The conceptualization of time is thus in some way derived from the perception of movement in space. In the same vein, studies of the development of the concept of time have described an initial sensory-motor stage, during which preschool children confuse time with spatial dimensions or speed of movement. When they see two cars running at the same time on parallel tracks, they consistently judge that the car that travels faster and goes further has taken longer (Piaget, 1946). Levin (1977) also showed that young children judge the duration of illumination of more intense lights to last longer. Their judgments of time systematically depend on the processing of its physical contents; that is, the characteristics of the stimuli to be timed. The idea of a uniform time that makes it possible to measure different events independently of the characteristics of the contents or actions involved would seem to emerge later in infancy, when the ability to reason about time develops. Initially, children do not conceive of this uniform time but of multiple times that are intrinsically associated with the events or actions they experience (e.g., Droit-Volet, 1998; Droit-Volet & Rattat, 1999; Rattat & Droit-Volet, 2002). As suggested above, this does not mean that young children are unable to estimate time accurately when required to make an implicit judgment of time, or when they repeatedly experience the same event lasting for the same duration (distribution of temporal samples of an event).

Other and perhaps more convincing evidence for grounded time comes from the numerous examples of the expansion or contraction of subjective time in human adults (e.g., Eagleman, 2008; Tse et al., 2004; Wittmann et al., 2010). For example, an object moving toward an observer is subjectively perceived as longer in duration than the same object that is static or moving away (Wittmann et al., 2010). In a recent series of experiments that we ran in our laboratory using the temporal bisection task, we also found that the discrimination of the presentation duration of pictures of body postures varied as a function of the posture (Nather, Bueno, & Droit-Volet, 2011; Droit-Volet et al., 2013). For example, Droit-Volet et al. (2013) showed that the presentation duration of the posture of a man running was judged to last longer than that of a standing man (figure 23.4).

This suggests that the judgment of time is derived from the simulation of the movements involved in the depicted body posture. This finding is consistent with Pulvermüller's results (2005), which show that when participants simply read a word corresponding to an action, the motor system becomes active in a way that reflects its meaning. A verb referring to an arm or leg movement produces an arm or leg simulation in the corresponding areas of the

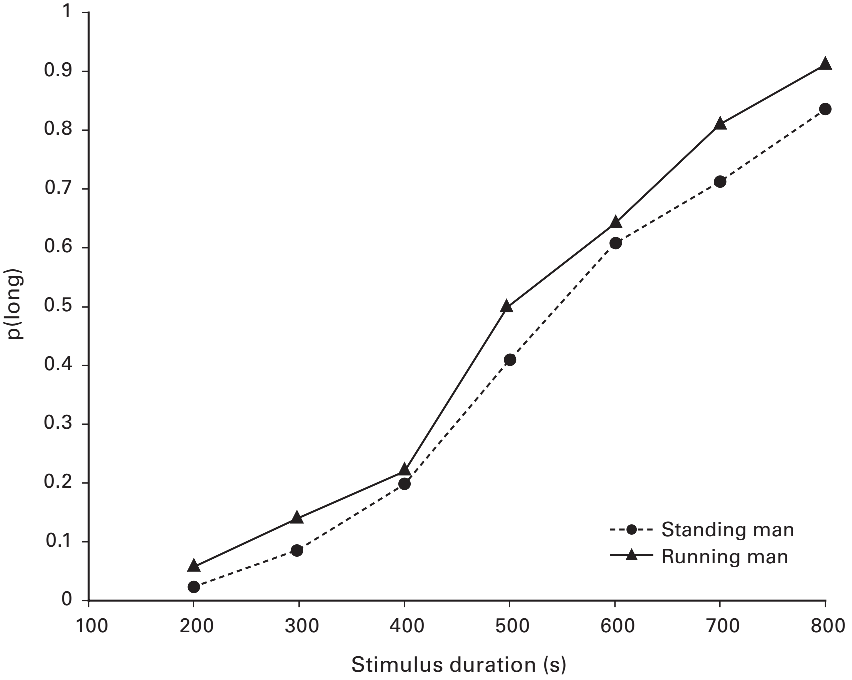


Figure 23.4

Proportion of long responses plotted against stimulus durations for body posture pictures (a running man and a standing man) in temporal bisection.

motor system. Finally, the greatest volume of data in support of the theory of grounded time probably comes from studies of emotions reported previously, which suggest that the perception of other individuals' emotional facial expressions triggers the embodied simulation of the corresponding emotions and consequently affects time judgments (for a more detailed description, see Droit-Volet & Gil, 2009).

In social psychology, the importance of time has often been neglected in the same way that experts in time psychology have ignored the role of social variables in temporal judgments. However, the efficiency of social interaction depends on the temporal dynamic of interactions, on the ability of human beings to coordinate with one another, to "share" the same time. Conway (2004) showed that people who interact with one another experience a more similar passage of time than people who do not interact in the same way. In other words, the efficiency of social interaction depends on our ability to synchronize with others, to internalize their time, i.e., to temporally resonate with them. In a recent study, we showed that the subjective experience of time is influenced by the embodiment of the speed of motor movement of elderly people (Chambon et al., 2005; Chambon, Droit-Volet, & Niedenthal, 2008). More precisely, in a temporal bisection task, the participants viewed pictures of faces of elderly and young people. The perception of elderly faces significantly shifted the psychophysical function toward the right compared to the young faces, thus indicating that the presentation of the elderly faces was underestimated. A further analysis of the data revealed a slope effect, suggesting that this temporal underestimation was linked to a slowing down of the internal clock. This is entirely consistent with studies in social psychology that have shown that the memory activation of the "elderly person" stereotype causes people to walk slowly (Bargh, Chen, & Burrows, 1996).

Within the framework of theories of grounded cognition, our results can thus be explained in terms of the bodily reenactment of the experience of the slow movements of elderly people. The embodied simulation of the speed of movement of the elderly therefore seems to have slowed down the internal clock, which in turn slowed down subjective time. Our feelings of time are therefore directly derived from changes in our bodily states. Recently, Craig (2009) advocated a similar idea by suggesting that the interoceptive cortex (anterior insular cortex) plays a central role in our feelings of time. In the same vein, we reported results showing that the simple perception of pictures of faces expressing emotion affects the perception of time. Several studies of emotions have shown that the understanding of other people involves the simulation of their emotional states through the mimicry of their facial expressions. Indeed, people spontaneously mimic the perceived facial expressions of others (Dimberg, Thunberg, & Elmehed, 2000). Furthermore, this facial mimicry elicits the associated emotional states (Adolphs et al., 2000; Decety & Chaminade, 2003). For example, Wicker et al. (2003) showed that the perception of the facial expression of disgust activates the same brain area (insula) as is activated during the actual experience of disgust. In a study of time, we were able to demonstrate specifically that the effect of emotional facial expressions on time perception occurs when participants can spontaneously mimic the facial

Figure 23.5
Picture of a participant holding a pen between her lips to prevent facial mimicry.

expressions of others, but not when this facial mimicry is impeded by a pen held between the lips (figure 23.5; Effron et al. 2006). Consequently, the judgment of time is directly affected by changes in the body produced by the embodied simulation of other people's emotional states.

In conclusion, it is well established that human beings are able to estimate time accurately. We believe that now is the moment to go beyond this demonstration and to try to gain a deeper understanding of when and why individuals are sometimes subject to time distortions. During the last century, philosophers and a number of pioneering psychologists suggested that our feelings of time are grounded in our experiences. We want to reconsider seriously this suggestion at a scientific level by analyzing the findings on time distortions within the framework of theories of grounded cognition. This opens up a new avenue of research for future studies, some of which will attempt to find new evidence in support of this theory of grounded time, and others its limitations.

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24 Embodied Time: The Experience of Time, the Body, and the Self

Marc Wittmann

24.1 Psychological and Neural Models of Time Perception

Daily rhythms of many biological and psychological functions are controlled by an endogenous biological clock with a period of approximately 24 h (Roenneberg, Daan, & Merrow, 2003). Circadian clocks, which are entrained by light, regulate physiology and behavior over the course of the day and enable an organism to anticipate and prepare for regular environmental changes. Circadian physiological rhythms define time units of a day that are biologically determined and have an impact on human experience and behavior (Wittmann et al., 2006a). Notably, the circadian clock seems to be related to human time perception for intervals in the hours range. Whereas the production of an hour interval has been shown to be proportional to the duration of wake time in human subjects living in experimental isolation, the production of 5 and 10 second intervals was not related to individual sleep-wake cycles (Aschoff, 1998). The circadian clock has long been described, and its structural and molecular properties are currently being deciphered (Merrow, Spoelstra, & Roenneberg, 2005); however, the neurobiological basis for the sense of time and the ability of prospective interval timing regarding durations of milliseconds, seconds, or minutes has yet to be identified.[1]

Since events occur over time, an organism has to adequately process temporal information in order to anticipate environmental demands and to plan actions. In humans, precise timing of intervals ranging from hundreds of milliseconds to a few seconds is essential for controlling complex behavior, for example when we communicate with others through music, dance, or conversation (Trevarthen, 1999; Wittmann & Pöppel, 1999). But time is also an experience; we sense the passage of time and feel the duration of events. A few minutes of a boring situation feel unbearably long. In contrast, we may wish that the encounter with a beloved person would last longer. The experience and anticipation of duration also influences decisions about how to act, such as whether to wait for the elevator or to take the stairs, whether to stand in line at the post office or to come back later. We make temporal decisions as we consider the temporal delay of different potential outcomes associated with our choices (Wittmann & Paulus, 2008; 2009). Although we are only transiently aware of time, the experience of duration can function as an error signal indicating that an event did not occur at the anticipated point in time. Reports of subjective time often express the difference between expected and objective time, the comparison of our sense of duration with clock time (Wackermann, 2008). Subjective time also relates to intrinsically felt disturbances of how long time intervals should last. When the pause in a conversation exceeds only a few seconds we become awkwardly aware of time. On the scale of several minutes, we suddenly experience duration when the ordered meal at a restaurant appears too early and thus interrupts the conversation that has just begun.

However essential the dimension of time is for human cognitive functioning, its neural basis is still unknown. On reviewing the diversity of sometimes competing psychological and neurophysiological models, it becomes clear that there is no consensus on *how* and *where* in the brain temporal information is processed (Wittmann & van Wassenhove, 2009). The most influential model for prospective time perception is based on the idea of a pacemaker-accumulator clock, whereby a pacemaker produces a series of pulses, analogous to the ticks of a clock, and the number of pulses recorded over a certain interval represents experienced duration (e.g., Gibbon, Church, & Meck, 1984; Treisman et al., 1990). In some variants of this cognitive model, an attentional gate opens when attention is directed to time. Only then are time units accumulated in the counter (Zakay & Block, 1997). According to this type of model, an observer divides attention between temporal and nontemporal processes (Grondin & Macar, 1992). The more attention is paid to the passage of time, the longer duration is experienced. In case we are distracted from paying attention to time, when one is absorbed in other activities, duration is relatively underestimated.

An alternative idea assumes that the amount of energy spent during cognitive and emotional processes defines the subjective experience of duration (Mach, 1911; Eagleman & Pariyadath, 2009; Marchetti, 2009). Novel experiences last relatively longer because of the greater demand of mental activities involved in analyzing a more complex or novel situation. In experiments probing milliseconds timing, the duration of an oddball (a rare event) in a series of identical stimuli is relatively overestimated as compared to standard stimuli (van Wassenhove et al., 2008). A greater amount of energy expenditure for the encoding of a deviant stimulus dilates experienced duration; repetition results in higher coding efficiency and in turn leads to comparably shorter estimates of duration (Eagleman & Pariyadath, 2009).

In another attempt to replace the pacemaker-accumulator clock model with more biologically plausible concepts, memory decay has been proposed to cause our experience of time (Staddon, 2005). Since memory strength decreases with time, memory decay could function as a clock. That way, the same processes would underlie forgetting as well as time perception. In a model of internal time representation, the *dual klepsydra model* (Wackermann & Ehm, 2006; Wackermann, 2008), subjective duration is represented by the state of a lossy accumulator, which receives inflow during the presentation of a stimulus that has to be judged. A simultaneous constant outflow reflects the loss of representation, leading to typical responses in psychophysical tasks that are indicative of subjective shortening of stored duration over time.

Regarding the neuroanatomical question of which brain areas are dominantly involved in prospective duration judgments, a number of candidate brain sites have been identified and discussed together with assumed functional properties; for example, coincidence detection mechanisms using oscillatory signals in cortico-striatal circuits (Matell & Meck, 2004); generalized magnitude processing for time, space, and number in the right posterior parietal cortex (Bueti & Walsh, 2009); event timing in the cerebellum (Ivry et al., 2002); and working memory–related integration in the right prefrontal cortex (Lewis & Miall, 2006). Alternatively, it has been proposed that if neural networks possess intrinsic temporal-processing properties, many brain areas would contribute to the perception of time, depending on the modality and the type of task. The perception of time would not be related to a central clock, but time-dependent neural changes such as short-term synaptic plasticity would define subjective duration. In the state-dependent network model, the experience of duration would result as an emergent property from specific stimulus- and modality-related processes (Buonomano, Bramen, & Khodadadifar, 2009). This is in line with the notion put forward in the two-step model by van Wassenhove (2009), in which (1) automatic processes of the brain that have specific temporal properties (but do not lead to conscious perception of time per se) (2) are read out as abstract representations during an attention based re-encoding process, which in turn leads to an explicit sense of duration.

A number of reasons can be identified to explain why it is so difficult to find an agreement on *how* and *where* in the brain time is processed (for a detailed discussion, see Wittmann, 2009). One way to reduce the apparent variance of theories is to assign different time scales to different temporal processing mechanisms in the brain (Pöppel, 1997, 2009; Gibbon et al. 1997). It is unlikely that all durations, ranging from tens of milliseconds to seconds and minutes, would be under the control of the same process.[2] For example, empirical evidence suggests that state-dependent networks might only be responsible for the encoding of durations not exceeding 300 ms (Buonomano et al., 2009). A similar time range of integration for intervals of 200 to 300 ms has been proposed for sensorimotor processing (Wittmann, von Steinbüchel, & Szelag, 2001) and for auditory-visual integration (van Wassenhove, Grant, & Poeppel, 2007). Additional evidence comes from a meta-analysis of neuroimaging data suggesting the existence of two distinct neural timing systems: an automatic timing system for shorter intervals up to approximately one second, which recruits motor systems of the brain (supplementary motor area, basal ganglia, cerebellum), and a more cognitively controlled system for time intervals with durations up to a few seconds (the maximum range of most neuroimaging studies) related to right prefrontal and parietal cortical areas (Lewis & Miall, 2003). In another line of research, it has repeatedly been argued that sensorimotor processing of temporal intervals up to 2 to 3 seconds is governed by different mechanisms than intervals exceeding this approximate time limit (for overviews, see Pöppel, 1978, 1997; Fraisse, 1984; Szelag et al., 2004); that is, an integration mechanism of

2 to 3 seconds duration is a prerequisite for temporally structuring perception and action. This integration mechanism will be discussed more thoroughly below.

Findings across studies regarding the identification of different temporal processes for different time scales are not unequivocal, since “break points” in performance on time perception tasks are not always detected, or they are dependent on the specifics of the task and modality (Noulhiane, Pouthas, & Samson, 2008; Lewis & Miall, 2009). In summary, the core neural substrates and the processes accounting for the encoding of duration on different time scales, which form a timekeeping mechanism, are still debated.

25.2 Body Signals, Feelings, and Time

The experience of time can be painful. When we are bored, we have the impression that time passes too slowly. We feel “trapped” in time. Impulsive individuals, when they are not able to act on their impulsive urges, are even more likely to feel trapped in time and overestimate presented time intervals considerably (Wittmann & Paulus, 2008). The perception of time is intimately tied to our emotional states. In periods of mental distress such as depressed mood or anxiety, the passage of time slows down and subjective duration expands (Bschor et al., 2004; Wittmann et al., 2006b). The absence of a stimulating environment and the feeling of meaninglessness both can manifest themselves in a state of distress and an existential vacuum that leads to the impression of time passing too slowly.

In laboratory experiments exploring the relationship between emotion and the experience of time, subjects overestimate the duration of highly unpleasant emotional stimuli that last several hundred milliseconds to a few seconds (Noulhiane et al., 2007; Droit-Volet & Gil, 2009). Depending on induced arousal levels and emotional valence, under- or overestimations of duration can occur, paradoxical effects that are interpreted as indicative of attention- or arousal-driven modulations of perception. The experiences of time and emotion are both embodied. An overestimation of duration of presented emotional faces is only detected when an observer can spontaneously imitate perceived facial expressions. When subjects are requested to hold a pen in their mouth while perceiving the stimuli and thus cannot mimic the faces, relative overestimation of duration does not occur (Effron et al., 2006). A temporal limit of affective states on time perception seems to exist, since only durations filled with emotional content up to approximately 3 seconds are overestimated; longer emotional stimuli are not overestimated as compared with more neutral stimuli (Noulhiane et al., 2007).

Emotions are inseparable from the physiological condition of the body. Bodily signals and visceral and somatosensory feedback from the peripheral nervous system enact subjective feelings from the body (such as thirst, itch, touch, temperature, visceral sensations) as well as emotional feelings—the latter through integration with contextual information (Damasio, 1999). The insular cortex of primates is considered the primary interoceptive cortex, the receptive area for physiological states of the body (Craig, 2002; Critchley et al., 2004). Conscious awareness of complex feeling states and the self is based on a posterior-to-mid-to-anterior progression of bodily representations in the insula, in a progressive integration with cognitive and motivational information that culminates in the anterior insula (Craig, 2009a; Singer, Critchley, & Preuschoff, 2009). These processes enable a feeling for the homeostatic condition of the body and the self, the *material me*, expressed as immediate needs and desires, which guide decision making and initiate behavior. According to Craig (2009b), the anterior insula builds a unified meta-representation of homeostatic feelings that constitutes the experienced self at one moment. A succession of meta-representations of the self across time provides a continuity of subjective awareness, a series of elementary emotional moments. Moreover, the experience of time would be created by these successive moments of self-realization, informed by the body. Generally speaking, our experience of time is related to the temporal integration of emotional and visceral processes linked to the interoceptive system.

In a recent study employing fMRI, time-activity curves of neural activation during an auditory duration-reproduction task showed that bilateral dorsal parts of the posterior insula built up activation when individuals were presented with 9 and 18 second tone intervals (Wittmann et al., 2010a). Since the build-up of neuronal activation peaked at the end of the encoding interval, this neural signature was interpreted as an accumulator-type activity used to encode duration. In the reproduction interval, where subjects had to stop the tone when they felt it had reached the length of the encoding interval, similar time-activity curves that peaked shortly before the button press were detected in the bilateral anterior insula and frontal cortex. Neurophysiological studies in animals have shown the relation of increasing neuronal activity, interpreted as a temporal integration function, with the encoding and production of shorter intervals (Durstewitz, 2003; Reutimann et al., 2004). Because of the close connection between the dorsal posterior insula and ascending body signals, it was suggested that the accumulation of physiological changes in body states encodes subjective duration (Wittmann et al., 2010a). Once a representation of duration has been established, the anterior insula and areas of the frontal cortex get engaged in the reproduction phase, potentially requiring a stronger awareness of actual duration due to motor demands and decision processes.

The idea expressed here is that physiological changes form an internal signal to encode the passage of time and the duration of external events (Craig, 2009b; Wittmann, 2009). The ascending pathways to the insular cortex signal the ongoing status of the body and could be used as a timekeeping system when we transiently focus our attention to time and estimate duration. Similar to the aforementioned pacemaker-accumulator model, the number and rate of accumulated body signals over a given time span could define duration. When attending to time, a neural system in the brain transiently taps into the ongoing interoceptive signaling and accumulates this bodily information over the given time span. This sketch of a model would also be in line with empirical findings showing that increased attention to time as well as increased arousal levels lead to longer estimates of duration. In both cases, more bodily signals would be registered in an assumed temporal integrator. Complementing findings of the strong association between time and embodied emotion (Droit-Volet & Gil, 2009), evidence of a direct relationship between body temperature and the estimation of time supports this idea. Individuals with increased body temperature typically overestimate duration. A higher arousal level with higher body temperature leads to the production of shorter time intervals, which is interpreted as resulting from a higher pacemaker rate (Wearden & Penton-Voak, 1995). Similarly, the circadian fluctuations in normal body temperature correlate negatively with the length of produced time intervals in the seconds range; the higher the temperature, the shorter the intervals produced (Aschoff, 1998).

Ultimately, one has to ask what we refer to by the expression *attention to time*. Time is not a property of the external world that we could attend to. Time is not perceived in the outside world, but, according to this idea, through the inner sense, the material substrate of the self. Many thinkers have related the experience of time to the experience of a self that unfolds in time; that is, the feeling of a self is only possible as an entity over time. Hartocollis (1983, 17) summarizes this philosophical tradition as follows: "Inner time and duration is virtually indistinguishable from the awareness of the self, the experience of the self as an enduring, unitary entity that is constantly becoming." Modern neurobiology has contributed knowledge of the neuroanatomical and neurophysiological substrates related to the awareness of a material self (Craig, 2009a). The bodily self, the continuous visceral and proprioceptive input from the body, which is a basis for our mental self, is the functional anchor of phenomenal experience (Metzinger, 2008). Subjective time emerges through (or is bound to) the existence of the self across time as an enduring and embodied entity.

25.3 Time Consciousness, the Present Moment, and the Self

Phenomenal analyses of time experience by Edmund Husserl (1928) or William James (1890) discerned two complementary aspects of temporality. Subjective time is described as a continuous flow and with the feeling of a present. Events that have a certain duration and are experienced constantly slip into the past. The flow constitutes itself through an event that is anticipated, then experienced, and later remembered. Nevertheless, and paradoxically, we simultaneously seem to feel the unity of the present moment, or *nowness,* as a basic property of consciousness that distinguishes past and future and contains the qualitative (phenomenal) character of subjective experience (Varela, 1999; Lloyd, 2004; Franck & Atmanspacher, 2009).

The experience of a present moment seems a convincing intuition, and it is complemented by many empirical findings pointing to the existence of discrete windows or processing epochs that fuse successive events into a unitary experience (Pöppel, 1978; Ruhnau, 1995). Several temporal thresholds of perception in the subsecond range (e.g., at 30 ms and 300 ms) have been determined that are related to mechanisms integrating sensory information (Poeppel, 2003; Ulbrich et al., 2009; Wackermann, 2007). These thresholds are indicative of elementary temporal building blocks of perception, because below such a temporal threshold a succession of events, their temporal order, is not perceived. In several different conceptualizations, these elementary units have been termed subjective time quanta, perceptual moments, or snapshots of experience (Varela, 1999; van Wassenhove, 2009). Yet one temporal mechanism seems to exist that integrates these successive units into a perceptual gestalt with a duration of approximately 2 to 3 seconds (Pöppel, 1978; 1997; Fraisse, 1984). We do not perceive the world as a sequence of individual events, but as a temporally integrated whole. Music and language are only conceivable as consisting of larger units, melodies and phrases, which interconnect individual musical and linguistic elements (Wittmann & Pöppel, 1999). Since this temporal segmentation has been reported in many qualitatively different experiments and settings in perception and movement control, these findings have led to the suggestion that a universal mechanism in the brain exists that creates temporal windows within which conscious activity is implemented (Pöppel, 2009). This temporal integration mechanism in the range of 2 to 3 seconds provides a logistical basis for conscious representation and for the phenomenal present, the feeling of *nowness*.

However, it has been argued that the existence of temporal integration in the brain does not necessarily entail a uniquely distinguished present; that is, events are perceived at present, experiences are confined to the present, but the present is not experienced—*being present* is not a phenomenal property of experience (Callender, 2008). In other words, evidence for the discreteness of temporal processing does not necessarily entail the existence of discreteness in the subjective experience of time (van Wassenhove, 2009). Moreover, there are many conceptual pitfalls concerning the notion of a distinct phenomenal present, notably how to conceive of an experiential connectedness (a phenomenal continuity) across successive presents (Dainton, 2009). In more general terms, there is a puzzle of how we can have the experience of a continuous flow of time when we process the world through individual snapshots (Kelly, 2005). Even under the assumption that several static snapshots are integrated to form experiential units of a felt presence with 2 to 3 second duration, which bind individual moments in a higher-order unit, the problem remains how these individual phenomenal *nows* are processed to generate the experience of continuity of perception and the flow of time. Dainton (2009) provides a thorough discussion of several conceptual models that aim at resolving this issue.

Our experience is not temporally punctual, a static snapshot, a durationless instant in time. Our experience is embedded in a temporal field; that is, the content of experience is always extended through time reaching both into the past and into the future (Lloyd, 2004; Kiverstein, 2009). Experiences intrinsically possess a quantifiable limit of extension. When listening to a metronome, which produces a train of beats with regular interstimulus intervals, perceptual units are formed, such as that an accent on every other or every third beat is perceived (1–2, 1–2 or 1-2-3, 1-2-3). This temporal grouping is a mental construct, because physically speaking there is no discrete structure. The duration of these perceptual units varies with the speed of the metronome, but has a lower limit of around 250 ms and an upper limit of approximately 2 seconds (Szelag et al. 1996; London, 2002). If interbeat intervals are shorter than the lower limit, the perceived train of beats is too fast and subjective accentuation is no longer possible. If interbeat intervals exceed the upper limit (i.e., the beat is too slow), we perceive individual events that are subjectively not related with each other. Similarly, the ability to synchronize one's own movements (finger taps) to a regular beat is only possible with interstimulus and respective intertap intervals above 250 ms (Peters, 1989). Effortless and automatic synchronization breaks down with interbeat intervals longer than 2 seconds (Mates et al., 1994). These limits of beat perception and subjective rhythmization are taken as paradigmatic examples of an automatic integration process that defines the present moment in experience (Pöppel, 2009).

Ultimately, phenomenal consciousness is the generation of a world that is present: that is, it is the generation of an island of presence in the continuous flow of time, a window of presence concerned with what is happening right now (Metzinger, 2004; Revonsuo, 2006). To have conscious experiences implies "that there is something it is like to *be* that organism—something it is like *for* that organism" (Nagel, 1974). Conscious states have a first-person *mode of givenness*, an experience inherently given to me; phenomenal experience is mine (Metzinger, 2008; Kiverstein, 2009). This quality of mineness in experience thus includes a minimal sense of self. An object *x* that I perceive appears to me and, therefore, includes a basic form of (pre-reflective) self-consciousness (Zahavi, 2005). Moreover, I can be self-aware that I am perceiving object *x*, and I can be self-reflective—that is, conscious that I am having certain experiences. As stated above, complex experiences are *per definitionem* temporally extended. The temporal property of any experience, its perceived duration, is a combination of memory of the past moments of an ongoing event, present awareness of the event, and anticipation of the further duration of that event (in Husserl's [1928] terms: *retention*, *impression*, *protention*). In other words, the experienced present of an event always carries the event's history and possible future (Lloyd, 2002). This is an implicit temporal structure of any conscious experience. It has been argued that this awareness of ongoing experience, with its tripartite structure, enables self-reflective consciousness (Kiverstein, 2009). I become aware of what is happening now to me through memory of what happened (to me) and expectations of what might happen (to me). Only through this temporal structure of consciousness can the realization of a self emerge. According to Kiverstein's (2009) idea, time consciousness and the experience of a self are manifestations of the same underlying process.[3] In other words, the present experience is a stage where the self emerges through the retentional and protentional part of an experience, which reflects what happened to me and what might come about for me.

As discussed in the previous chapter, philosophical insight has long assumed a connection between the perception of time and the self. Moreover, in the search for the neural basis of time experience, self-referential processes have been implicated (Craig, 2009b; Wittmann, 2009). The insular cortex of primates has been identified as the primary receptive area for sensory activity representing the physiological condition of the body, and re-representations of this homeostatic afferent activity have been proposed to provide the basis for self-awareness (Craig, 2002, 2009a). In this model of consciousness, the anterior insula creates a series of emotional moments across time. It has been suggested that this continuous processing from moment to moment that establishes our capacity to experience the self advances with a frame rate of ~8 Hz; thus, the temporal building blocks of perception would lie in the range of ca. 125 ms (Picard & Craig, 2009). Fusing these lines of research, one could argue that the individual processing units or building blocks are integrated to form the present moment of conscious experience with an approximate duration of 2 to 3 seconds (Pöppel, 2009) as well as integrated as *mental presence* within the working-memory span of multiple seconds duration (Wittmann, 2011).

In the context of the tripartite structure of time, analyses of functional neuroimaging data support the view that time consciousness—that is, the experience of the flow of events and of *nowness*—can be mapped onto brain function (Lloyd, 2002). The proposal made here is that empirical evidence points to the insular cortex as the neural basis of time consciousness. The insula is dominantly activated when the duration of a continuous tone of several seconds' duration has to be timed (Wittmann et al., 2010a). To speak in the terminology of the phenomenological approach, when perceiving a tone we are conscious of this experience as having started a while ago, as continuing in the present and going on for some time more; and we are not only conscious of the temporality of the tone but of its mode of givenness (Lloyd, 2004; Kiverstein, 2009). Retention, primal impression, and protention are continuously part of tone perception.

Moreover, through the specifics of the duration-reproduction task, it is perhaps possible to assume a stronger part of retention during the encoding phase and a relatively stronger part of protention during the reproduction phase. In the duration-reproduction study mentioned above (Wittmann et al., 2010a), participants were instructed to reproduce the duration of tones by pressing a key when they believed that a second comparison tone (reproduction interval) had reached the length of a previously presented tone (encoding interval; Wittmann et al., 2010a). In the encoding phase, individuals do not yet know how long the tone will last; in the reproduction phase, they have a representation of tone duration that is used to reproduce the length of the first tone. Time intervals of 9 and 18 seconds had to be encoded and, therefore, necessitated the integration of several present moments (retention), an integration that, according to the results, was related to the accumulation of (posterior) insular cortex activation. Anticipation of duration (protention) comes relatively stronger into play with an accumulation of activity in the reproduction phase of the task, when individuals actively stop the second tone (the subject has to estimate when the second tone has reached the length of the first tone). In this latter phase, an accumulation of anterior insula and frontal cortex activation was recorded.

In a neuroimaging study on temporal decision making, in which individuals had to make choices between monetary options with different delays that varied in the time range of multiple seconds, the anterior insula (together with the striatum) was active during the decision phase, when subjects had to take into account anticipated delays (Wittmann et al. 2010a). The anterior insula, along with the striatum, has repeatedly been identified with the anticipation of rewards and the expectation and evaluation of upcoming events (Lovero et al., 2009). Therefore, the anterior insula has been hypothesized to generate a predictive model that provides an individual with a signal of how she will feel (Paulus & Stein, 2006). The integration of the phenomenology and the neuroscience approaches provides us with the sketch of a model on how and where time consciousness is implemented in the brain, namely through insular activity in a posterior-to-mid-to-anterior progression that culminates in the anterior insula (Craig, 2009b). In cognitive neuroscience, the anterior insula (as well as the striatum) has long been identified as associated with the anticipation of rewards and the expectation of events. The insular cortex has also been implicated in the explicit perception of time. This brain structure thus seems to be a prime candidate for the neural correlates of time consciousness.

25.4 Concluding Remarks

The ideas brought forward are rather speculative. I have put together several lines of research in neuroscience and psychology on time perception and the present moment and related them to the philosophical concept of time consciousness. First, there is the notion of the *emotional moment,* which provides the basis for the experience of the mental and bodily self and of time (Craig, 2009a, 2009b), and which is identified with the insular cortex as locus of control. It is suggested that the *emotional moment* as conceptualized by Craig (2009a, 2009b) forms elementary building blocks which—following the concept of Pöppel (1997, 2009)—are integrated by a higher-order mechanism with a range of 2 to 3 seconds that defines the *present moment* or the feeling of *nowness*. Moreover, working memory which integrates events over multiple seconds forms a further higher-order mechanism for creating mental presence (Wittmann 2011). Empirical evidence is provided that links the insular cortex to implicit temporal mechanisms such as the anticipation of events as well as explicit judgments of time. Moreover, the phenomenological analysis of the temporal structure of conscious experience is related to the abovementioned theoretical and empirical approaches in neuroscience.

The following points summarize the line of thought presented here.

(i) The bodily self and time perception. Neural signals from the body as integrated in the insular cortex constitute the *material me,* and they are the basis for the representation of a self (Craig, 2009a). This ongoing creation of a self over time could function as a measure of time by matching the duration of external events with interoceptive afferent activity. Subjective time, the experience of duration, is generated through the existence of the self across time.

(ii) Integration of successive moments into the extended present moment. Phenomenological analysis points to two complementary aspects of time consciousness, namely the *flow of time* and the *present moment*. In the conceptualization of Pöppel (2009), a temporal integration mechanism binds elementary perceptual units into a perceptual gestalt of 2 to 3 second duration, and provides the basis for the phenomenal (conscious) present.
(iii) Philosophical inquiry links time consciousness with self awareness. What is experienced at the present moment reaches into the future (the expectation of what is about to occur) and past (the awareness that an experience has been going on for some time). Conscious experience includes a minimal sense of self because an experience is inherently given to the perceiver as extended through time. That is, self-reflective consciousness might emerge through the temporal structure of conscious experience. Time consciousness and the self are determined by the same underlying process.
(iv) The insula as primary interoceptive cortex. Empirical evidence points to the insular cortex as the neural basis of the phenomenological concept of time consciousness; that is, the experience of the present moment, which involves what is just passed and what is about to occur. It has been linked to the perception of time and conscious awareness (Craig, 2009b).

The integration of all these concepts to some extent has to remain a daring undertaking. For example, the equalization of protention with mechanisms of anticipation and expectation is questionable. Usually, protention is seen as an experiential part of the present moment, spanning several seconds, and related to the minimal self. The minimal self refers to the immediate experience of a self and can be discerned from the narrative self that is made up of the various stories we tell about ourselves (Gallagher, 2000). There are several temporal levels of prediction concerned with one's life that can span a few seconds to, in principle, decades. Typical investigations that show anterior insula involvement in the expectation of rewards lie in the seconds to minutes range (Wittmann et al., 2010b). That is, it is debatable whether all these phenomena fall into the same category. In fact, it has been argued that *protention* in Husserl's sense refers more to openness to what is about to happen than to a kind of expectation or concrete prediction (Varela, 1999). Besides, although I have concentrated on theoretical assumptions and empirical evidence concerning the insular cortex as locus of control for the perception of time and time consciousness, an elaborate model of the relation between time, the self, and consciousness will integrate a wider range of brain structures; that is, mesial brain regions of the so-called "default mode network" are also implicated in the perception of time and self-referential processing (Morillon, Kell, & Giraud, 2009; Wittmann et al., 2010c).

Ultimately, the basic question as to how and where time is processed in the brain remains unresolved. In contrast to most other fields of expertise in the cognitive neurosciences concerning a fundamental aspect of our experience, there is no consensus among researchers on psychological or neurophysiological mechanisms (Wittmann & van Wassenhove, 2009). At this stage, a speculative element in conceptualizing cannot do any damage; however, empirical evidence will have to be collected to substantiate these ideas.

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Notes

1. Note that in cognitive models of time perception, prospective and retrospective time perception is distinguished (Zakay & Block, 1997). Prospective time perception (also referred to as timing-with-a-timer) is concerned with the phenomenon under discussion in this paper: the perception of duration as presently experienced. In retrospective time perception (also referred to as timing-without-a-timer), duration is reconstructed from memory. The more changes we perceived during a certain time span—which are stored in memory and later retrieved—the longer the duration is subjectively experienced in retrospect (Flaherty, Freidin, & Sautu, 2005; Bailey & Areni, 2006). Whereas prospective time perception only applies to intervals up to a few minutes (an assumed prospective timing mechanism has a limit of temporal integration), retrospective time perception can refer to an individual's lifetime (Wittmann & Lehnhoff, 2005).

2. The upper limit of integration for prospective time perception mechanism might be bound to the duration of a few minutes. Neurological patients who suffer from anterograde amnesia are reported to live within a moving temporal window of their short-term memory; i.e., events cannot be recalled after a few minutes because they are not stored in long-term memory (Damasio, 1999). This time span could also represent the limit of integration for prospective time perception. An upper limit also follows from duration-reproduction experiments, in which a decreasing steepness of duration reproduction with increasing intervals suggests an ultimate temporal horizon (Wackermann, 2007).

3. As an aside: drug-induced altered states of consciousness typically are associated with a distortion in the experience of time (Wittmann et al. 2007). In extreme drug-induced states, an experienced annihilation of self-identity is accompanied by a feeling of atemporality (Shanon, 2001).

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X Altered Times

As the preceding chapters have made evident, in many settings humans are inept timers. One might suppose that our collective defects are momentary, acute episodes, hiccups in the flow of subjective time. Perhaps our misapprehensions are each fairly quickly corrected by some combination of internal and external cues. In contrast, the chapters in this section consider chronic time distortions of several types. Valdas Noreika, Christine Falter, and Till Wagner begin with a survey of duration distortions arising in natural contexts (e.g., time of day, or time of menstrual cycle), in different stimulus environments, in altered states of consciousness (hypnosis and LSD), and in the psychiatric conditions of schizophrenia and depression. Some of these themes look back to previous chapters, and some anticipate chapters to follow. Having them together here affords a proposed formal model and a practical step toward unity among all the observed, behavioral aspects of subjective time. The authors offer this formal anatomy of perceived duration:

$$D_{perceived} = D_{physical} \cdot f_1(x_1) \cdot \ldots \cdot f_n(x_n).$$

Subjective time has something to do with physical time, but the mystery of temporality is in $f_1(x_1) \cdot \ldots \cdot f_n(x_n)$, coefficients that refract time. One example of $f(x)$ is overall illumination: brighter environmental lighting leads to longer time estimates (in the seconds to minutes range; Aschof & Daan, 1997). In this case, $f(x)$ increases with x (ambient light). Another is sensory modality, the well-known observation that sounds are judged to last longer than visual stimuli of the same duration. The equation reminds us that perceived duration is always subject to multiple modifiers, even if several are irrelevant (=1) for many situations. Noreika, Falter, and Wagner also point out that the refractors of time might cancel each other out. A set of bad timers pulling in opposite directions could yield time judgments that are good enough on average, most of the time.

These big formal questions reappear in concrete discussions in the three following chapters. In chapter 26, Falter and Noreika continue their wide survey with a review of timing in developmental disorders of dyslexia, attention-deficit/hyperactivity disorder (ADHD), and autism spectrum disorders (ASD). Time-order and simultaneity judgments are less exact in children with dyslexia, but not in ADHD and ASD. Interval timing and rhythm are variable in ADHD and ASD. As Falter and Noreika's extensive tables demonstrate, studies yield various results according to the tasks and intervals used.

The three developmental disorders begin to suggest a larger issue, namely, to what extent are these disorders constituted by timing deficits, as opposed to displaying timing problems as side effects of some other underlying processing differences? Falter and Noreika make the useful distinction between the time of neural processing and the neural processing of time. Dyslexia is widely supposed to result from deviations in the normal speed of processing pathways involved in detecting fast audio and visual events. Reading involves keeping time order straight, but is this skill tantamount to a skill in making time-order judgments? In other words, is the wobbly mechanism that undermines reading and writing in dyslexia the very mechanism deployed in time-order and simultaneity judgments?

In chapter 27, Allison Kurti, Dale Swanton, and Matthew Matell discuss interval timing as a contributor to drug abuse (especially cocaine and methamphetamine). In this case, the path from timing to drug-taking behavior is more complex. Under the influence of drugs of abuse, intervals are judged long (and reproduced short). Thus, the internal virtual clock speeds on speed. How might this distortion influence the decision to take a drug, a decision which might be made in a non-drugged state? Kurti, Swanton, and Matell propose that temporal distortion contributes to the balancing of short-term and long-term benefits estimates in the choice to use drugs. Abusers tend to prefer benefits in the near-term (getting high) to deferred rewards (health and welfare). The deferred benefits are greater, but their pull is discounted by the waiting time. Abusers tend toward higher discount rates, also manifested as greater impulsivity. The clock speeds while drugs are in use, so the duration of the drug experience is misremembered. Drug-distorted temporal estimations are then averaged with normal estimations, and the temporal horizon of all experience is pushed back. Drug abuse is thus partly sustained by a kind of feedback in which the temporal landscape highlights near-term gains while rendering deferred benefits more distant. Thus, even when abusers are without drugs and presumably timing in near-normal ways, their temporal memories remain distorted. The temporal perspective of drug abuse is chronically stretched.

To build this tentative conclusion, Kurti et al. establish that temporal averaging can occur through a series of experiments with rats and humans. In the rodent variation, animals learn two intervals cued by two different signals (light and sound, for example). If both cues appear simultaneously, the rats look for their reward in the middle of the two durations. Similarly, rats can take into account the concentration of narcotics in their blood, when this is used as a cue for a distinct interval. The rat brain thus turns out to be capable of some temporal mathematics. By implication, our brains are likewise averaging expectations cued by multiple environmental conditions. The earlier conjecture that multiple distortions of time (the various $f_n(x_n)$ above) counterbalance one another could be supported.

The chapter illustrates that a behavioral disposition, a motivational state like a craving, is partly constituted by time estimations. To rate a need for a quick fix as more compelling than a need for a healthy and stable life is not merely to rate one state as more pleasant than another. The rating is conditioned by waiting time. Temporality is folded into the hedonic calculus.

In chapter 28, Peter Naish turns toward another chronic condition of time distortion, the state of hypnosis and the disposition of hypnotic suggestibility. As Naish mentions, hypnosis has been subject to skepticism about its nature and status as a distinctive psychological state. Hypnosis subjects consistently underestimate durations while under hypnosis, as if their internal clock has slowed. In the opening pages of the chapter, Naish works through many possible indirect explanations of this observation. Perhaps the slow clock follows from relaxation, or from attentional focus, or from amnesia, fatigue, or other conditions that might accompany a hypnotic induction. It turns out to be distinct from all of these. Timing thus helps to establish the "specialness" of the hypnotic state.

One parahypnotic condition does, however, resemble hypnosis in its temporal effects, and that is vivid visualization. Naish connects this influence on time with another condition of slow timekeeping, schizophrenia. The common ground, subjectively, is the substitution of a vivid internal reality for the external world, a displacement that at its extreme includes hallucinations. This leads to the plausible conjecture that subjective reality is in part constructed from subjective time. Subjective time slips away from clock time as perception drifts from the actual world. Conversely, synchronicity with the clock is attunement to the perceptual world. Naish cautions that the analogy between schizophrenia and hypnosis may be a superficial effect of two very different mechanisms, but despite that caveat, the parallels lead to some interesting conjectures about the neural mechanisms of timing. Both schizophrenia and hypnosis affect right-hemisphere processing, particularly in the prefrontal cortex.

Subjective time is indeed the "infrastructure of consciousness" (Zahavi, 1999, 82), a theme extended by Melissa Allman, Bin Yin, and Warren Meck (chapter 29) in their consideration of the temporal experiences of chronic mental dysfunction, especially schizophrenia and autism. Patients seem to suffer a storm of confused time perceptions, and, as in the other chapters in this section, specific and isolable dysfunctions provide clues to the mechanisms of normal time perception. Allman, Yin, and Meck note a further stream of clues: namely, the compensations patients sometimes display. Autistic children engage in stereotypic repetitive behaviors, a variation perhaps of the finger and foot tapping characteristic of waiting and boredom. Rhythmic behavior could be imposing some temporal regularity in experiences that are loose or unstructured in time.

Allman, Yin, and Meck also underline a theme that weaves though this book: namely, the diversity of timing mechanisms and timing behaviors. They review the peak interval procedure, where subjects learn a specific interval and then reproduce it (for the sake of determining the duration at which their button-presses peak). The paradigm affords subtle probes of memory for time and motivation, and already implicates a process with several components, a recurrent theme of this collection. Even if we knew everything about PI performance and its underlying mechanisms, however, we would still be asking about time order judgments, simultaneity, motion, succession, and passage. We return to this diversity of times in the afterword.

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25 Variability of Duration Perception: From Natural and Induced Alterations to Psychiatric Disorders

Valdas Noreika, Christine M. Falter, and Till M. Wagner

25.1 Introduction

In an early paper on the experience of time in mental disorders, Lewis (1932, 617–618) provided a number of subjective reports of unusual temporal distortions collected from psychiatric patients, such as that by an individual suffering from “involutional melancholia”[1]:

> I can’t estimate time. I can’t say what time it is because it’s an artificial day; what you call a day with the artificial day is very much shorter than the ordinary day. The time goes very much quicker … I noticed my watch was accelerated. … What I mean is this; since we had breakfast this morning, according to your time it is eight hours, isn’t it? Well, we haven’t had eight hours since this morning by Greenwich time. The time you keep here isn’t Greenwich time. Yours is only a quarter of the real time … Probably in my months it’d be a couple of months since I came here, in what I call the ordinary time. But, of course, in your reckoning it’d be eight months, what you call a month. … Time in the sense of being heavy on your hands is terrible here, I can’t do anything. By Greenwich time it goes very quick. But (considering) whether you find the moments interesting, time passes very slowly: every moment that passes is, you know, tedious and wearisome. Time in the sense of a period, though, is very quick. It would be about August, 1930, now by Greenwich time. I’m certain because I know Greenwich time couldn’t have gone as quickly as July, 1931 (the date of the interview). The past seems a long way off, but that is only the tremendous tedium since. Figuratively speaking it seems years since I was out in the normal world.

Apparently, such deficits of subjective sense of time passage are tremendous in their extent as well as grueling in their impact on everyday life, as the patient concludes at the end: “I never know any moment what is going to happen. It’s the most terrible outlook I’ve ever had to look to. It’s all perpetual. I’ve got to suffer perpetually.” Notably, such reports are rather frequent among psychiatric patients, but are not limited to patient populations. Somewhat comparable but much less explored are temporal distortions in neurocognitive alterations of consciousness. For instance, in hypnosis or psychopharmacologically modulated states, mentally healthy people may experience transient but very strong cognitive changes in the perception of time, such as seeing the world as a slowed-down movie, or the opposite experience of external events running unusually fast compared to the somewhat frozen inner sense of self. Among other bizarre mental states, a reversed temporal order of experiences is occasionally reported, as if time is flowing in the backward direction. For instance, in a study of temporal aspects of dreaming and concurrent EEG processing, Moiseeva (1975, 574) reported that:

> In 5 cases of complex dreams, the reverse procession of events was noted: the subject first saw what happened afterwards and then the beginning. For instance, in a dream a schoolboy saw himself in a street-car, then he saw how, before he had boarded the street-car, he had taken his transistor radio out of a brief-case and then, still before that, how the transistor radio had been playing in the brief-case. In all such dreams a subjective perception of acceleration of the time flow was noted.

Since they are challenging for any theory of time perception, such subjective reports are difficult to analyze systematically due to a lack of experimental control when such experiences occur, as well as linguistic uncertainties of the reports themselves. Even more difficult is their comparison to psychophysical tasks of time processing. As Lewis (1932) noticed, patients who report the most dramatic changes in their experience of time may show a rather precise perception of duration under laboratory examination. Besides occasional references to subjective reports as intriguing cases that motivate investigation of neurocognitive alterations of time, the focus of the current chapter will be on behavioral studies of duration perception as measured by estimation, production, discrimination, and bisection tasks, leaving aside other aspects of subjective time, such as the phenomenology of time passage or the perception of simultaneity and temporal-order judgments. Furthermore, we will only occasionally distinguish between different interval scales, and in general will treat all intervals under a single continuum of duration. Arguably, such an integrative approach is more suitable for the main purposes of the present chapter, which are to provide a brief review of the literature on duration perception in several selected clinical, temporarily induced, or naturally occurring neurocognitive alterations of mind; to propose a formal model for the sources of such variability in perceived duration; and to suggest some ways how different alterations of duration perception could be related or differentiated. At the same time, we acknowledge that a more detailed elaboration of the proposed framework might require differentiation between various interval scales (Lewis & Miall, 2003; Rammsayer, 1999).

The following sections will start with a brief review of exemplary neurocognitive alterations of the perception of duration, including two major psychiatric disorders, schizophrenia and depression, and two artificially induced neurocognitive alterations that can be observed in healthy individuals, hypnosis and lysergic acid diethylamide (LSD) psychomodulation. Subsequently, we will shift our attention to arguably less intense but more common naturally occurring alterations of duration perception, such as those caused by emotional changes, environmental constraints, or periodically fluctuating changes across the circadian or the menstrual cycle. All these alterations and associated changes in duration perception demonstrate the enormous flexibility of duration-processing mechanisms in the healthy as well as disordered brain. Arguably, healthy individuals can employ duration-processing mechanisms adaptively depending on the demands of a particular assignment or time of the day. In contrast, alterations of this flexibility may be associated with psychiatric disorders that show timing-related deficits. In the final section, we will highlight the resemblance between normal and abnormal timing and will speculate whether certain changes in duration perception seen in people suffering from psychiatric disorders may be related to naturally flexible and frequently fluctuating time-processing mechanisms in healthy individuals.

25.2 Pathological Distortions of Duration Perception

Distortions of duration perception have been reported in various psychiatric conditions, such as stimulant dependence (Wittmann et al., 2007), mania (Bschor et al., 2004), or borderline personality disorder (Berlin, Rolls, & Iversen, 2005). In the following, we will focus on two disorders, schizophrenia and depression, as exemplary pathological alterations of perceived duration.

25.2.1 Schizophrenia

Patients with schizophrenia may occasionally experience subjective distortions of time processing, such as a breakdown of temporal order of external events or an altered speed of subjective versus objective time passage. Freedman (1974) analyzed over fifty autobiographical books or articles written by individuals with schizophrenia and documented frequent reports of time passing very slowly or even standing still in the acute stage of the disorder. A number of studies have approached such subjective observations using behavioral tasks of duration perception. For instance, Tysk (1983a) instructed schizophrenia patients and control participants to adjust a metronome to one beat per second. Patients showed a strong overestimation of the 1 s interval; that is, they set the metronome too fast, whereas controls tended to underestimate the same interval. Similar overestimation of intervals up to 30 s was observed in schizophrenic patients when patient and control groups were tested with verbal estimation and duration-production tasks. Interestingly, no group differences emerged when participants were unexpectedly asked how much time had elapsed since they had entered the room (5–10 min).

In a large follow-up study using the same tasks, patients with schizophrenia overestimated all intervals, including retrospective judgments of 5–10 min intervals (Tysk, 1983b). Even though production of 30 s intervals appeared to be the best discriminator between the schizophrenia and control groups, it did not discriminate chronic or subchronic patients from patients in remission, suggesting that overestimation of duration might be a general vulnerability factor or a cognitive trait in individuals with schizophrenia rather than a specific state-dependent deficit. Similarly, there were no timing differences between paranoid and “nonparanoid” patients. In addition, a later study showed no duration-estimation differences between schizophrenic patients with predominantly positive or predominantly negative symptoms (Tysk, 1990). All in all, most of the psychophysically oriented schizophrenia studies report overestimation or underproduction of suprasecond intervals in schizophrenia, especially using such tasks as retrospective and prospective duration estimation (Johnson & Petzel, 1971; Densen, 1977; Wahl & Sieg, 1980). Thus, a chronic overestimation of 1 s to 1 min intervals seems to be a widely confirmed finding in schizophrenia studies, although Johnson and Petzel (1971) observed an opposite tendency toward underestimation of 2 min intervals in a group of schizophrenic patients. Tysk (1983a, 1983b) speculated that the duration overestimation in schizophrenia might be related to an overloaded perceptual system and increased arousal, which may lead to temporal intervals being filled with more mental content compared to healthy individuals.

Duration perception in a subsecond interval range was tested in 23 individuals with schizophrenia and 22 healthy controls in a temporal bisection task[2] with a long 300 ms and a short 600 ms anchor interval, and five intermediate intervals equidistant by 50 ms (Carroll et al., 2008). The schizophrenia group showed significantly greater response variability in the auditory modality, but there were no large group differences in the visual modality. Contrary to studies using suprasecond intervals (Densen, 1977; Johnson & Petzel, 1971; Tysk 1983a, 1983b; Wahl & Sieg, 1980), analysis of bisection point values showed no systematic overestimation or underestimation of subsecond intervals between individuals with schizophrenia and healthy controls.

In order to investigate the neurophysiology of duration perception in schizophrenia, Ortuño, Lopez, Ojeda, and Cervera (2005) instructed 11 schizophrenic patients and 10 healthy controls to count mentally for a period of about 2 min at the rate of one number per second, and contrasted their brain activity using positron emission tomography. Even though no statistically significant differences were observed in the 2 min estimation, the patient group showed decreased activation of the right supplementary motor area, which has been implicated earlier in suprasecond duration reproduction in healthy individuals (Macar et al., 2002). Several studies investigated neuronal processes underlying duration-discrimination thresholds in schizophrenia. Volz et al. (2001) reported that schizophrenia patients have higher duration-discrimination thresholds for 1,000 ms and 1,400 ms standards than healthy controls. A functional magnetic resonance imaging contrast between pitch and duration discrimination showed timing-specific fronto-thalamo-striatal dysfunction in the schizophrenia group. Todd, Michie, and Jablensky (2003) investigated associations between behaviorally estimated auditory duration-discrimination thresholds (starting with a 50 ms standard) and brain responses to temporally deviating sounds (50 ms standard versus 125 ms deviant) in the mismatch negativity paradigm[3] when no behavioral judgments are required. The schizophrenia group showed higher duration-discrimination thresholds in both filled and unfilled duration tasks, as well as reduced and delayed mismatch-negativity amplitudes. Interestingly, unfilled duration discrimination correlated negatively with mismatch negativity amplitudes over the left mastoid and Fz electrode sites among schizophrenia patients, but this pattern was not observed in healthy controls. This finding suggests an association between a relatively low-level detection of temporal irregularities and perceptually more complex duration discrimination in schizophrenia.

To conclude, schizophrenic patients have abnormal perception of duration in a range of temporal intervals from 50 ms to 1 min and longer; in particular, they tend to overestimate temporal intervals and have higher duration-discrimination thresholds. Most of the schizophrenia studies report timing deficits in amodal and auditory tasks, although perceived duration of visual stimuli seems to be impaired as well (Davalos, Kisley, & Ross, 2002).

25.2.2 Depression

Not only schizophrenia but also affective disorders characterized by sad feelings and depressive mood seem to predict a change in duration processing. Indeed, a common observation is that time seems to pass more slowly for individuals suffering from a depressive state, as evidenced by frequent subjective reports (Kenna & Sedman, 1964). It has been suggested that major depressive episodes might be characterized by a slowing of subjectively experienced time, whereas manic episodes might be associated with a speeding-up of subjective time (Bschor et al., 2004). The question has been raised, though, as to whether such subjective judgments of the passage of time indicate a more profound alteration of duration perception (Bech, 1975; Gil & Droit-Volet, 2009).

In addition to the subjective passage of time assessment, Bschor et al. (2004) have tested duration processing objectively (7–109 s) in patients during a major depressive episode (N=32) and patients during a manic episode (N=30). In contrast to the opposing experience of the passage of time elicited by manic and depressive states, both patient groups overestimated long time spans in a duration production task as compared to healthy controls (N=31). In addition, manic patients also overestimated time spans in the estimation task more than depressed patients and controls. Interestingly, the control participants also overestimated longer time spans in the estimation task. Hence, the significantly enhanced overestimation in the manic patients might be regarded as an alteration of duration processing in the same direction, but exceeding the normal range of duration-processing variation.

Recently, Gil and Droit-Volet (2009) used the temporal bisection task to test duration processing in a range of 400–1600 ms in unhospitalized participants with various depression scores measured with the Beck Depression Inventory (Beck & Beamesderfer, 1974). The presented durations had to be categorized as either short (close to 400 ms) or long (close to 1600 ms). The authors found that the discriminative sensitivity to durations was not different between depressed and nondepressed participants, as indicated by similar Weber ratios. However, for the depressed participants the bisection function was shifted toward the longer durations, which indicates that they judged the durations as shorter than the nondepressive participants. Interestingly, the higher the depression score, the shorter the presented durations were judged to be. Overall, these results suggest that the experience of a slowing down of time in depressive states might indeed be based on physiological differences in timing mechanisms rather than a subjective expression of the mood per se. Indeed, although sadness scores were correlated with duration estimates (the higher the sadness score, the shorter the duration estimate), the performance variance explained by sadness alone was relatively low, indicating that additional factors must play a role in the difference in duration perception between depressive and nondepressive individuals (Gil & Droit-Volet, 2009).

25.3 Artificially Induced Distortions of Duration Perception

Variability of time processing is further evidenced by changes of perceived duration in deliberately induced neurocognitive alterations, sometimes called altered states of consciousness, such as hypnosis and LSD psychomodulation.

25.3.1 Hypnosis

A typical clinical or experimental hypnosis session starts with an induction phase, when participants are mentally guided through certain relaxation techniques, and are at the same time suggested to be falling into a hypnotic state. Individuals who are highly susceptible to hypnosis may experience very unusual cognitive and perceptual alterations in response to suggestions given after the induction phase, including positive and negative hallucinations, age regression, hypnotic dreams, and even posthypnotic amnesia (Farthing, 1992). Interestingly, one of the most consistently reported cognitive effects of hypnosis, even when no specific post-induction suggestions are given, is a chronic underestimation of duration (Naish, 2007). Participants from low-, medium-, and high-hypnotizability groups underestimated the duration of a hypnosis session by 20–50 percent (Bowers, 1979). Naish (2001) used different retrospective and prospective time estimation tasks to explore hypnosis effects on perception of intervals ranging from 2 s to about 30 min, and found underestimation or overproduction of all intervals when the hypnotic state was compared to the prehypnotic state.

When hypnotized participants listened to different stories, each lasting 8.5 min, individuals with high-hypnotizability trait showed strong underestimation of the length of a highly involving story (5.87 min) in contrast to individuals with low hypnotizability trait (9.93 min; St. Jean & MacLeod, 1983). A less involving story was rated to last on average 11 min in the high-hypnotizability group, and 12.7 min in the low-hypnotizability group. In a follow-up study, the same highly involving story was narrated in two different conditions under hypnosis: in an absorption condition, participants were instructed to relax and simply listen to an interesting story about a little boy named Charles, whereas in an attention condition they were requested to count how many sentences there were in the story or how many times the name Charles was mentioned (St. Jean & Robertson, 1986). Significant underestimation of duration was observed in the attention condition, but contrary to expectations, this time there were no differences between the low- and the high-hypnotizability groups. St. Jean (1980) aimed to deliberately distort perception of duration under hypnosis. A number of words, each lasting for 2 s, was presented after giving the following hypnotic suggestions: the time is slowing down and the words will appear on the screen to last three times longer than usual (explicit time distortion), or simply that each word will be experienced as lasting for 6 s (implicit time distortion). Participants with high but not with low hypnotizability estimated the time-distortive trials to be significantly longer (M=3.75 s) than neutral hypnosis trials (M=2.42 s), in which no time-related suggestions were given to them. Notably, such hypnotic effects might stem from the social compliance and imagination of highly susceptible individuals rather than from the induction of an altered state of consciousness (for discussion of different theories of hypnosis, see Kallio & Revonsuo, 2003).

Despite the robustness of hypnotic underestimation of duration, the exact neurocognitive processes underlying distorted perception of duration under hypnosis remain unclear. Bowers (1979) observed especially strong underestimation of passed time in a group that received a posthypnotic amnesia suggestion. St. Jean and MacLeod (1983) linked underestimation of duration to absorption, while the follow-up study from the same group reported an association with attentional demand of the task rather than the degree of absorption (St. Jean & Robertson, 1986), which was later conceptualized as the busy beaver hypothesis (St. Jean et al., 1994). According to this hypothesis, a hypnotized person is so occupied by attentionally demanding tasks that little processing resources are left to monitor time-related cues, which consequently leads to the underestimation of duration (for a critique, see Naish, 2007). Recently, it has been suggested that poor duration estimation under hypnosis could be caused by the disruption of neural processing in the timing-sensitive anterior cingulate cortex (Naish, 2007). Interestingly, this cortical region might be involved in control of the test-and-predict loop of reality monitoring (Gray, 1995), suggesting a possible link between abnormal interval timing and reality distortions under hypnosis.

25.3.2 LSD Psychomodulation

Distorted perception of time is one of the most intense cognitive disturbances produced by LSD psychomodulation (DeShon, Rinkel, & Solomon, 1952). In one of the early studies (Kenna & Sedman, 1964, 283), 8 psychiatric patients out of 29 reported various time distortions after a medically controlled session of LSD psychomodulation. They reported: “there was a feeling of eternity, of timelessness” (female, insecure personality disorder); “[I was] losing all track of time, as though there were no time at all, and yet the time seemed to pass slowly” (female, schizoaffective disorder); “[I] felt remote spatially and temporally, as regards the latter both past and future seemed very far away” (male, depressive psychosis). Seven out of 12 patients who did not experience time alterations during the first LSD session experienced temporal distortions during the following sessions with higher dosage of the drug. For example, a female patient reported that “she could no longer measure her sense of time; she couldn’t tell whether she was taking a few seconds or five minutes to answer questions” (Kenna and Sedman, 285). In another LSD study, 24 healthy participants were instructed to notify the experimenter when 15, 60, 120, and 240 min had passed (Aronson, Silverstein, & Klee, 1959). The LSD condition was marked by a stronger underproduction of duration (on average 11.0, 44.5, 74.5, and 140.5 min) when compared to the control condition (13.5, 58.0, 112.0, and 212.5 min). Hence, this finding suggested that clock time is running subjectively faster under LSD psychomodulation.

Contrary, neither overestimation nor underestimation of duration was observed when 4 healthy participants were instructed to estimate whether auditory tones varying between 0.01 and 9.99 s in steps of 0.1 s had lasted for 1 s, with the tests being carried out before and after LSD administration (Boardman, Goldstone, & Lhamon, 1957). Interestingly, all 4 participants reported that it was difficult to maintain a stable concept of a second under LSD, which was also evident in higher coefficients of variation for duration perception in the drug condition. Even though subjective reports of time distortions under LSD psychomodulation are remarkable, its effects on human perception of brief intervals have not been properly documented. Many scientific questions regarding neurocognitive mechanisms of duration perception under LSD psychomodulation have remained unresolved after research into the psychological effects of LSD abated during the 1960s and 1970s.

25.4 Natural Alterations

Boredom can be sufficient to induce measurable alterations in our perception of duration. Naturally occurring fluctuations of duration perception usually go unnoticed, but nevertheless show relatively strong effects when measured. The obvious discrepancy between subjective awareness and objective measures might be related to the slow speed of such changes. Large differences between perceived duration in the morning and the evening are readily observable in laboratory tests. Yet to the individual, such alterations of duration perception are not discernible.

25.4.1 Diurnal and Circadian Fluctuations

One danger of turning off your alarm clock early in the morning and lying in for a few minutes is that the minutes will go much faster than you would have assumed, putting you at risk of oversleeping. In fact, duration perception fluctuates from the early morning to the late evening as well as during the night, as has been demonstrated in a number of studies of diurnal (i.e., periodically occurring throughout the daytime) and circadian (i.e., periodically occurring across the whole 24 hour period) cycles. When healthy participants were tested several times after awakening from nighttime or daytime sleep, the ratio of spontaneously estimated clock time to actual time decreased from the first to the last trial (Aritake-Okada et al., 2009). Changes in time-estimation ratios were related to the preceding amount of slow wave sleep. In another study, 4 male participants were instructed to sit on a chair and stay awake for 36 hours; each second hour they were instructed to produce 10 s and 60 s intervals (Nakajima et al., 1998). Produced intervals were the longest early in the morning, whereas simple reaction times peaked at 07:00. This finding is confounded by a total sleep deprivation that preceded the morning testing; however, the experiment continued until 15:00, increasing sleep deprivation even more, but the produced intervals became shorter, more accurate, and similar to the intervals produced before the sleep-deprivation night.

Kuriyama et al. (2005) showed that variation in production of 10 s intervals over a 30 hour period correlate strongly with circadian changes in core body temperature and serum melatonin levels. Most probably, circadian variation of duration perception is mediated by a complex interaction between light condition, sleep pressure, temperature changes, and hormonal fluctuations. In a more neurophysiologically oriented study, Soshi et al. (2010) carried out 10 s production tests at 21:00 and 9:00 with either a normal or deprived period of night sleep between the tests, and reported that a lack of sleep further modulates diurnal variation of duration production. After sleep deprivation, participants tended to produce shorter intervals during the morning test, whereas after a night of normal sleep the same participants produced significantly longer intervals in the morning when compared to the evening test. Near-infrared spectroscopy measurements showed that sleep deprivation–induced modulation of duration production was mediated by increased hemodynamic response in the left prefrontal cortex, even though the right prefrontal cortex usually shows a stronger involvement in duration perception during daytime (e.g., Pouthas et al. 2005).

Most of the studies of circadian influences on time perception focused on relatively long intervals, starting with about 10 s. In a study of shorter timescales, Rammsayer and Netter (1989) instructed participants to report which one of two consecutive acoustic intervals was longer: a 50 ms standard duration or one of the 35–65 ms comparison durations. There were no differences between participant groups tested in the morning (between 09:00 and 11:00) and in the afternoon (between 13:00 and 15:00). It is possible that circadian influences are limited to longer and more cognitively controlled intervals. More studies are needed to explore this suggestion, as Rammsayer and Netter did not test participants during the evening and the night hours. In addition, the 4 hour period when the experiment took place might be too short to detect a mild diurnal variation.

25.4.2 Menstrual Cycle

Various cognitive and neurophysiological functions, such as spatial memory (e.g., Postma et al., 1999), have been reported to change across the menstrual cycle, and several studies suggest duration processing might be no exception, although existing reports are not entirely consistent. Kopell et al. (1969) showed that women produced the longest 15 s and 30 s intervals in the premenstrual period, on the 28th day of the cycle compared to the 3rd through the 26th days. Similarly, the threshold of temporal fusion of two light flashes tended to be the highest by the end of the menstrual cycle, but it did not reach statistical significance. Interestingly, time-production estimates were negatively correlated with "concentration" and "social affection" scores from the Mood Adjective Check List (Nowlis 1965); that is, the shorter the duration estimates, the higher concentration and social affection scores.

In a similar experiment, Montgomery (1979) tested female participants with regular cycles on the 3rd day of the cycle (early follicular period), midway through the cycle (late follicular to early luteal period), and 3–4 days and 24 hours (late luteal period) before the end of the cycle. As in the study by Kopell et al. (1969), production of 15 s and 30 s intervals was altered 3–4 days before menstruation, but this time, surprisingly, participants underproduced requested durations, yielding intervals as short as 10.6 s and 15.7 s, respectively. Even though both studies used the same amodal duration-production task and identical intervals, other possibly confounding factors, such as time of day when the testing took place or differences in testing surroundings, are not specified in the two studies and could have led to the discrepant findings. Montgomery (1979) additionally tested 10 male participants assigned as controls on the 3rd, 14th, 26th, and 28th day of a "pseudocycle." They tended to overproduce the intervals and did not show any cyclic variation. More recently, Morofushi, Shinohara, and Kimura (2001) asked female participants to produce intervals ranging from 6 s to 60 s in the follicular, early luteal, and late luteal phases of the menstrual cycle. To control possible diurnal effects, tests were carried out at 08:00, 14:00, and 20:00. Healthy women significantly overproduced 36, 48, and 60 s intervals at 08:00 compared to 14:00 and 20:00 in the follicular phase, and overproduced tested time intervals at 20:00 in the late luteal phase when compared to the follicular and the early luteal phases. These results suggest that for healthy women, subjective time slows down in the morning in the follicular phase and in the evening in the late luteal phase.

Notably, duration production has been demonstrated to shorten with increasing body temperature (Fox, Bradbury, & Hampton, 1967; for a review, see Wearden & Penton-Voak, 1995), and an interaction between body temperature and circadian effects has been suggested for duration perception (Kuriyama et al., 2005). The basal body temperature changes across the menstrual cycle also seem to be related to cognitive performance (Beaudoin & Marrocco, 2005). Thus, variation in body temperature might be a unifying factor for timing variation across the circadian and menstrual cycle. This hypothesis could be directly tested by controlling circadian fluctuations of duration perception and body temperature within different phases of the menstrual cycle.

25.4.3 Effects of Light and Color

Physical properties of the immediate environment, such as color and brightness of the light in a room, modulate the way participants perceive duration. In a classic study with rhesus monkeys, Humphrey and Keeble (1977) showed that self-manipulated color of the light in the testing chamber might affect time processing. In a series of experiments, monkeys held the button for consistently longer periods of time when it produced blue light compared to red light on the screen, suggesting that subjective time was going faster in the red light condition. Different variations of the experimental design showed that duration effects could not be explained by a mere aesthetic preference for the color blue (e.g., when allowed, monkeys did not refrain from changing the screen color from blue to red).

In human studies, diurnal effects of duration perception are often related to the naturally changing levels of exposure to light, even though at least some of the circadian effects on duration perception remain present even when the light factor is controlled (e.g., Nakajima et al., 1998). Morita et al. (2007) demonstrated that artificially changing the level of light can also affect time estimation despite invariant clock time. A group of participants exposed to bright light for 6 hours after waking up at 07:00 showed stronger underestimation of 5–15 s intervals than a group tested at the same time of the day, but exposed to dim light. Aschoff and Daan (1997) reported a study of 18 participants who lived for a total of 24 days on average in the laboratory with a constant, either low or high, light intensity. In this environment, intervals ranging from 10 s to 2 min were produced significantly longer in the high-intensity condition, whereas production of 1 hour intervals fluctuated independently of the light conditions and correlated positively with the duration of being awake. Interestingly, the production of 10 s intervals correlated negatively with body temperature, but this factor appeared to be independent of the light effect, as temperature increased rather than decreased in the bright light condition.

25.4.4 Spatial Effects

During the last few years, a number of studies demonstrated an interaction between perception of duration and perception of space, suggesting that both magnitudes might be coded by the same generalized magnitude system in the brain (Bueti & Walsh, 2009). For instance, Xuan et al. (2007) presented a sequence of paired stimuli that differed in size (from 0.8° × 0.8° to 3.4° × 3.4°) or other magnitudes (numerosity and luminance) on a computer screen, and manipulated stimuli-presentation intervals (600–937 ms) in a Stroop-like paradigm. Larger-sized stimuli were judged to last longer than smaller-sized stimuli, and a similar interaction was observed between duration and other magnitudes. Most such experiments on interactions between space and duration perception are carried out in a relatively artificial environment via manipulating visual stimuli on a computer screen. Nevertheless, studies with more ecologically valid setups suggest that perceived duration may also change depending on how large or crowded the room the participant stands in is. Collett (1974) reported that personal space, which was defined as an area that a person perceives their body to occupy, correlates negatively with the production of an interval of 40 s in a group of male participants: the smaller perceived personal space was judged to be, the longer the interval they produced. In other words, underestimation of one magnitude was associated with underestimation of another magnitude, providing support for a theory of generalized magnitude coding in the brain (Walsh, 2003). Interestingly, such an interaction was not observed in a group of female participants, who in contrast even showed a positive correlation, suggesting that a relationship between personal space and duration perception might be gender dependent. There might be a confound of menstrual cycle though, which was not controlled in this study.

DeLong (1981) asked student participants to familiarize themselves with three environmental models consisting of small lounges, furniture, and human figures, which were designed at different scales: 1/6, 1/12, and 1/24 of full size. Participants were instructed to imagine being a scaled figure and to engage in imagined activities appropriate to the model environment. In addition, they were asked to report when they subjectively felt 30 min had passed for an imagined figure since the beginning of the task. A series of experiments showed that participants felt 30 min passed much faster for figures in undersized models as compared to standard clock time. Most interestingly, overestimation (i.e., underproduction) of 30 min was proportional to the scale of the imagined environment model. In one of the experiments, 30 min was subjectively felt to pass in just 5.43 min (i.e., 1/5.52 of the standard 30 min period) in the 1/6 scale environment, in 2.66 min (i.e., 1/11.28 of the standard) in the 1/12 scale environment, and in 1.49 min (i.e., 1/20.13 of the standard) in the 1/24 environment. Notably, the proportion of spatial and temporal scales was almost constant and equal to 1.

The results reported in this study represent one of the most dramatic distortions of subjective time reported in literature. Arguably, one of the main reasons for such a large overestimation in this study was unusual measurement of subjective passage of time for imagined activities combined with a prospective duration-production task. In addition, participants were instructed to evaluate duration for imagined rather than real activities, and it has been reported that 5 min of imagined activities are underestimated by ~20 percent (Naish, 2003). Furthermore, the judgments had to be based on feelings rather than thoughts—that is, participants had to inform researchers "when they subjectively felt (not thought) the scale figure had been engaged in the activity in the scale model environment for 30 min" (DeLong, 1981), which might have been rather unnatural if not vague for participants. New developments in virtual reality techniques might allow future studies to investigate possible influences of environmental scale on time perception in more controlled settings.

25.4.5 Emotions

It is common knowledge that time flies when we are having fun (e.g., Danckert & Allman, 2005). To what extent such distortions of subjective time are caused by emotions has been an ongoing and recently increasing focus of research into human time processing. In an article on the "time-emotion paradox," Droit-Volet and Gil (2009) discuss why we generally have such a refined ability to process precise timing, which can become highly inaccurate when we are experiencing emotions. Droit-Volet and Gil argue for a departure from the idea of distortions of time and instead for understanding the variability of duration perception as a result of mechanisms flexibly adjusting to the environment. However, not only transient emotional states but also more permanent traits, such as proneness to boredom, are reported to predict duration-perception errors. For instance, in a study by Danckert and

Allman (2005), high boredom–prone individuals showed an overestimation of temporal intervals compared to low boredom–prone individuals.

In addition, emotions expressed by other individuals can influence the observer's duration perception. For example, participants judged the duration of fearful and angry faces as longer compared to neutral faces (Droit-Volet and Gil, 2009; Gil, Niedenthal, and Droit-Volet, 2007; Tipples, 2008). The authors suggest that such an effect might serve the purpose of preparing humans to act in dangerous situations. Therefore, Droit-Volet and Meck (2007) hypothesized that emotions perceived in other individuals, which requires a readiness for action, will increase arousal in an individual and thereby will affect the processing of duration. Alternatively, perception of emotions in others might selectively increase the allocation of attentional resources to time. This suggestion has, for example, been discussed with respect to the lengthening of subjective duration experienced by impulsive individuals (Wittmann and Paulus, 2008).

Effects of time-processing distortions are complex, however, and it seems that several factors, such as modality, arousal, and valence, need to be taken into account in an attempt to explain them. In a study using prospective duration judgments (2–6 s), participants were presented with pictures weighted for affective valence and arousal from the International Affective Picture System (Angrilli et al., 1997). Angrilli et al. found an interaction effect of valence and arousal on duration judgments. While durations of negative pictures were judged to be longer than durations of positive pictures for high-arousal pictures, the opposite was true for low-arousal pictures. The authors interpreted this interaction as evidence for the coexistence of two different duration perception mechanisms, a fast emotion-driven, high-arousal mechanism, and a slower, attention-driven, low-arousal mechanism. Similar findings for auditory stimuli have been reported by Noulhiane et al. (2007), who showed that emotional stimuli are judged as longer than neutral ones and negative sounds are judged as longer than positive ones. However, while in both studies main effects of an influence of valence and arousal on time processing were found, in the visual domain these effects were found to interact (Angrilli et al., 1997), whereas in the auditory domain these factors were suggested to be independent (Noulhiane et al., 2007). These differences are in line with results from studies of modality effects on time processing suggesting selective duration-processing signatures associated with auditory versus visual stimuli (Wearden et al., 1998).

25.4.6 Stimulus Properties

Behavioral studies of duration perception frequently use stimuli presented on a computer screen or through a set of headphones. As mentioned earlier, various seemingly irrelevant properties of such stimuli might affect how long the stimuli are perceived to last (e.g., Xuan et al., 2007). A detailed description of such interactions is beyond the scope of this chapter. We will restrict the description to a few exemplary phenomena that demonstrate that the subjective duration of concrete events depends not only on their physical duration, but also on their nontemporal features. Perhaps the most widely referred to modality-dependent effect of duration perception is that auditory stimuli are generally judged to last longer than visual stimuli of the same duration (Wearden et al., 1998). Within the auditory modality, filled intervals are perceived as longer than unfilled intervals (Wearden et al., 2007), whereas 900 ms tones of relatively lower frequencies are estimated to last longer than tones of relatively higher frequency (Yoblick & Salvendy, 1970). Various distortions of duration perception have also been reported in the visual modality. For instance, van Wassenhove et al. (2008) found that a target looming disk embedded in a series of steady disks lengthens perceived duration of a target stimulus, whereas the opposite results are obtained when a steady disk is embedded in a series of looming disks. In addition, as mentioned earlier, increasing visual magnitudes of stimuli in nontemporal dimensions (larger stimulus size, larger number of stimuli, increased stimulus luminance, and larger numerical value of presented digits) results in observers judging their duration as longer (Xuan et al., 2007).

25.5 First Steps toward Conceptual Formalization of Variability of Duration Perception

As previous sections have demonstrated, perceived duration varies not only between patient groups and healthy controls, but also within individuals. Interestingly, within-participant changes in duration perception under artificially induced or naturally occurring alterations of mind may accord with duration perception in certain psychiatric disorders. For instance, it has been reported that depressed patients chronically underestimate duration when compared to controls (Gil & Droit-Volet, 2009), and a similar underestimation of time takes place when otherwise healthy individuals are hypnotized (Naish, 2001), even though different timing tasks and intervals have been used in these two studies.

Arguably, patients' perception of duration may differ from perception of healthy individuals when both groups are tested under identical conditions, but it might occasionally converge when patients and controls are tested under different conditions. Would such similarities imply that healthy individuals temporarily approach pathological abnormalities of duration perception, which are chronically observed in neuropsychiatric patients? For example, is underestimation of duration in depression and hypnosis mediated by the same cognitive processes? If so, could we model certain pathological alterations of duration perception by artificially inducing them in healthy participants? In the following sections, we suggest a conceptual framework that may help to investigate various natural, induced, and pathological alterations of duration perception within a unified scope.

25.5.1 Conceptual Formalization of Distortions of Duration Perception

In discussing cognitive and physiological mechanisms of duration overestimation under LSD psychomodulation, Aronson et al. (1959) suggested that duration perception may depend upon a combination of distinct factors rather than being a function of a single factor. Extending this line of reasoning, our review of natural neurocognitive alterations demonstrates that perception of duration, as measured by a concrete behavioral task, is a multifactorial function involving a large number of externally and internally driven factors, such as emotions, spatial properties of stimuli and environment, time of day, and so on. In the following we express this idea formally, proposing that a perceived duration $D_{perceived}$ depends not only on the physical duration $D_{physical}$, but also on a number n of modulating factors x_i, whose effects are mathematically described by functions f_i and which are multiplied with $D_{physical}$:

$$D_{perceived} = D_{physical} \cdot f_1(x_1) \cdot \ldots \cdot f_n(x_n) \tag{1}$$

Each function f_i, which depends on a factor x_i, be it an environmental influence, a stimulus property, or an internal state of the participant, has its own range of possible values. Changing these values leads to changes in $D_{perceived}$. Function values less than 1 shorten $D_{perceived}$, whereas function values greater than 1 have a lengthening effect on $D_{perceived}$. This way, a function f_k with a range of possible values of [0.8–1.2] might have a more restricted upper-range limit of values for lengthening $D_{perceived}$ than function f_l with a range of [0.8–1.4]. When f_i has a value of 1, its effect for $D_{perceived}$ is null.

To illustrate this with a concrete example, let us think of a person who is asked to produce 10 s intervals in two different conditions, where only two factors—the light x_{light}, where f_{light} has a range of [0.5–1.5], and the body temperature $x_{temperature}$, where $f_{temperature}$ has a range of [0.85–1.15]—have effective values on $D_{perceived}$. In condition A, the person is producing intervals in a brightly lit laboratory, f_{light} (1000 cd/m^2) = 1.2, and has a body temperature of 37.4 ºC, $f_{temperature}$(37.4 ºC) = 1.05. In this case, $D_{perceived}$ would equal to a produced interval of 12.6 s. In condition B, the laboratory is darkened, f_{light}(0.1 cd/m^2) = 0.95, and the person has a body temperature of 36.8 ºC, $f_{temperature}$(36.8 ºC) = 1, resulting in $D_{perceived}$ = 9.5 s.

In model (1), distinct factors may potentially cancel each others' effects. For instance, if in a certain condition the value of $f_k(x_k)$ would be 1.25 and the value of $f_l(x_l)$ would be 0.8, and all other functions would have a value of 1, then $D_{perceived}$ would be equal to $D_{physical}$. Such a cancellation of modulating factors was observed by Soshi et al. (2010), who replicated the earlier findings by Nakajima et al. (1998) and Kuriyama et al. (2003) that a produced 10 s interval is longer in the morning than in the evening. However, this circadian effect vanished after a night of sleep deprivation, when production of 10 s did not differ significantly between the morning and the previous evening. This way, the lengthening effect of the circadian cycle was compensated by the shortening effect of sleep deprivation. This poses a caveat for research studies, in that a factor might be wrongly concluded to have no influence on time perception due to cancellation by one or more other factors.

Even though the suggested model is rather formal, it can be used to integrate published results in order to generate empirical predictions for new experiments. For instance, Wearden et al. (1998) compared the verbal estimates of the length of auditory and visual stimuli and found that 1 s auditory tones are correctly estimated to last 1 s, whereas visual stimuli are underestimated by approximately 20 percent and are judged to last for ~800 ms. Using the same auditory durations, Wearden et al. (2007) compared verbal estimates of filled and unfilled intervals and found that unfilled 1 s intervals are underestimated by 40 percent, i.e., ~600 ms, whereas filled auditory tones are correctly estimated to last 1 s, replicating the previous findings (Wearden et al., 1998). Based on the results of these two studies, and assuming that the factors' modality (auditory versus visual) and content (filled versus unfilled) are independent of each other, the suggested model would predict that an unfilled visual interval of 1,000 ms would be estimated to last for 480 ms:

$$D_{perceived} = D_{physical} \cdot f_{modality}(visual) \cdot f_{content}(unfilled)$$

$$D_{perceived} = 1{,}000\text{ ms} \cdot 0.8 \cdot 0.6 = 480\text{ ms}$$

Notably, model (1) assumes independence of all individual factors, i.e., function f_k depends only on factor x_k, and in turn factor x_k is thought to have no influence on the value of any other function f_l. Most probably, such an assumption oversimplifies the actual network of influences between the factors modulating $D_{perceived}$. For instance, it has been reported that circadian fluctuation of duration perception yields the longest intervals early in the morning (Nakajima et al., 1998). Yet Kuriyama et al. (2005) demonstrated that fluctuation of produced intervals over a 30 h period correlates with circadian changes in core body temperature, serum melatonin levels, and alertness, suggesting their association, either causal or correlative, with duration perception. Possibly, at least some of the circadian and menstrual effects on $D_{perceived}$ may be interrelated, together contributing to a body temperature or another arousal-related function. Thus, model (1) could be extended to:

$$D_{perceived} = D_{physical} \cdot f_1(x_1) \cdot \ldots \cdot f_n(x_n) \cdot f_{n+1}(x_{n+1}, y_{n+1}, \ldots) \cdot \ldots \cdot f_o(x_o, y_o, \ldots) \qquad (2)$$

The first n functions depend only on one independent factor, such as sound frequency or personal space, whereas the $n + 1$ to o functions $f_n + 1, \ldots, f_o$ depend on two or more factors. For instance, a function f_{cycle} might be modulated by several factors, for example circadian cycle, menstrual cycle, and body temperature, which are mutually interacting in certain experimental conditions alongside some other functions that are modulated by independent factors such as $f_{modality}(x_{modality})$ and $f_{color}(x_{color})$. Then $D_{perceived} = D_{physical} \cdot f_{modality}(x_{modality}) \cdot f_{color}(x_{color}) \cdot f_{cycle}(x_{circadian}, x_{menstrual}, x_{temperature})$. The formula indicates that under certain conditions factors $x_{modality}$ and x_{color} are independent of all other factors, whereas $x_{circadian}$ is pairwise independent of $x_{modality}$ and x_{color}, but interacts with $x_{menstrual}$ and $x_{temperature}$.

It should also be noted that despite a large number of functions that modulate $D_{perceived}$, judgments in duration-perception tasks are very precise on average (e.g., Wearden & McShane, 1988; Ferrara, Lejeune, & Wearden, 1997). Thus, it could be concluded that the product of all modulating factors is calibrated around 1 in the human interval timing system. The enigma of how the brain achieves such accuracy despite various $D_{perceived}$ alterations remains unresolved.

25.5.2 Variability Sources for Perceived Duration

In addition to the generation of concrete empirical predictions, the suggested model points out how various functions modulating $D_{perceived}$ could be systematized. First of all, already known factors could be differentiated into functions of mutually independent factors and functions that depend on more than one factor. Another important implication of the proposed model is the formal description of the variability sources for $D_{perceived}$; there seem to be several routes for how functions can modulate $D_{perceived}$, which will be explicated in the following. Some of these routes consider variability of effective values of functions, whereas other routes are based on a change of the modulating functions themselves.

Variability Induced by Range Changes Duration-perception alterations in certain pathological conditions might be partially related to the ordinary variance in duration processing that loses its natural variability in certain disorders. For instance, the same functions could be involved when identical tasks are conducted by patients and controls, and the group differences emerge simply due to a limited effective range of values that certain functions have in a patient group. For instance, f_1 with a range of [0.5–1.5] and f_2 with a range of [0.5–2] in a healthy person might correspond to f_1 with a range of [0.6–1] and f_2 with a range of [0.5–1] in a depressed patient, and to f_1 with a range of [1–1.5] and f_2 with a range of [1–1.9] in a psychotic patient. Such an explanation may address the study mentioned above on diurnal and menstrual cycle effects, in which a duration-production task was carried out by healthy women and women diagnosed with premenstrual syndrome (Morofushi et al., 2001). Healthy women produced longer time intervals at 08:00, 14:00, and 20:00 in the follicular phase and at 20:00 in the early luteal phase of the cycle, when compared to other circadian and menstrual phases. In contrast, no statistically significant within-participant variation of produced intervals was observed in women suffering from premenstrual syndrome; speculatively, this may be due to a decrease of variability of hormonal fluctuation across the cycle. Following the suggested model, a range of values of circadian and menstrual functions in the premenstrual syndrome group may have been narrowed to values above 1.

Alternatively, under certain conditions the range of some functions might be broadened rather than narrowed, for example, f_1 with a range of [0.8–1.2] of healthy controls may shift to f_1 with a range of [0.8–2] or f_1 with a range of [0.4–1.2] in particular patients. In such a case, some of the $D_{perceived}$ judgments from a patient group may exceed all of the $D_{perceived}$ judgments observed in a control group. That is, some of the patients would underestimate or overestimate durations to a degree not observed in any of the control participants. Such observations are not possible in the range-narrowing account, in which patients are expected to show performance falling within the range of healthy controls. For instance, Bschor et al. (2004) reported that manic patients overestimated temporal intervals more than healthy participants, even though overestimation was observed in both groups. Hence, the significantly enhanced overestimation in the patient group may have been influenced by range broadening of functions that had effective values above 1 in both groups, but the upper-range limit was higher in the mania than in the control group.

The range of a function may also shift under certain conditions and states, leading to properties of both range narrowing and range broadening. For instance, f_1 may have a range of [0.6–1.4] in condition A, which is shifted to a range of [0.8–1.6.] in condition B. This way, the shortening effect of f_1 for $D_{perceived}$ would be narrowed from [0.6–1] to [0.8–1] and the lengthening effect for $D_{perceived}$ would be broadened from [1–1.4] to [1–1.6], whereas the absolute size of range would remain constant.

Variability Induced by Factor Changes Differences in $D_{perceived}$ between participant groups or between different within-participant conditions might be caused by the involvement of different sets of modulating factors. Factor reduction would take place if some of the functions modulating $D_{perceived}$ in experimental condition A (e.g., f_1, f_2, f_3, f_4) would show a value 1 and would lose their effectiveness for $D_{perceived}$ in condition B, which consequently would have a smaller number of modulating functions (e.g., f_1, f_3). For instance, both Angrilli et al. (1997) and Noulhiane et al. (2007) report that only for intervals shorter than 4 s can an effect of emotions on duration perception be observed in healthy participants. Arguably, for longer intervals, $f_{emotions}$ might become irrelevant; that is, its value approximates 1.

Contrary to factor reduction, factor increase takes place when a previously irrelevant factor—a factor whose functional value is always 1—becomes effective for modulating $D_{perceived}$ in some other condition. Obviously, such a factor increase is relative, and in principle could be identified with factor reduction. Thus, coming back to conditions A and B from the previous paragraph, condition A could be described as undergoing factor increase relative to B, whereas condition B could be described as undergoing factor reduction relative to condition A. Nevertheless, a distinction of factor reduction and factor increase is meaningful in the clinical context, where a certain pathological condition may have a smaller (i.e., factor reduction) or a larger (i.e., factor increase) number of modulating functions in comparison to the normal baseline condition. Alternatively, certain medical drugs might lead to $D_{perceived}$ modulation only in patients compared to healthy individuals. Another possibility is that the same number of modulating factors might be involved in several conditions, with the functions themselves being partially or completely different, such as f_1, f_2, f_3, f_4 in a control group and f_3, f_4, f_5, f_6 in a patient group.

Finally, these conceptual possibilities are not mutually exclusive, and in some concrete cases one function might undergo range narrowing, another function might have a shifted range, whereas still another function might be completely missing under specific alterations of mind.

25.6 Where to Go from Here?

In the following, several suggestions will be described for how the proposed model could be implemented in empirical research, particularly in psychopathology studies. Generally, both healthy individuals and psychiatric patients show relatively high variation of duration perception when one or two isolated factors are tested and other factors are controlled. Yet a product of all modulating factors in a typically functioning interval timing system usually converges to 1, whereas in patients flexibility of interval timing is much less orderly, often resulting in chronic duration underestimation or overestimation. Presumably, flexibility of typical duration perception reflects the ability of the human brain to adapt to a changing environment, and part of this ability might be lost in certain psychiatric conditions. Certainly, more research is needed to assess whether the loss of adaptive flexibility of timing among psychiatric patients is associated or might even cause maladaptive cognition and behavior. Presumably, at least some timing abnormalities observed in psychopathologies have no causal efficacy and are mere epiphenomena of some other neurocognitive abnormalities.

At the same time, considerable similarities of duration perception can be noticed between healthy individuals undergoing natural or induced alterations of mind and individuals suffering from a psychopathology. That is, temporal intervals may be perceived as shorter or longer, not only by patients with schizophrenia or depression, but also by healthy individuals situated in certain chromatic or spatial setups or during different phases of their circadian or menstrual cycles. If associations of time-perception distortions between altered and psychopathological states turn out to be functionally grounded, an intriguing implication would be to try to model $D_{perceived}$ distortions in psychiatric disorders (e.g., depression) by means of varying the factors of natural alterations (e.g., emotional stimuli) in healthy individuals.

It has recently been demonstrated that repetitive transcranial magnetic stimulation over the right posterior parietal cortex induces a rightward bias in a duration bisection task, similar to the shift observed in stroke patients suffering from neglect (Oliveri et al., 2009), which provides a new way of investigating neglect-like duration perception deficits by direct interference with brain functioning in healthy individuals. Arguably, much simpler manipulations with natural alterations of duration occurring as a result of environmental changes or biological rhythms and with alterations induced by hypnotic induction or hallucinogen administration could be similarly employed to replicate and investigate pathological duration perception. For instance, the mechanisms of alterations of perceived duration in patients with certain mood or anxiety disorders could be investigated in healthy participants, if mood induction would lead to equivalent $D_{perceived}$ changes as those observed in patients.

At the same time, a conceptual analysis of variability sources shows that similarities between distorted perception of duration in natural and induced neurocognitive alterations and certain pathological states of mind do not necessarily depend on the same combination of modulating factors and their effective values. Even if the mean of $D_{perceived}$ would be behaviorally identical in an induced alteration of mind and in a psychiatric disorder, e.g., overestimation of intervals of 1 s to 10 s by 20 percent under LSD effects and in schizophrenia, this would not imply that the underlying sources for such overestimation are necessarily the same. In fact, there is an unlimited amount of different combinations between effective values of modulating factors that can produce a behaviorally identical $D_{perceived}$. Consequently, convincing research into pathological changes in duration perception via studies of healthy participants, who temporarily experience natural or induced alterations, would require more direct evidence that the underlying sources of variability are the same for the healthy participant group as *explanans,* and the patient group as its *explanandum*.

Deficits in the natural alterations in duration perception might be one of the reasons why certain psychiatric disorders are marked by abnormal perception of temporal intervals. For instance, given that (1) duration perception fluctuates within the circadian cycle (Kuriyama et al., 2005; Nakajima et al., 1998); (2) schizophrenia patients show impaired perception of duration (Tysk, 1983a; 1983b); and (3) schizophrenia is also marked by various circadian disturbances, such as medication-related abnormal rest-activity cycle (Wirz-Justice, Haug, & Cajochen, 2001) or diminished day/night structure of heart rate patterns (Addis, Stampfer, & Lyons, 2003), it could be speculated that certain impairments of duration perception seen in these patients are related to circadian disturbances. If circadian factors causing natural fluctuation of $D_{perceived}$ in healthy people are altered in schizophrenia, this should consequently induce pathological $D_{perceived}$ changes as well. If so, neurocognitive mechanisms underlying certain $D_{perceived}$ changes in schizophrenia could be investigated by studying mechanisms of $D_{perceived}$ fluctuations across different phases of the circadian cycle in a healthy individual. Interestingly, a similar link between the experience of time, biological clock speed, and circadian cycle abnormalities has recently been proposed in the discussion of the phenomenology of bipolar disorder (Ghaemi, 2007).

An important step toward an empirical implementation of the suggested model would be a differentiation of modulating factors into two broad classes: independent and dependent factors. For this, a series of studies is needed in which several factors are systematically manipulated. This way, additive effects on interval timing can be differentiated from interactive effects, the latter of which can be described by a single function.

Furthermore, factors will need to be differentiated concerning which types of variability they are causing for interval timing, such as range shifting or range broadening. Employing well-controlled experimental setups, the type of variability that a relevant factor causes for $D_{perceived}$ could be determined on the basis of variation coefficients and measures of central tendency. Range broadening and narrowing could be inferred from increases and decreases in variation coefficients, whereas range shifts would be implied by changes in central tendency. Factor reduction and factor increase could be inferred from changes in group x factor interactions (i.e., when factors would show an impact on one group's performance only). For instance, stimuli of positive affect (e.g., smiling face) may modulate $D_{perceived}$ in healthy participants in comparison to stimuli of neutral affect (e.g., neutral face), while neither might show an effect for $D_{perceived}$ in depressed patients, suggesting that interval timing in the respective patient group is characterized by function reduction.

A straightforward way to test whether interval timing deficits in a disorder are related to impaired factor alterations would be to correlate interval timing performance with the extent of factor alteration. For instance, the relationship between abnormal interval timing and degree of circadian cycle deviation in schizophrenia could be directly tested. Predictions would be that (1) the mean responses in a duration perception task would differ between the patient and the control group; (2) these groups would also differ in the circadian cycle patterns; and (3) there would be a significant two-way interaction between experimental group and measures of circadian cycle variation, in that circadian cycle variation would only have an effect on performance in the control group, not in the schizophrenia group, or have different effects in the two groups. Furthermore, (4) duration-perception deficits would be correlated to circadian cycle dysfunctions in the patient group.

Finally, despite some intriguing similarities between duration perception in natural or induced alterations and psychiatric conditions, many comparisons, such as between hypnosis and depression, remain largely suggestive. Various methodological problems unique to each field of research and different temporal intervals or behavioral timing tasks used in various studies add to the inconsistency of findings and the lack of successful replications. For instance, many participants with depression are on medication at the time of testing without a possibility of statistically controlling for certain types of medication due to a small number of patients taking the same type of medication (as discussed in Bschor et al., 2004). Secondly, studies of depression and duration processing have almost exclusively used test durations in the range of several seconds, whereas hypnosis studies frequently test the range of several minutes. Thirdly, the tasks used to assess duration processing in depression are frequently based on motor timing or duration production tasks rather than mere duration perception (see Gil and Droit-Volet 2009). Consequently, the literature on the effect of depression on duration perception is not unequivocal; various studies show a modulation of duration processing by depression (e.g., Bschor et al., 2004; Sévigny, Everett, & Grondin, 2003), in contrast to several other studies that do not find such effects (e.g., Bech, 1975; Hawkins et al., 1988). These inconsistencies will only be overcome by systemizing $D_{perceived}$ research in various fields by means of employment of the same task battery, including a range of absolute time scales, modalities, and response types.

25.7 Conclusion

A number of studies show that perception of duration can change depending on various natural contexts, under certain altered states of mind or in psychiatric disorders. In this chapter, we have provided a formal framework for how variability of duration perception in diverse neurocognitive alterations, natural, induced, or pathological, could be related and how intriguing similarities and differences of perceived duration in these states could be further investigated. This conceptual formalization allows a generation of predictions with respect to interval-timing modulating factors, which will need to be validated by future research. Despite numerous forms of alterations, human interval timing is precise on average. The enigma of how the brain achieves such accuracy despite various $D_{perceived}$ alterations remains unresolved.

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Notes

1. “Involutional melancholia”—a traditional name, mostly used in the first half of the twentieth century for a form of depression that occurs in late middle age (40–55 in women and 50–65 in men). It is frequently accompanied by paranoia, and its symptoms include somatization and hypochondriasis (Brown et al., 1984).

2. Temporal bisection tasks usually consist of two phases. First, participants are taught to discriminate between two standard stimuli of different durations (one “short” and one “long”) in the training phase. In the subsequent testing phase, participants are presented with probes of varying durations and have to decide which standard category they belong to (i.e., “short” or “long”).

3. The mismatch negativity is a neurophysiological index of the detection of a deviating stimulus in a sequence of standard stimuli. It is calculated by subtracting event-related potentials to the standard stimuli from potentials to the deviating stimuli.

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26 Time Processing in Developmental Disorders: A Comparative View

Christine M. Falter and Valdas Noreika

26.1 Developmental Disorders: Primary and Secondary Dysfunctions

Developmental disorders typically manifest themselves during infancy or childhood. In contrast to disorders acquired in adulthood, disorders with an onset early in development can lead to further cascading effects on brain functions that are not primarily affected by influencing the pace and direction of developmental trajectories. Dysfunctions associated with developmental disorders are not confined to the specific diagnostic features as set out in the diagnostic classification systems (DSM-IV-TR, APA, 2000; ICD-10, WHO, 1993). Secondary dysfunctions in general domains such as impaired perception, cognition, or motor processing are common. This chapter will be concerned with the role of secondary dysfunctions in the time processing domain that are relevant for three developmental disorders: developmental dyslexia, attention-deficit/hyperactivity disorder (ADHD), and autism spectrum disorders (ASD).

Developmental dyslexia is a specific neurobehavioral disability characterized by a marked developmental delay in learning to read, write, and spell despite normal intelligence, adequate educational opportunities and instructions, and an absence of any major sensory conditions. The cause and neural basis of dyslexia remains an issue of controversy. One approach focuses on phonological awareness, which is the ability to represent or perceive the smallest speech segments (phonemes). A phonological deficit in developmental dyslexia (Snowling, 2000) has been suggested to lead to an inability to relate spoken language, or phonemes, to written language, or graphemes. Although the phonological deficit theory is generally supported, the causal relations within the pattern of dyslexic deficits remain unclear (e.g., Blau et al., 2009).

A theory that relates to the previous framework postulates a generalized sensory processing impairment underlying the phonological processing deficit. A particular deficit is hypothesized in the processing of rapidly changing sensory input that causes an inability to discriminate different phonemes, leading to an impairment of the development of phonological representations and abnormal phonological processing. It has been suggested (Stein, 2001) that the rapid sensory processing deficit in dyslexia might be due to a malfunctioning of the magnocellular pathway of the early visual system and its auditory equivalent. Indeed, findings of impairments in the processing of temporally modulated non–speech related auditory stimuli (e.g., Tallal, Miller, & Fitch, 1993; Stein, 2001) and possibly across sensory modalities (e.g., Laasonen, Service, & Virsu, 2001) have cast doubt on the assumption that dyslexia is a purely language-specific disorder. Nonetheless, the role of sensory processing abnormalities for phonological skills and reading impairment is still debated (e.g., Caylak, 2011; Ramus, 2003; Rosen, 2003; Valdois, Bosse, & Tainturier, 2004), for instance because of a lack of universality of sensory processing difficulties among patients diagnosed with dyslexia (see Ramus, 2003).

ADHD (DSM-IV-TR, APA, 2000), or hyperkinetic disorder (ICD-10, WHO, 1993), is a behavioral disorder that manifests during childhood and can persist into adulthood. The behavioral symptoms comprise inattention (e.g., a decreased ability to concentrate, being disorganized and forgetful), hyperactivity (e.g., inability to sit still, difficulty engaging in quiet activities), and impulsivity (e.g., inability to wait, acting without considering the consequences). The heterogeneity of ADHD is not only represented by different types of affected individuals, such as the predominantly inattentive type, the predominantly hyperactive-impulsive type, and the combined type, but associated features such as abnormal motor development (Pitcher, Piek, & Hay, 2003) and diverse language-related difficulties (Camarata & Gibson, 1999; Tirosh & Cohen, 1998) contribute as well.

ASD is an umbrella term for a spectrum of conditions characterized by qualitative impairments in social interaction, communication, and creativity. It has been established that additional nondiagnostic features in perception, motion, and cognition characterize ASD. For instance, many individuals with ASD show visual (Ashwin et al., 2009) and auditory hypersensitivity (Mottron et al., 2006). Research into visual cognition has found a pattern of deficits (e.g., Deruelle et al., 2004; Falter, Plaisted-Grant, & Davis, 2010) as well as superior abilities (e.g., Falter, Plaisted, & Davis, 2008; Plaisted, O'Riordan, & Baron-Cohen, 1998; Shah & Frith, 1983, 1993). Similarly, motor problems are often associated with ASD. For example, clumsiness is a typical symptom in ASD, and motor control problems have been frequently observed in children (e.g., Ming, Brimacombe, & Wagner, 2007) and adults with ASD (Sahlander, Mattsson, & Bejerot, 2008).

26.2 Does Time Processing Unify or Distinguish between Developmental Disorders?

Events in the world are temporally defined by their relation to each other, in the sense of simultaneity or succession and order (i.e., event timing), and by their absolute and relative duration (i.e., interval timing). Time processing is the perception or motor control, or both, of event timing and interval timing.

Strikingly, time processing deficits represent an aspect of cognitive malfunctioning that seems to be shared by many developmental disorders. The above-described disorders are otherwise distinct with respect to their individual primary symptom clusters. Hence, the question arises: What role do time processing abnormalities play in the causal chain leading to the cognitive and behavioral outcome of developmental disorders? The seeming unifying nature of time processing impairment, in contrast to the distinct individual diagnostic characteristics, renders it unlikely for abnormal time processing to become a marker of dyslexia, ADHD, or ASD. It might be rather an epiphenomenon of abnormal neurological development that is causally unrelated to primary symptoms.

However, to accept such a dismissal of time processing as an irrelevant by-product of abnormal neurodevelopmental pathways, it first needs to be clarified whether the developmental disorders in question are truly etiologically independent and whether they indeed share signatures of abnormal time processing. An exploration of the latter will be the focus of the current chapter, which discusses the universality of time processing abnormalities within each disorder and the specificity of abnormal time-processing *patterns* to dyslexia, ADHD, and ASD. Should time processing abnormalities not be shared by all developmental disorders (or their subtypes), then it may be possible to use specific signatures of time processing as cognitive markers distinguishing between distinct disorders or subtypes.

The question of etiological independence between the spectra of the three developmental disorders is beyond the scope of this chapter. Nevertheless, it should be mentioned that their complete distinctiveness is questionable. Studies into the genetic basis of developmental disorders suggest they might lie on genetic susceptibility spectra, which makes a link between them possible. Susceptibility genes might be shared, for instance, between ADHD and ASD (see Castellanos & Tannock, 2002). Similarly, an overlapping genetic basis has been suggested for reading disorders and ADHD (Willcutt et al., 2002), as well as for reading disorders and ASD (Pagnamenta et al., 2010). Consequently, the current chapter aims to evaluate the two possibilities of time-processing abnormalities as either a unifying characteristic of developmental disorders, or of time processing signatures representing distinguishing markers between those disorders.

26.3 Developmental Dyslexia

Tallal (1980; 1984) proposed that an impairment of auditory temporal processing in children with developmental dyslexia might underlie phonemic-processing difficulties. There have been vast numbers of studies investigating temporal-processing skills in children and adults with dyslexia since (see table 26.1), and the theory has been extended to the visual domain in terms of a general multimodal temporal-processing deficit (Farmer & Klein, 1995; Stein & Talcott, 1999).

However, a major problem has led to confusion in evaluating the literature on time processing in dyslexia: a lack of definition of terminology. The term “temporal processing” has been inflated and subsumes diverse paradigms and functions, a criticism first stated by Studdert-Kennedy and Mody (1995). They claimed that two diverse aspects, rate of processing and processing of rate, have been subsumed under the term “temporal processing.”

Table 26.1

Studies on explicit time processing in developmental dyslexia

Paradigm		Modality	Difference	Task	Study[a]
Event timing	**Temporal order**	aud	yes	Binaural tones (TOT[b])	Heath et al., 1999
		aud	yes	Binaural tones (TOT)	Cacace et al., 2000
		vis	yes	Geometric forms, same location (TOT)	
		vis	yes	Pair of bars, vertically arranged (0–0.210 s)	Hari et al., 2001
		vis	yes	Light flashes, spatially separated (TOT)	Laasonen et al., 2001
		aud	yes	Different pitch tones (TOT)	
		tactile	yes	Indentations of index/middle fingertips (TOT)	
		aud	yes	Linguistic stimuli (0.01/0.07/0.5 s)	Breier et al., 2002
		aud	no	Nonlinguistic stimuli (0.01/0.07/0.5 s)	
		aud	yes	TOJ of two different pitch tones (0.008–0.150 s)	Heiervang et al., 2002
		aud	yes	TOJ of 3, 4, or 5 different pitch tones (0.008–0.150 s)	
		aud-tactile	yes	Variation of procedure by Laasonen et al. 2001	Laasonen et al., 2002
		vis-tactile	yes		
		aud-vis	no		
		aud	yes	Reproduce order of two consonants	Rey et al., 2002
		aud	no	TOJ of two different pitch tones (0.008–0.305 s)	Share et al., 2002
		aud	yes	TOJ of two different pitch tones (0.428 s)	
		aud	yes	4-AFC[c] of stimulus sequences (0.01–0.3 s), different pitch tones	Bretherton & Holmes, 2003
		vis	yes	4-AFC[c] of stimulus sequences (0.01–0.3 s), visual symbols	
		aud	no	Identify odd one out of four intervals of stimulus pairs (different pitch tones) (0.02/0.2 s)	Griffiths et al., 2003
		aud-tactile	yes	See Laasonen et al. (2002)	Virsu et al., 2003
		vis-tactile	yes		
		aud-vis	yes		
		aud	yes	4-AFC of stimulus sequences (0.08–0.15 s), different pitch tones	Ben-Artzi et al., 2005
		vis	yes	Pair of circles, vertically arranged (TOT)	Hairston et al., 2005
		aud	yes	Different pitch tones (0.008–0.305 s)	Chung et al., 2008
		vis	yes	Pair of circles and crosses (0.008–0.305 s)	
		vis	yes	Horizontally and vertically arranged rectangles (0–0.188 s)	Jaśkowski & Rusiak, 2008
		vis	yes	Geometric forms, lateralized (0.015–0.105 s)	Liddle et al., 2009

	Simultaneity	aud	yes	Tone-onset time (0–0.06 s)	Breier et al., 2001
		aud	yes	Voice-onset time (0–0.06 s)	
		vis	yes	Light flashes, spatially separated (ST^{d})	Laasonen et al., 2001
		aud	yes	Different pitch tones (ST^{d})	
		tactile	yes	Indentations of index/middle fingertips (ST^{d})	
		aud-tactile	yes	Variation of procedure by Laasonen et al. (2001)	Laasonen et al., 2002
		vis-tactile	yes		
		aud-vis	no		
		aud	yes	Tone-onset asynchrony detection thresholds	Breier et al., 2003
		aud-tactile	yes	See Laasonen et al. (2002)	Virsu et al., 2003
		vis-tactile	yes		
		aud-vis	yes		
		vis	no^{e}	Vertical bars, lateralized (0–0.110 s)	Shanagher & Elliott, 2006
Interval timing	**Perceptual**	aud	yes	Duration discrimination (0.4–2 s)	Nicolson et al., 1995
		–	no	Prospective duration estimation, passive (30 s)	McGee et al., 2004
		–	no	Prospective duration estimation, active (30 s)	
		–	no	Retrospective duration estimation, active (14 min)	
		aud	yes	Rhythm pattern discrimination, linguistic and nonlinguistic stimuli	Meyler & Breznitz, 2005
		vis	yes		
		aud-vis	yes		
		aud	yes	Event-related potential (mismatch negativity) study (0.1/0.033 s)	Corbera et al., 2006
		aud	yes	Adaptive duration discrimination (0.4–0.64 s)	Thomson et al., 2006
		aud	no	Tempi discrimination	
		vis	yes^{f}	Duration discrimination (0.1–1 s)	Johnston et al., 2008
		aud	yes	Adaptive duration discrimination (0.16 s)	Thomson & Goswami, 2008
		aud	no	Tempi discrimination	
		aud	yes	Duration discrimination (0.3/0.6 s and 0.2/0.4 s)	Murphy & Schochat, 2009
		aud	yes	Duration ordering (0.3/0.6 s and 0.2/0.4 s)	
	Motor	aud	yes	Synchronized tapping with tones (0.5/0.67 s)	Wolff, 2002
		aud	yes	Synchronized tapping, incremental (from 0.5/0.67 s)	
		aud	yes	Reproduction of rhythmic patterns (0.25/0.5 s)	
		aud	yes	Reproduction of speech rhythm	

Table 26.1

(Continued)

Paradigm	Modality	Difference	Task	Study[a]
	–	no	Free tapping	Tiffin-Richards et al., 2004
	aud—aud	no	Synchronized tapping (0.263–1 s)	
		no	Continuation after tones (0.263–1 s)	
		no	Rhythm reproduction	
	aud	yes[g]	Synchronized tapping with tones (1.5/2/2.5 Hz)	Thomson et al., 2006
	–	no	Continuation after tones (1.5/2/2.5 Hz)	
	aud	yes[g]	Synchronized tapping with tones (1.5/2/2.5 Hz)	Thomson & Goswami, 2008
	–	no	Continuation after tones (1.5/2/2.5 Hz)	

a. Not included are studies from before 1995, which have been mentioned in a comprehensive review by Farmer and Klein (1995).

b. Temporal order threshold.

c. Four-alternative forced choice task.

d. Simultaneity threshold.

e. There was a response bias toward nonsimultaneity in individuals with dyslexia (see main text).

f. Individuals with dyslexia did not show the typical distortion of duration perception after adaptation to invisible flicker (60 Hz).

g. Although between-group mean performance did not differ, variability was found to be larger in the ADHD group compared to controls.

Indeed, a distinction needs to be made between the perception of time or of temporal aspects of stimuli and the speed of neuronal processes. Given that the purpose of this chapter is to provide a comparative overview of time processing abnormalities across developmental disorders, we will *not* discuss temporal processing in its broadest sense, as it is referred to in the dyslexia literature, and we do not aim to reach an evaluation of its relevance for phonological processing in dyslexia. We rather confine our overview to explicit interval- and event-timing tasks, which have been tested in dyslexia as well as ADHD and ASD and therefore allow a comparison across disorders. Explicit time processing refers to those tasks that require participants to explicitly attend to the temporal aspects of stimulation and make judgments about them or produce motor output in unison with them (Coull & Nobre, 2008). Although relevant for dyslexia and phonological processing, other auditory tasks such as dynamic auditory processing (e.g., Vandermosten et al., 2010), frequency modulation (e.g., Dawes et al., 2009), motion perception (e.g., Talcott et al., 2000), or any tasks involving the processing of speech sounds (e.g., Rey et al. 2002) will not be discussed in this chapter, since they are not comparable to tasks used in other developmental disorders discussed.

26.3.1 Review of Event Timing in Developmental Dyslexia

In a review of time processing studies conducted since the early work by Tallal (1980), Farmer and Klein (1995) were able to confirm an impairment of auditory temporal order judgment (TOJ) in dyslexia. In contrast, evidence for a visual TOJ impairment was conflicting according to the authors, although their review suggested it is impaired in younger and strongly affected individuals with dyslexia. Since then several studies have corroborated a deficit in auditory TOJ (Ben-Artzi, Fostick, & Babkoff, 2005; Bretherton, & Holmes, 2003; Cacace et al., 2000; Chung et al., 2008; Heath, Hogben & Clark, 1999; Heiervang, Stevenson, & Hugdahl, 2002; Laasonen et al., 2001; Rey et al., 2002; Share et al., 2002; but see Share et al. 2002 for short intervals and Griffiths et al. 2003), as well as visual TOJ (Bretherton & Holmes, 2003; Cacace et al., 2000; Chung et al., 2008; Hairston et al., 2005; Hari, Renvall, & Tanskanen, 2001; Jaśkowski, & Rusiak, 2008; Laasonen et al., 2001; Liddle et al., 2009), and crossmodal TOJ (Laasonen, Service, & Virsu, 2002; Virsu, Lahti-Nuuttila, & Laasonen, 2003). The question remains, though, to what extent visual and auditory TOJ deficits are associated in the same individuals. Cestnick (2001) performed a correlation study to assess this question, and found that only in one type of dyslexia (phonological dyslexia, but not surface dyslexia) were visual and auditory TOJ related. Bretherton and Holmes (2003) divided their participants with dyslexia into poor and average performers on an auditory TOJ task and found no difference between the two groups on a visual TOJ task, which speaks against an association between time processing abnormalities in both modalities.

Despite the majority of studies on TOJ in dyslexia showing impairment in comparison to controls, Griffiths et al. (2003) did not replicate this finding. Participants were presented with four pairs of tones in each trial. Three tone pairs consisted of a leading standard-frequency tone followed by a higher-frequency tone, whereas the target tone pair was characterized by reversed order of frequencies. The two tones within a pair were separated either by 20 or 200 ms. The frequency of the tones was varied to determine a threshold for each participant. Individuals with dyslexia were equally able as controls to detect the target tone pair, and no difference in threshold was found. In contrast to other studies, the task used by Griffiths et al. (2003) arguably loaded more on pitch processing than event timing, which could be responsible for the discrepant results.

Compared to the TOJ literature, studies on simultaneity perception are much more scarce in dyslexia research, with most of the studies conducted by one research group (Laasonen et al., 2001, 2002; Virsu et al., 2003). They found evidence for impaired performance on visual, auditory, tactile, and crossmodal simultaneity judgments in individuals with dyslexia. In another study on perceptual simultaneity, Shanagher and Elliott (2006) did not replicate an abnormal simultaneity threshold in dyslexia. However, they found that individuals with dyslexia showed a response bias toward non-simultaneity when asked to report whether two bars were presented simultaneously or not. This bias, the authors argued, might be a sign of sensitivity to event timing being attenuated in dyslexia, which does not necessarily need to be reflected in threshold shifts. Concerning a relation between modalities for simultaneity task performance, Laasonen et al. (2002) report an association between different crossmodal simultaneity tasks as revealed by a principle component analysis.

26.3.2 Review of Interval Timing in Developmental Dyslexia

Only in the past few years has interval timing become a topic of interest in dyslexia studies. Several studies tested perceptual interval timing in dyslexia (Corbera, Escera, & Artigas, 2006; Johnston et al., 2008; Murphy, & Schochat, 2009; Nicolson, Fawcett, & Dean, 1995; Thomson et al., 2006; Thomson & Goswami, 2008; but see McGee et al., 2004). McGee et al. (2004) tested amodal duration estimation of longer intervals (30 s, 14 min) and found that individuals with a reading disorder were unimpaired. However, several studies show group differences when auditory stimuli are employed (Corbera et al., 2006; Murphy & Schochat, 2009; Nicolson et al., 1995; Thomson & Goswami, 2008; Thomson et al., 2006). For instance, adults with dyslexia have been found to have higher auditory duration–discrimination thresholds than controls (Thomson et al., 2006; Thomson & Goswami, 2008). An early study tested for a cerebellar involvement in the disorder by assessing auditory duration comparisons in the range of 400–2000 ms (Nicolson et al., 1995). Although performance in a loudness-estimation task was typical in individuals with dyslexia in three age groups (9, 14, and 18 years), they were impaired on the duration task in comparison to chronological-, mental-, and reading age–matched controls. These behavioral findings are corroborated by an event-related potential study showing that children with dyslexia were impaired on duration discrimination and demonstrated abnormal mismatch negativity (MMN) amplitudes for deviant durations (33 ms) in a series of standard (100 ms) durations (Corbera et al., 2006).

The only study assessing duration discrimination in the visual domain (Johnston et al., 2008) used a task that typically taps magnocellular functioning. Invisible flicker adaptation typically reduces the perceived duration of a stimulus in controls, but this was not the case in individuals with dyslexia. This abnormal finding was restricted to 60 Hz flicker, though, which suggests that there is no general absence of flicker adaptation in dyslexia. This finding confirms earlier reports of lower flicker-fusion thresholds in dyslexia (Talcott et al., 1998).

The literature on motor timing in dyslexia is also confined to a few studies (Meyler & Breznitz, 2005; Thomson et al., 2006; Thomson & Goswami, 2008; Tiffin-Richards et al., 2004; Wolff, 2002) and shows complex findings. Wolff (2002) reports that students with dyslexia anticipated metronome beats in a tapping task by intervals 3–4 times as long as those shown by controls and had more difficulties tracking beats when these were incremented. In addition, individuals with dyslexia were impaired in reproducing rhythms with even greater difficulties when rhythmic patterns needed to be synchronized to a metronome. In contrast, Thomson et al. (2006) and Thomson and Goswami (2008) did not find group differences in anticipation time. This discrepancy in findings might have been due to procedural differences, as argued by the authors. However, significantly increased intra-individual variability was found in individuals with dyslexia by Thomson et al. (2006), and significant group differences in mean discrepancy of actual and expected intervals as well as increased intra-individual variability for 2 Hz and 2.5 Hz were found by Thomson and Goswami (2008).

The abnormalities in rhythm-reproduction tasks (Wolff, 2002) are corroborated by a perceptual rhythm study by Meyler and Breznitz (2005) testing rhythm discrimination and showing deficits for adults with dyslexia in the auditory, visual, and crossmodal domain for both linguistic and nonlinguistic stimuli. In contrast, though, there was no threshold difference in dyslexia in an auditory tempi comparison task in which participants had to compare stimuli of same or different interstimulus intervals (ISIs; Thomson et al., 2006; Thomson & Goswami, 2008). It may well be that the comparison of complex rhythmic patterns is more challenging for individuals with dyslexia than simple discrimination between tempi.

In contrast to the studies described above, reproduction of rhythmic patterns as well as free, synchronized, and continued tapping were unimpaired in dyslexia in a study by Tiffin-Richards et al. (2004), who found only slightly worse performance in dyslexia confined to more complex rhythmic patterns, but without significant group differences. The sample size (dyslexia, $N = 17$; dyslexia and ADHD, $N = 17$) tested in the study by Tiffin-Richards et al. (2004) was not that different from those tested in the other studies, precluding the possibility of a lack of statistical power. Ideally, in future research both expressive and perceived timing of rhythm speeds (tempi) as well as rhythmic patterns should be tested in the same individuals in order to clarify previous results.

26.3.3 Discussion of Time Processing in Developmental Dyslexia

The current review confirms Farmer and Klein's (1995) proposal that an auditory time processing deficit is a feature of dyslexia, and it shows that this deficit can be extended to the visual domain. In fact, evidence of a time processing impairment in dyslexia is particularly striking concerning event timing. With the exception of a few findings (e.g., Griffiths et al., 2003), there is agreement that an auditory as well as visual abnormality of event timing is one characteristic of dyslexia. Furthermore, although the findings are not as clear as those for event timing, interval timing seems to be deficient in dyslexia as well. For longer intervals in the range of several seconds to minutes, no impairment has been found in dyslexia (McGee et al., 2004), and motor-timing tasks yielded variable results. However, there is overall converging evidence for a deficit of processing intervals in the range of hundreds of milliseconds.

Importantly, though, it is frequently found that only a subgroup of participants is affected by deficient timing task performance, and direct evidence for an interrelation of visual and auditory time processing abnormalities is scarce and contradictory. In addition, between-group differences may be caused by greater performance variability in dyslexia, while a large overlap of performance values can often be observed between dyslexia and control groups (e.g., Laasonen et al., 2001, 2002).

The use of a variety of tasks with unknown construct validity, a lack of agreement regarding the definition of temporal processing, and the inclusion of subgroups with differences in performance profiles and possibly different etiological pathways might go a long way in explaining inconsistencies in the literature on time processing in dyslexia. Yet research over the previous decades allows the conclusion that a majority of individuals with dyslexia indeed show time processing abnormalities of nonverbal stimuli, in particular concerning event timing, pointing to a domain-general impairment. Whether this subgroup represents phonological dyslexics as opposed to surface dyslexics, as suggested by Cestnick (2001), remains to be investigated further. It should be acknowledged that the common consensus in developmental dyslexia research is that dyslexic impairments lie on a continuum rather than falling into clear-cut categories (Harley, 2001), posing a particular challenge for relating temporal-processing difficulties to any particular subtype of dyslexia.

In summary, nonphonological impairments of time processing undoubtedly exist in developmental dyslexia in both the visual and auditory domains. Although a causal role cannot be confirmed by the current state of knowledge and an in-depth discussion thereof is beyond the scope of this chapter, time processing impairments might be considered as vulnerability factors that should be accounted for by a comprehensive etiological theory.

26.4 Attention-Deficit/Hyperactivity Disorder

In an influential study, Barkley (1997) conceptualized ADHD as a disorder of impaired behavioral inhibition that manifests in four executive neuropsychological functions:

working memory, self-regulation of affect-motivation-arousal, internalization of speech, and reconstitution of behavior. Among the eight secondary impairments of working memory, Barkley (1997) included deficient sense of time and several other time-related cognitive functions: retrospective function, prospective function, anticipatory set, and cross-temporal integration of behavior. Barkley's model inspired many studies on time processing in ADHD that consisted almost exclusively of studies testing various aspects of perceptual and motor timing of intervals.

Moreover, implicit time processing that is not consciously accessible but can be tracked behaviorally (van Wassenhove, 2009) might function abnormally in ADHD, as suggested by performance in temporal-discounting tasks. In such tasks, participants have to choose between small immediate rewards and larger rewards after a certain delay. It has been reported that individuals with ADHD show a stronger preference for immediate over delayed rewards than controls (for a review see Luman, Oosterlaan, & Sergeant, 2005).

Overall, timing mechanisms seem to function abnormally in individuals with ADHD. In this section, we review studies on explicit time perception (see table 26.2) and its relation to other behavioral characteristics in ADHD.

26.4.1 Review of Event Timing in Attention-Deficit/Hyperactivity Disorder

Very few studies have assessed perception of event timing in ADHD. Visual simultaneity thresholds were tested in 8 participants with ADHD (mean age 14 years) and age- and gender-matched control participants (Brown & Vickers, 2004). ADHD participants were tested on medication and 48 hours after the last dose (6 received treatment with methylphenidate [MPH] and 2 with dextroamphetamine) in counterbalanced order. There was neither a group difference between the ADHD and the control group nor an effect of medication. Interpretation of these results is impeded by the very small sample size, which might not have allowed for adequate power to detect group differences. However, auditory temporal-order judgments (10, 70, and 500 ms) on speech and nonspeech stimuli were tested in 29 children with ADHD, 38 children with reading disorder, 32 children with combined ADHD and reading disorder, and 43 typically developing children (all aged 7–14 years; Breier et al., 2002). Children with ADHD did not perform differently from controls in any of the tasks.

The only study reporting impaired performance in an event-timing task in ADHD tested thresholds of tone-onset asynchrony detection (Breier et al., 2003). However, performance was reduced in all of the employed tasks in individuals with ADHD and was not specific to timing tasks. In summary, event timing seems to be unimpaired in ADHD.

26.4.2 Review of Interval Timing in Attention-Deficit/Hyperactivity Disorder

Time seems to run slower for people with ADHD, and a characteristic response of a child with ADHD after a 14 min task is "Oh! That took 3 hours!" (McGee et al., 2004, 488). A chronic overestimation of duration, which is often demonstrated as underreproduction of a given interval, is one of the most often proclaimed findings in ADHD studies of time

Table 26.2

Studies on explicit time processing in attention deficit/hyperactivity disorder

Paradigm		Modality	Difference	Task	Study
Event timing	**Temporal order**	aud	no	Linguistic stimuli (0.01/0.07/0.5 s)	Breier et al., 2002
		aud	no	Nonlinguistic stimuli (0.01/0.07/0.5 s)	
	Simultaneity	aud	no	Tone-onset time (0–0.06 s)	Breier et al., 2001
		aud	no	Voice-onset time (0–0.06 s)	
		aud	yes	Tone-onset asynchrony detection thresholds	Breier et al., 2003
		vis	no	Judging simultaneity of flashes	Brown & Vickers, 2004
Interval timing	**Perceptual**	–	yes	Duration reproduction (12–60 sec)	Barkley et al., 1997
		vis	yes	Duration production (5/15 sec)	Sonuga-Barke et al., 1998
		vis	yes	Anticipation (5, 15 sec)	
		vis	no	Duration discrimination (3, 5 s);	Rubia et al., 1999
		vis	(yes)[a]	Anticipation (6 s);	
		vis	yes	Duration reproduction (0.5–6 s)	West et al., 2000
		aud	no		
		–	yes[b]	Duration estimation (2–60 s)	Barkley et al., 2001a
		–	yes	Duration reproduction (2–60 s)	
		–	no	Duration estimation (2–60 s)	Barkley et al., 2001b
		–	yes	Duration reproduction (2–60 s)	
		vis	yes	Duration reproduction (3–17 sec)	Kerns et al., 2001
		vis	yes	Duration discrimination threshold	Smith et al., 2002
		vis	yes[b]	Duration reproduction (12 sec)	
		vis	no	Duration reproduction (5 sec)	
		–	no	Duration estimation (10 sec)	
		vis	yes	Duration reproduction (3–17 s)	McInerney & Kerns, 2003
		vis	yes	Duration discrimination (3, 5 s);	Rubia et al., 2003
		vis	(yes)[a]	Anticipation (6 s);	
		vis	no	Retrospective duration estimation (3–24 s)	Meaux & Chelonis, 2003
		vis	yes	Duration reproduction (3–24 s)	
		aud	yes	Unfilled interval discrimination thresholds; children	Toplak et al., 2003
		aud	yes	Unfilled interval reproduction (0.4/2/6 s); children	
		aud	yes	Unfilled interval discrimination thresholds; adolescents	
		aud	(yes)[a]	Unfilled interval reproduction (0.4/2/6 s); adolescents	

–	no	Prospective duration estimation, passive (30 s)	McGee et al., 2004
–	no	Prospective duration estimation, active (30 s)	
–	yes	Retrospective duration estimation, active (14 min)	
aud	no	Unfilled interval discrimination (0.55 s)	Radonovich & Mostofsky, 2004
aud	yes	Unfilled interval discrimination (4 s)	
vis	no	Duration estimation (6–33 s)	Bauermeister et al., 2005
vis	yes	Duration reproduction (6–33 s)	
vis	yes	Duration reproduction (2–60 s)	Mullins et al., 2005
aud	yes	Duration discrimination thresholds (0.2/1 s)	Toplak & Tannock, 2005a
vis	yes		
vis	yes[c]	Anticipation (0.4/1/2 s)	Toplak & Tannock, 2005b
vis	yes	Duration discrimination (1–1.5 s)	Rubia et al., 2007
vis	yes	Duration reproduction (4–20 s)	Rommelse et al., 2007
aud	yes		
vis	yes	Unfilled interval discrimination (0.3–1.2 s)	Yang et al., 2007
vis	yes	Duration reproduction (2.5–5.5 s)	González-Garrido et al., 2008
aud	yes	Duration reproduction (1 s)	Rommelse et al., 2008
aud-vis	yes	Duration reproduction (1–60 s)	Plummer & Humphrey, 2009
vis	no	Duration discrimination (1–1.5 s)	Rubia et al., 2009
vis	yes	Retrospective duration estimation (3–90 s)	Hurks & Hendriksen, 2010
vis	yes	Duration reproduction (3–90 s)	
vis	yes	Duration reproduction (5–17 s)	Hwang et al., 2010
–	yes	Duration production (2–48 s)	Marx et al., 2010
vis	yes	Duration reproduction (2–48 s)	
vis	yes	Duration discrimination thresholds (1 s standard)	
vis	yes	Duration discrimination (0.45–1 s)	Valko et al., 2010
vis	yes	Duration reproduction (1–8 s)	
aud	yes	Duration discrimination thresholds (0.4–1.2 s)	Gooch et al., 2011
vis	yes	Duration reproduction (2–10 s)	
aud	yes	Duration production (1–24 s)	Huang et al., 2012
vis	yes	Duration reproduction (3–45 s)	
vis	yes	Duration discrimination thresholds (0.3–1.2 s)	

Table 26.2
(Continued)

Paradigm	Modality	Difference	Task	Study
Motor	–	(yes)[a]	Free tapping	Rubia et al., 1999
	vis	(yes)[a]	Synchronized tapping (0.7–1.8 s)	
	aud	no	Synchronized tapping with tones (0.3/0.6 s)	Vongher et al., 2001
	–	(yes)[a]	Continuation after tones (0.3/0.6 s)	
	aud	yes	Synchronized tapping (0.3 sec)	Pitcher et al., 2003
	aud/vis	yes	Synchronized tapping (adjusting to variable frequency of 1–6 Hz)	Ben-Pazi et al., 2003
	–	(yes)[a]	Free tapping	Rubia et al., 2003
	vis	(yes)[a]	Synchronized tapping (0.7–1.8 s)	
	–	no	Free tapping	Tiffin-Richards et al., 2004
	aud—aud	no	Synchronized tapping (0.263–1 s)	
		no	Continuation after tones (0.263–1 s)	
		no	Rhythm reproduction	
	aud	no	Synchronized and continued tapping (0.4/1 s)	Toplak & Tannock, 2005b
	vis	(yes)[ad]		
	aud-vis	(yes)[a]	Synchronized tapping (0.2–1 s)	Ben-Pazi et al., 2006
	aud	(yes)[a]	Synchronized tapping (1–2 s)	Gilden & Marusich, 2009
	aud	(yes)[a]	Synchronized tapping (0.5 s)	Zelaznik et al., 2012

a. Although between-group mean performance did not differ, variability was found to be larger in the ADHD group compared to the controls.

b. These tasks initially yielded significant group differences, but were not significant after IQ was controlled for.

c. Group difference found for 2 s only.

d. Group difference found for 1 s only.

(Barkley et al., 1997; Barkley, Murphy, & Bush, 2001b; Huang et al., 2012; Hurks & Hendriksen, 2010; González-Garrido et al., 2008; Kerns, McInerney,& Wilde, 2001; Marx et al., 2010; McInerney & Kerns, 2003; Mullins et al., 2005; Smith et al., 2002; Valko et al., 2010; West et al., 2000; however see Barkley et al., 1997; McInerney & Kerns, 2003; Plummer & Humphrey, 2009; Toplak et al., 2003; West et al., 2000, who found overreproduction of intervals among participants with ADHD). For instance, Kerns et al. (2001) asked 21 children with ADHD, aged between 6 and 13 years, and 21 typically developing controls to reproduce the duration of a light bulb appearing on a computer screen for a 3, 5, 6, 9, 12, or 17 s interval. The ADHD group reproduced shorter intervals than the control group, even though both groups underreproduced the target intervals. Similarly, in one of the largest studies on this topic, 160 participants were instructed to reproduce a specific interval, of 2, 4, 12, 15, 45, or 60 s, by telling the experimenter when the interval should start and when it should end (Barkley et al. 2001b). The ADHD group ($N = 97$) underreproduced all given intervals and performed significantly differently from the control group for 15 and 60 s intervals. These findings could not be explained by the IQ scores, which are often lower in ADHD, as additional control for IQ did not change time-reproduction results. Similarly, in a computer game simulation test, 22 children with ADHD (aged 7–14 years) reproduced the target interval of 12 s as shorter intervals than 22 typically developing controls (Smith et al., 2002). Contrary to the earlier report by Barkley et al. (2001b), this finding missed significance after controlling for IQ and short-term memory scores, but nevertheless still showed a strong trend ($p = 0.056$). For a similar game with a 5 s target interval, there was no difference between the groups. Therefore, the authors suggested that time deficits in ADHD are linked to impulsivity and related cognitive processes that load more heavily on relatively longer durations.

The described studies seem to support the initial notion that subjective time runs slower in people with ADHD. Nevertheless, the interpretation of such studies is not unequivocal, since duration-reproduction paradigms do not distinguish between cognitive and motor components of time processing. Subjective overestimation of duration is arguably more evident in tasks presenting only single intervals (i.e., interval estimation rather than comparison or production). For example, McGee et al. (2004) performed a retrospective interval-estimation study with 43 children with ADHD, 45 children with reading disorder, and 42 clinical controls without ADHD or reading disorder. All children underwent a continuous performance test lasting 14 minutes. The ADHD group made significantly longer and more variable estimates of how long the test took as compared to the group with reading disorder and the clinical control group. Similar findings for suprasecond intervals were reported by Barkley et al. (2001b) and Hurks and Hendriksen (2010). However, four other studies did not find significant differences in duration estimation between ADHD and control groups (Barkley et al., 2001a; Bauermeister et al., 2005; Meaux & Chelonis, 2003; Smith et al., 2002).

The interpretation of interval timing abnormalities in ADHD is further complicated by inconsistencies of impairments for some but not all durations (e.g., Barkley et al., 1997;

Barkley et al., 2001b; Huang et al., 2012; Hurks & Hendriksen, 2010; Hwang et al., 2010; Marx et al., 2010; Sonuga-Barke, Saxton, & Hall, 1998; Sonuga-Barke, 2002). For example, Barkley et al. (1997) reported the reversal of error direction when children (aged 6–14 years) were instructed to reproduce intervals for a given target of 12, 24, 36, 48, and 60 s, with distraction occurring in half of the trials. Compared to typical controls (*N* = 26), the ADHD group (*N* = 12) overreproduced short durations, underreproduced long durations, and was precise in reproduction of the middle 36 s interval. Similar high response accuracy at the medium duration but no reversal of error was reported by Sonuga-Barke (2002), who asked participants to view target stimuli for 5, 10, or 15 s and then to find the target stimulus in an array of 6 stimuli. Twelve children with hyperactive and 10 children with combined ADHD (8–12 years) gave fewer correct responses for 5 s and 15 s trials, while there was no difference between them and a typically developing control group for 10 s trials. In another study, hyperactive children more often overestimated 5 s intervals, but more often underestimated 15 s intervals (Sonuga-Barke et al., 1998).

Most duration-discrimination studies suggest that time processing deficits might not only occur for suprasecond durations but seem to occur within the millisecond range as well (Gooch, Snowling, & Hulme, 2011; Huang et al., 2012; Marx et al., 2010; Rubia et al., 2007; Smith et al., 2002; Toplak et al., 2003; Toplak & Tannock, 2005a; Valko et al., 2010; Yang et al., 2007). Smith et al. (2002) demonstrated that individuals with ADHD have higher visual duration-discrimination thresholds (i.e., the shortest duration difference between two stimuli that is required to reliably differentiate them) than controls (190 vs. 240 ms). The standard stimuli they used were 1,000 ms, and the comparison stimuli changed in 15 ms steps starting from 1,300 ms. Likewise, Toplak and Tannock (2005a) reported that ADHD participants have higher discrimination thresholds than controls for 200 ms and 1000 ms standards in both visual and auditory tasks. Similarly, Yang et al. (2007) showed that a group of 40 children with ADHD (mean age 8 years) showed higher discrimination thresholds than a group of 40 typically developing children at each of the tested standard intervals, 300 ms, 800 ms, and 1200 ms. Although the ADHD group had significantly lower IQ scores than the control group, the group differences on discrimination thresholds remained after taking IQ differences into account. Similar to the earlier report by Toplak and Tannock (2005a), the largest effect size of group differences was found in the 1,200 ms standard condition (Yang et al. 2007).

In an fMRI study, 12 typical controls (11–16 years) and 12 children with ADHD (10–15 years) did not show a performance difference in comparing a visual standard stimulus of 1,000 ms and comparison stimuli of 1,300, 1,400, and 1,500 ms (Rubia et al., 2009). However, the lack of a group difference in performance scores in this study is in line with thresholds found in previous studies (e.g., 240 ms for 1,000 ms standard; Smith et al., 2002), which are lower than the smallest duration difference participants had to discriminate in the study by Rubia and colleagues. Hence, the observed performance might be due to a ceiling effect. Nevertheless, an analysis of brain activation for a contrast between the discrimination task and a temporal-order task showed several activation differences, such as enhanced activation in bilateral orbitofrontal cortex, caudate, and anterior cingulate gyrus in the control group compared to the ADHD group. Thus, even in the absence of a performance difference, abnormalities in the employed neuronal mechanisms are found in time processing in ADHD, which corroborates reports of impaired interval timing in ADHD, over and above performance differences.

Although averaged group differences (of tapping speed or synchronization) tend not to be found in motor-timing tasks, individuals with ADHD are often reported to show increased performance variability. Vongher et al. (2001) reported preliminary findings (no statistical testing applied) of a tapping task. They instructed 12 adult participants with ADHD and 5 typical controls to tap synchronously with tones occurring at a certain rhythm (300 or 600 ms interstimulus intervals) in one task phase. Then, in a second task phase, they were required to continue tapping at the same rhythm beyond the tone sequence. When compared to controls, the participants with ADHD showed higher variability during the continuation phase of 300 ms tapping in contrast to tapping in synchrony with the tones. Instead of tones, Rubia et al. (2003) used visual stimuli in a similar sensorimotor synchronization task. Thirteen children with ADHD (aged 7–11 years) had to synchronize their motor tapping with visual stimuli appearing at fixed interstimulus intervals: 700, 900, 1200, or 1800 ms. Variability of synchronization was found to be higher in ADHD participants than in controls. Similarly, higher intraindividual tapping variability in ADHD relative to controls was reported by several other studies (Ben-Pazi et al., 2006; Gilden & Marusich, 2009; Rubia et al., 1999; Toplak & Tannock, 2005b; Zelaznik et al., 2012), confirming the motor-timing deficit in ADHD. However, Tiffin-Richards et al. (2004) did not find any consistently increased variability in individuals with ADHD for free, synchronized, and continuation tapping as well as rhythm reproduction. One reason for this discrepancy suggested by Tiffin-Richards et al. (2004) could be that they tested older participants (aged 10–13 years). Indeed, individual variability has been suggested to decrease with age (Barkley 1997).

26.4.3 Discussion of Time Processing in Attention-Deficit/Hyperactivity Disorder

The described studies strongly suggest that interval timing is impaired in ADHD. Although some studies have employed auditory paradigms showing impaired performance in individuals with ADHD, the interval-timing impairment might be more pronounced in the visual domain. In contrast to interval timing, event-timing performance is usually found to be within a typical range in individuals with ADHD, although very few studies (mainly from one research group) have investigated event timing in ADHD (with only one study employing visual stimuli). Hence any conclusions are tentative.

An important question is whether performance in interval-timing tasks might be abnormal due to generalized working memory deficits rather than a timing deficit per se. The behavioral disinhibition model suggests that time deficits seen in people with ADHD are due to the impaired functioning of working memory. If so, then the extent of time deficits in

ADHD should be related to working memory impairments. In a relevant study that could inform this idea, Radonovich and Mostofsky (2004) tested time processing performance on a subsecond as well as a suprasecond scale, assuming the mechanism for the former to be based in the cerebellum and the latter to be performed by the frontal lobe. The tasks required participants to compare successive unfilled auditory intervals. The first interval was fixed to 550 ms in the short task version or 4 s in the long version, and the second interval was either shorter or longer than 550 ms or 4 s. A threshold was calculated from those intervals that a participant could reliably distinguish. The authors found normal performance for short interval discrimination (around 550 ms) and impaired performance for long interval discrimination (around 4 s) in 27 children with ADHD as compared to 15 typically developing children (aged 8–13 years). The authors compared the observed pattern of a difference in the long task version and the absence of a group difference in the short task version to the performance patterns seen in patients with frontal lobe lesions (Mangels, Ivry, and Shimizu 1998). They suggest this pattern to indicate that the abnormalities found in time processing tasks in ADHD might be due to working memory deficits rather than pure timing deficits.

However, in section 26.4.2 we reviewed several studies showing, in contrast to the study by Radonovich and Mostofsky (2004), that time processing deficits in ADHD can also be found on a millisecond scale (e.g., Smith et al., 2002; Toplak & Tannock, 2005a; Yang et al., 2007). The main difference between the paradigms used in these studies and that used by Radonovich and Mostofsky (2004) is that the latter used auditory stimuli, while most of the other studies used visual stimuli (although see the auditory deficit found by Toplak & Tannock, 2005a). In addition, the study by Radonovich and Mostofsky (2004) was the only one employing unfilled intervals, which might be processed by different mechanisms than filled intervals (Falter et al., 2009; Wearden et al., 2007).

Thus, the fact that several studies have shown abnormal time processing performance in the millisecond scale is at least suggestive evidence that working memory deficits might not be the sole factor associated with abnormal time processing in ADHD. In fact, several studies on time processing in the suprasecond scale suggest that time deficits in ADHD are not due to working memory dysfunctions. For instance, Kerns et al. (2001) instructed their participants to reproduce light stimuli of 3–17 s intervals. The analysis of coefficients of accuracy revealed that the ADHD group underestimated target duration, and also performed worse in behavioral inhibition and attention tasks when compared to controls. Yet no group differences were found in the working memory tasks.

Nevertheless, several studies still suggest that working memory might be associated with time processing in ADHD. Toplak and Tannock (2005a) reported several significant unimodal and crossmodal correlations between time discrimination (using 200 ms and 1000 ms standards) and working memory tasks in the ADHD group that were absent in the control group. McInerney and Kerns (2003) tested how time-reproduction performance changed in 30 children with ADHD (aged 6–13 years) and 30 controls when their motivation level was manipulated and how it related to working memory and inhibition test performance. They found that impairment of interval timing in the ADHD group could be ameliorated by increasing motivation, but not to the level of performance shown by controls. In addition, working memory and inhibition were found to predict performance to a large extent. However, after controlling for working memory and inhibition, the time-reproduction deficit persisted in the ADHD group.

Another way to investigate the clinical relevance of time processing and its relation to working memory is to test whether it is improved by MPH administration. MPH has been reported to enhance working memory function (e.g., Mehta, Goodyer, & Sahakian, 2004). In a carefully designed study with several timing tasks, Rubia et al. (2003) tested 13 children with ADHD at baseline, after placebo drug intake, after a single MPH dose, and after 4 weeks of multiple MPH administration. When compared to the placebo condition, multiple MPH administration accelerated tapping and reduced its variability, making the ADHD group more similar to the typically developing control group. Similarly, multiple MPH administration reduced variability of temporal anticipation (6 s) and the amount of related impulsive errors. There were no MPH effects on free tapping or a visual time discrimination task, however. Baldwin et al. (2004) explored how MPH treatment affects time processing in clinically referred children by giving them a motor-production task (10–14 s) at 1–2 hours after a single MPH dose as well as after an MPH-free period of at least 18 hours. MPH significantly decreased the variability of produced intervals, but the means of produced intervals did not differ between conditions, and a tendency to yield more correct responses under MPH did not reach significance ($p = .09$). To summarize, research into the role of MPH treatment for time processing performance in ADHD is still in its beginnings, but shows a tendency that MPH might reduce performance variability and impulsivity effects on responding.

In conclusion, MPH treatment studies suggest that time processing abnormalities in ADHD may be related to clinical symptoms of ADHD to a certain extent. However, many of the ADHD studies testing for relations between performance on time processing and working memory tasks did not find a significant association, suggesting that working memory problems might aggravate timing performance in ADHD but are not the sole factor causing abnormal performance on interval-timing tasks.

26.5 Autism Spectrum Disorders

In comparison to dyslexia and ADHD, ASD has only very recently been associated with time processing abnormalities, and comparably few studies exist that directly test time processing in ASD (see table 26.3). As mentioned in the introduction, the characteristics of ASD are not confined to the diagnostic triad of symptoms. ASD is additionally associated with symptoms such as dysfunctional motor coordination (dyspraxia), sleeping difficulties (e.g., Richdale & Schreck, 2009), and problems with planning ahead (Hill 2004). A range of perceptual abnormalities have also been reported, such as impaired perception of biological (e.g., Blake et al., 2003) and coherent motion (Milne et al., 2003), as well as an impairment

Table 26.3

Studies on explicit time processing in autism spectrum disorders

Paradigm		Modality	Difference	Task	Study
Event timing	**Temporal order**	vis	no	Temporal order judgment (0–0.5 s)	Kwakye et al., 2011
		aud	yes		
		aud-vis	yes		
	Simultaneity	aud-vis	yes	Linguistic stimuli	Bebko et al., 2006
			no	Nonlinguistic stimuli	
		vis	yes[a]	Perceptual simultaneity judgments (0–0.1 s)	Falter et al., 2012a
	Anticipation	vis	no	Timing judgment of internal and external events	Glazebrook et al., 2008
Interval timing	**Perceptual**	aud	no	Unfilled interval discrimination thresholds (0.55 s)	Mostofsky et al., 2000
		vis	yes	Duration reproduction (1–5.5 s)	Szelag et al., 2004
		aud	yes		
		–	no	Duration estimation (2–45 s)	Wallace & Happe, 2008
		–	no	Duration reproduction (2–45 s)	
		–	yes[a]	Duration production (2–45 s)	
		aud	no	Duration discrimination thresholds (0.64 s)	Jones et al., 2009
		aud	yes	Duration reproduction (0.5–4.1 s)	Martin et al., 2010
		vis	yes	Duration bisection task (1–8 s)	Allman et al., 2011
		vis	yes	Duration reproduction (0.5–45 s)	Maister & Plaisted-Grant, 2011
		vis	yes	Temporal generalization task (0.3–1.5 s)	Falter et al., 2012b
		aud			
	Motor	aud	yes	Synchronized tapping (0.4–0.8 s)	Gowen & Miall, 2005
		–	yes	Continuation after tones (0.4–0.8 s)	

a. Superior performance in the ASD group.

b. Same paradigm employed on children with autism (Lepistö et al. 2005), children with Asperger syndrome (Lepistö et al. 2006), and adults with Asperger syndrome (Kujala et al. 2007).

of integrating local features into a whole percept over time (Nakano et al., 2009). These symptoms might be characteristic of an abnormality in neuronal-timing functions and time processing (Welsh, Ahn, & Placantonakis, 2005; Wimpory, 2002). There are anecdotal and clinical reports suggesting that individuals with ASD lack an intuitive sense of time (Boucher, 2001). Instead, they have an abnormal experience of passage of time (Gepner & Feron, 2009) and an abnormal perspective of themselves in the past, present, and future (Zukauskas, Silton, & Assumpcao, 2009). Trevarthen and Daniel (2005) have described one of the first signs of childhood autism to be a desynchronization of social interactions with caregivers. Disorganized rhythms of coregulation of social behavior in children with ASD are suggested to cause frustration in the caregiver and further decrease attempts at social interaction with the affected child.

26.5.1 Review of Event Timing in Autism Spectrum Disorders

Individuals with ASD showed selective language-related insensitivity to event timing (Bebko et al., 2006). The reaction of 16 young children (aged 4–6 years) with ASD, 15 developmentally disabled children without ASD, and 16 typically developing children to audiovisual synchrony versus asynchrony was tested using a preferential looking paradigm. The stimuli involved nonlinguistic and linguistic events. In this study, the two control groups would look longer at the synchronous compared to the asynchronous display, irrespective of linguistic or nonlinguistic content, whereas the ASD group showed random looking behavior regarding linguistic stimuli. However, the ASD group looked longer at synchronous than asynchronous nonlinguistic content. Hence, the possibility cannot readily be excluded that the pattern of performance in the ASD group was due to impaired language skills rather than generalized time processing impairments (Bebko et al. 2006).

Finally, judgment of timing of internal (movement initiation) and external (tone) events was tested in 12 individuals with ASD and 12 controls without ASD by Glazebrook, Elliott, and Lyons (2008) using tasks similar to the original protocol by Libet, Gleason, Wright, and Pearl (1983). No difference in performance was found between the groups. However, firm conclusions cannot be drawn from this study, because the experimental and control groups were not matched by mental age and a subgroup of the ASD group was taking medication. In our own recent study on visual simultaneity judgments, 16 adolescents and adults with high-functioning autism and Asperger syndrome exhibited lower simultaneity thresholds than typically developing controls matched by mental and chronological age (Falter, Elliott, & Bailey, 2012a). Half of the ASD group had thresholds below the twentieth percentile of the control group.

In contrast to findings of intact (Kwakye et al., 2011) or even superior (Falter et al., 2012a) visual simultaneity and temporal-order judgments, impairments have been found in the auditory and cross-modal domain for temporal-order judgments (Kwakye et al., 2011) and responses to a flash-beep illusion (Foss-Feig et al., 2010). Overall, the reviewed studies indicate that event timing of nonverbal events is spared or even superior in ASD with respect to the visual domain, whereas impairments have been found in auditory and cross-modal event timing.

26.5.2 Review of Interval Timing in Autism Spectrum Disorders

The few existing studies on time processing in ASD have almost exclusively focused on interval timing. Visual and auditory duration-reproduction tasks in the suprasecond range (1–5.5 s) were used by Szelag et al. (2004), who tested 7 children (mean age 12.6 years) with ASD and 7 typically developing controls. They found a severe impairment of duration reproduction in the visual as well as the auditory domain in the ASD group. Children with ASD reproduced all tested intervals on average as 3–3.5 s, and overall showed a much larger variability compared to the control group. The authors interpreted this outcome as evidence for a "temporal neglect" in ASD. However, the participating children were not mental-age matched (the ASD group had a lower range of IQs compared to the control group), and hence a mental age effect cannot be ruled out. Nevertheless, their results are in line with other studies that used more stringent matching criteria (Gowen & Miall, 2005; Maister & Plaisted-Grant, 2011; Martin, Poirier, & Bowler, 2010). Martin et al. (2010) tested auditory duration reproduction (0.5–4.1 s) in a larger sample of 20 adults with ASD (mean age 36 years) and 20 typical adult controls matched according to chronological and mental age. They found that individuals with ASD were less accurate and showed a larger variability in reproducing the durations in comparison to the control group. Similarly, Maister and Plaisted-Grant (2011) found increased errors of reproduction and increased variability of responses in a visual interval-timing task in high-functioning individuals with ASD. In particular, individuals with ASD were impaired in the reproduction of the shortest (0.5–2 s) and the longest (45 s) durations tested. Moreover, the authors suggest that the impairments in the shorter interval range might have been mediated by attentional abnormalities, whereas the impairments in the long interval tested might have been mediated by episodic memory abnormalities.

Gowen and Miall (2005) tested interval timing in the subsecond range using tapping tasks in 12 individuals with Asperger syndrome (mean age 27.4 years) and 12 typical individuals matched by sex and mental and chronological age. In the synchronization task, participants heard two beeps (with interstimulus intervals varying between trials from 400 to 800 ms) and had to press a button in synchrony with the following two beeps. The continuation task differed in that the participants only heard the first two beeps and had to continue the sequence by pressing the button two more times. In both tasks, the group of individuals with Asperger syndrome judged the intervals between beeps as shorter and showed greater variability in their performance than the control group.

While the reviewed studies are in agreement that time reproduction (despite a study by Wallace & Happe, 2008, as discussed below) and motor timing are deficient in ASD, the picture is less clear for purely perceptual interval timing. A series of investigations of MMN elicited by auditory interval deviations (100 ms standards/33 ms deviants) provide indirect tests of purely perceptual interval timing in ASD. Lepistö et al. (2005) tested 15 children with ASD and 15 age- and sex-matched controls (mean age 9.4 years). Although MMN amplitudes for pitch deviations were increased in ASD, which is in line with reports of perceptual hypersensitivity in ASD, amplitudes for duration deviations were reduced. This was particularly pronounced for speech sounds, but was also present for nonspeech sounds. The same paradigm was later tested in a group of 10 children with Asperger syndrome (mean age 8.11 years), confirming the previous pattern of findings (Lepistö et al., 2006). In contrast, Kujala et al. (2007) employed the same paradigm on a group of adults with Asperger syndrome and found enhanced MMN amplitudes for both pitch and duration conditions. Hence, there might be a selective developmental change of interval timing as opposed to other sound-processing aspects in ASD (MMN amplitudes for pitch were enhanced both in children and adults).

Using a psychophysical task, Allman, DeLeon, and Wearden (2011) also provided evidence for impaired perceptual interval timing in ASD. They used a visual temporal-bisection task and stimuli between 1 and 8 s in a group of 13 children (mean age 10.3 years) with ASD and 12 typically developing controls. A temporal-bisection task requires participants to discriminate between two standard stimuli of different durations (one “short” and one “long”) in a training stage with reinforcement. In the subsequent test stage (without reinforcement), participants are presented with stimuli of various durations between the two standard durations and have to decide which category they belong to (i.e., short or long). Using this method, Allman and colleagues (2011) were able to demonstrate that the bisection point was lower, and the sensitivity to longer durations was reduced in the ASD group compared to the control group. Interestingly, the authors found that the lower the bisection point in the ASD group, the more emphasized were language and communication impairments assessed using the diagnostic interview ADOS-G (Lord et al., 2000). Yet, again, the experimental and control groups were not matched according to mental age, and individuals with ASD on average exhibited lower overall IQ scores than the control group.

Our own recent study on visual, auditory, and crossmodal temporal generalization in 17 individuals with ASD and typically developing controls matched by age, verbal IQ, and performance IQ (Falter et al., 2012b) showed that interval-timing performance conforms to the scalar property (i.e., proportionality of the standard deviation to the mean) in the ASD group. Nevertheless, sensitivity to time intervals decreased in ASD, which is in line with previous findings by Szelag et al. (2004). Moreover, response criteria employed by individuals with ASD were significantly more conservative than those employed by the control group, possibly due to increased task difficulty and thus lower confidence (Droit-Volet, 2002) in the ASD group.

The described studies on perceptual interval timing in ASD are in stark contrast to a study by Wallace and Happe (2008), who tested 25 individuals with ASD (mean age 14.10 years) and 25 chronological- and mental-age matched typical controls on three timing tasks. The tasks were performed using a stopwatch, and the participants were required to estimate, produce, and reproduce intervals in the range between 2 and 45 s. Wallace and Happe (2008) found normal performance in the estimation and production tasks in the ASD group and a tendency of a benefit in the ASD group over the control group in the reproduction task. Although these findings differ from the interval tasks described before, the studies are not easily comparable in that Wallace and Happe (2008) employed amodal stopwatch tasks that are very different in nature to the computerized timing tasks used in other studies, which make use of simple visual or auditory stimuli. In addition, the range of durations was larger and comprised much longer durations than in the contrasted studies, which could therefore have tapped different time processing mechanisms and allowed for counting to assist task performance. Nonetheless, in line with Wallace and Happe's (2008) findings, two other studies report typical performance on purely perceptual auditory interval timing in ASD using computerized tasks (Jones et al., 2009; Mostofsky et al., 2000). For instance, Mostofsky et al. (2000) tested 11 children with ASD (mean age 13.3 years) and 17 mental- and chronological-age matched typically developing children, who had to discriminate unfilled auditory intervals around 550 ms. The thresholds of ASD and control groups did not differ.

An interesting difference between these and previously reported perceptual interval-timing studies was that the tasks by Jones et al. (2009) and Mostofsky et al. (2000) required a shorter-longer type response. This type of response might be less ambivalent than a same-different type response, such as that used by Falter et al. (2012b), or a categorization type response, such as that used by Allman et al. (2011). Indeed, in the study by Falter and colleagues, individuals with ASD showed a profoundly more conservative response criterion and responded "same" much less often than the control group. It will need to be tested whether differences in response type may cause group differences by inducing different response strategies in individuals with ASD.

In summary, this leads to a very tentative conclusion that ASD may be associated with a motor time processing deficit, which is evident in timing tasks that require interval (re) production and synchronous tapping. In contrast, purely perceptual interval-timing tasks, such as discrimination tasks, yielded inconsistent results. To what extent these differences might have been influenced by sampling, task specificities (e.g., interval range tested), or choice of response type will need to be clarified by future research.

26.5.3 Discussion of Time Processing in Autism Spectrum Disorders

Time processing has been found to be impaired in ASD with respect to interval timing in many (Allman et al., 2011; Falter et al., 2012b; Kujala et al., 2007; Lepistö et al., 2005; Lepistö et al., 2006; Maister & Plaisted-Grant, 2011; Martin et al., 2010; Szelag et al., 2004) but not all studies (Jones et al., 2009; Mostofsky et al., 2000; Wallace & Happe, 2008). In contrast, event timing seems to be functioning at a typical if not superior level in the visual domain (Falter et al., 2012a; Kwakye et al., 2011), whereas auditory and crossmodal event timing was found to be impaired (Foss-Feig et al., 2010; Kwakye et al.,. 2011). Impairments of the speed of neuronal processing might be related to deviant interval timing, as discussed above for dyslexia. Although it is not the main focus of the current chapter, a brief overview will be given here. Oram Cardy et al. (2005) used magnetoencephalography to test rapid auditory processing in children with autism and several control groups (typical adults, typically developing children, and children with Asperger syndrome). They found that auditory evoked responses to the second tone in a tone pair (separated by 150 ms) only led to typical evoked responses in 35 percent of participants from the autism group, as compared to 80 percent of control participants. Similarly, an event-related potential study by McPartland et al. (2004) showed slowed neuronal speed of face processing in 9 individuals with autism (aged 15–42 years) as compared to 14 typically developing control participants. In addition, Groen et al. (2009) reported that individuals with ASD were less able than controls to integrate auditory information presented in temporal dips in background noise. Such studies, as well as other suggestions that the timing of neuronal activity might be disturbed in ASD (e.g., Welsh et al., 2005), gave rise to a recent proposal that ASD might be characterized as a temporospatial processing disorder due to neuronal disconnectivity and dissynchrony (Gepner & Feron, 2009).

Although most studies of time processing in ASD, in particular those focusing on motor timing, report impairments, there are also studies reporting performance in a typical range and even superior performance on some time processing tasks. In summary, it seems that time processing in ASD is characterized by an abnormal pattern of selective impairments and typical or even superior functioning. The task characteristics eliciting impaired versus intact performance should be scrutinized in future research.

26.6 Direct Comparisons of Developmental Disorders

There are very few studies directly comparing developmental disorders using the same time processing tasks. Most of these have compared individuals with ADHD and dyslexia (see table 26.4). Event timing in ADHD and dyslexia has been contrasted in three studies by Breier and colleagues (2001, 2002, 2003). Breier et al. (2001) compared sensitivity to tone-onset time (i.e., two tones perceived as simultaneous or not) and voice-onset time between children with a pure diagnosis of ADHD, pure diagnosis of reading disorder, comorbid diagnosis of ADHD and reading disorder, and typically developing children. The reading disorder group was impaired in both tasks independent of ADHD comorbidity. In a later study, Breier et al. (2003) tested tone-onset asynchrony thresholds together with other nontiming tasks in a similar design. The reading disorder group showed a specific deficit in the former task, whereas the ADHD group showed decreased performance in all tasks (including nontiming tasks). These comparative studies confirm the impression gained from the reviews above that dyslexia and ADHD seem to be dissociated with respect to event timing. Dyslexia seems to be characterized by impaired event timing, whereas individuals with ADHD either show no impairment or a generalized impairment across tasks (not specific to event timing).

Interval timing has also been compared for participants with dyslexia and ADHD within the same study. For instance, Toplak et al. (2003) tested children and adolescents with a

Table 26.4
Comparative studies on time processing in DD, ADHD, and ASD

Paradigm	Modality	DD	ADHD	ASD	Task	Study
Temporal order	aud	yes	no	–	Linguistic stimuli (0.01/0.07/0.5 s)	Breier et al., 2002
	aud	no	no	–	Nonlinguistic stimuli (0.01/0.07/0.5 s)	
Simultaneity	aud	yes	no	–	Tone-onset time (0–0.06 s)	Breier et al., 2001
	aud	yes	no	–	Voice-onset time (0–0.06 s)	
	aud	yes	yes	–	Tone-onset asynchrony detection thresholds	Breier et al., 2003
Perceptual Interval Timing	–	–	no	no	Duration estimation (2–45 s)	Wallace & Happe, 2008)
	–	–	yes	no	Duration reproduction (2–45 s)	Barkley et al., 2001b
	–	–	–	yes	Duration production (2–45 s)	
	aud	yes[a]	yes	–	Unfilled interval discrimination thresholds; children	Toplak et al., 2003
	aud	yes	yes	–	Unfilled interval reproduction (0.4/2/6 s); children	
	aud	yes	yes	–	Unfilled interval discrimination thresholds; adolescents	
	aud	no	no	–	Unfilled interval reproduction (0.4/2/6 s); adolescents	
	–	no	no	–	Prospective duration estimation, passive (30 s)	McGee et al., 2004
	–	no	no	–	Prospective duration estimation, active (30 s)	
	–	no	yes	–	Retrospective duration estimation, active (14 min)	
	aud	–	no	no	Unfilled interval discrimination (0.55 s)	Radonovich & Mostofsky, 2004/Mostofsky et al., 2000
	aud	–	yes	–	Unfilled interval discrimination (4 s)	
Motor Timing	–	no	no	–	Free tapping	Tiffin-Richards et al., 2004
	aud	no	no	–	Synchronized tapping (0.263–1 s)	
	aud	no	no	–	Continuation after tones (0.263–1 s)	
	aud	no	no	–	Rhythm reproduction	

a. Participants with ADHD and a comorbid reading disorder.

pure diagnosis of ADHD and with comorbid reading difficulty (but no pure dyslexia group) as well as typically developing controls on auditory interval timing (0.4–6 s). Although both experimental groups showed different unfilled interval-discrimination thresholds than the control group, they did not differ from each other in performance. However, the comorbid group underreproduced long (6 s) unfilled intervals compared to the ADHD group. Overall, there were no consistent performance differences between a pure ADHD and a comorbid group in this study. In a double-dissociation study, McGee et al. (2004) tested 43 children with ADHD and 45 children with a reading disorder (17 of whom presented with comorbid ADHD) and compared them to 42 clinical controls with a different diagnosis (mean age 8.8 years) on prospective time estimation (30 s), retrospective time estimation (14 min), and a nontiming phonological task. While the reading disorder group only showed impairment on the phonological task, the ADHD group could be distinguished from the reading disorder group on the basis of deficits in retrospective duration estimation. Furthermore, the children with ADHD were characterized by a large overestimation of the 14 minutes interval and additionally by large variability. When the comorbid group was compared to the combined pure diagnosis groups, they showed increased impairment in retrospective time estimation. The authors interpreted these findings as support for the idea that ADHD and developmental dyslexia are etiologically distinct disorders. In general, a distinction between ADHD and dyslexia has been found for retrospective time estimation of a relatively large time interval (14 min), but no dissociation could be found for auditory interval discrimination and reproduction on a shorter (0.4–6 s) scale.

Studies directly comparing individuals with ASD and other developmental disorders on time processing do not exist to date. However, two pairs of studies testing participants with ASD and ADHD, respectively, have used the same tasks. Discrimination of unfilled subsecond intervals was tested in participants with ASD (Mostofsky et al., 2000) and ADHD (Radonovich & Mostofsky, 2004). In both studies there were no group differences between patients and controls, suggesting that unfilled interval processing might function typically in developmental disorders. Unfortunately, the additional suprasecond (4 s) version of the task, in which Radonovich and Mostofsky (2004) found abnormal performance in the ADHD group as compared to controls, had not been used in the previous ASD study (Mostofsky et al., 2000). Hence, a potential difference between diagnostic groups with respect to suprasecond unfilled interval discrimination cannot be excluded. Similarly, the same time-estimation and -reproduction tasks (2–45 s) were tested on a group of individuals with ADHD (Barkley et al., 2001b) and individuals with ASD (Wallace & Happe, 2008). In both studies, the experimental groups did not differ from the control groups with respect to duration estimation. However, only the ADHD group showed impaired duration reproduction compared to the typically developing control group. Thus, ADHD and ASD were dissociated on the basis of interval reproduction, although this was confined to two out of six tested intervals (12, 45 s). Time reproduction arguably imposes a stronger demand on inhibitory skills than time estimation. Inhibitory skills have been suggested to be impaired in

ADHD but spared in ASD (Ozonoff & Jensen, 1999). A general tendency to underreproduce presented time intervals would consequently be confined to ADHD. Such an interpretation is in line with the findings by Szelag et al. (2004) and Martin et al. (2010) that individuals with ASD do not generally underestimate durations, but rather show an overestimation of shorter durations and underestimation of longer durations than 3 seconds, which resembles an overpronounced effect of Vierordt's law (for details, see Wearden, 2003).

In summary, direct comparisons confirmed the pattern emerging from individual reviews that event-timing deficits are a specific feature of dyslexia, in contrast to ADHD and ASD. Although individual reviews seemed to point toward different interval-timing performance patterns, the studies reported in this section did not show major performance differences between developmental disorders. This might partly be due to null findings for the experimental groups in comparison to their respective control groups, however. Nevertheless, the comparative studies reviewed here represent a promising starting point for direct comparisons of performance patterns between developmental disorders.

26.7 General Discussion

Several patterns of time processing differences have emerged from the reviews. Event-timing impairments in vision seem to be confined to developmental dyslexia and spared in ADHD and ASD. Concerning interval timing, deficits in dyslexia are usually found in the millisecond range, whereas in ADHD and ASD results were mixed, with some studies showing impaired performance for medium timescales (in the range of several seconds) in ASD and even for intervals of several minutes in ADHD. However, studies of the different disorders might have been biased in the choice of time ranges tested.

Differences between the developmental disorders were also found for motor timing. Group differences have been found in some rhythm studies in ASD and dyslexia. In contrast, there are generally no group differences between individuals with ADHD and controls on averaged speed of motor timing, but there is a consistently enhanced variability of performance in the ADHD group compared to controls. This pattern might signify that a motor-timing abnormality in ADHD may be a problem of inattentiveness (causing delayed responses) and impulsivity (causing premature responses). This idea is also reflected in suggestions that interval-timing abnormalities in ADHD could be explained by executive functions, including working memory, inhibition, and motivation (McInerney & Kerns, 2003). For instance, in duration-reproduction tasks, individuals with ADHD often underreproduce durations, suggesting a strong link to inhibition problems.

Research on interval timing in ASD is to date not conclusive. In general, a difference in the way temporal intervals are processed has been established in ASD in several studies. However, two studies assessing interval-timing thresholds did not find group differences. It remains to be shown whether time processing abnormalities in ASD can only be observed in relation to other cognitive dysfunctions. As a speculation, the impairment might not be located at the stage of processing of temporal-stimulus properties, but might rather be related to the use of timing information by other cognitive functions. In a similar argument, Maister and Plaisted-Grant (2011) have argued that timing abnormalities might be mediated by abnormalities in episodic memory functions and attention. Such speculations would be in line with recent ideas of abnormal cross talk in the autistic brain and abnormal cortical connectivity (e.g., Belmonte et al., 2004).

In the course of this review, it has become clear that reaching a conclusion with respect to the significance of time processing differences between developmental disorders is somewhat hampered by the inconsistency of findings within each area of research. The use of a variety of different timing tasks renders it possible that timing functions tested in different studies tapped different mechanisms. Hence, future research using the same battery of timing tasks on different populations might turn out to be more fruitful. In addition, study designs including individuals with pure diagnoses as well as comorbid individuals have the power to show meaningful associations between disorders. For instance, assuming disorders to be etiologically distinct, the prediction would be warranted that comorbid individuals would show additive effects of impairment in comparison to individuals with pure diagnoses (see McGee et al., 2004).

Finally, a problem with comparing cognitive functions between individuals with developmental disorders is that different studies sometimes test very different age ranges. Different stages of developmental pathways might be associated with different signatures of cognitive functioning. This was illustrated by the reviewed studies on MMN amplitudes associated with interval timing. While children with autism and Asperger syndrome showed decreased MMN amplitudes to interval differences (Lepistö et al. 2005; 2006), adults with Asperger syndrome showed enhanced amplitudes compared to controls (Kujala et al. 2007).

Studies on relations of time processing impairments and other cognitive dysfunctions can on the one hand inform research on developmental disorders, and on the other hand highlight mechanisms underlying time processing in general. Longitudinal studies remain the gold standard to test the relevance and developmental change of time processing in relation to other cognitive functions. For instance, Hood and Conlon (2004) investigated whether event timing is associated with early reading development. They found that a temporal-order judgment task conducted in 125 healthy preschoolers predicted their reading accuracy and fluency in the first grade. Presumably, studies like this could establish whether abnormal timing contributes to the development of concrete symptoms of developmental disorders.

26.8 Conclusion

Time processing abnormalities have been associated with a number of disorders. Here we reviewed three spectra of developmental disorders, developmental dyslexia, ADHD, and ASD, all of which have been reported to show abnormal time processing functioning. In all three fields of research, opinions have been divided concerning the explanatory relevance of time-processing abnormalities for the respective disorder. The fact that time processing is supposed to be disordered in otherwise symptomatologically different disorders raises the suspicion that an abnormality of time processing might be a mere epiphenomenon of abnormal developmental pathways, rather than a meaningful marker of specific disorders. However, the current review of literature has revealed that time processing deficits vary considerably between developmental disorders. In particular, an impairment of visual event timing seems to be a specific marker of developmental dyslexia. In contrast, visual event timing was found to be spared in ADHD and ASD, the latter possibly even showing superior event timing in comparison to typically developing control individuals.

In contrast, interval timing was found to be impaired in all reviewed developmental disorders. Nevertheless, there are pattern differences between disorders. Interval-timing deficits in ADHD and ASD seem to span large timescales, while in dyslexia particularly short timescales seem to be affected. Importantly, time processing deficits are not universally found within each of the disorders. While some individuals show deficits, a number of participants usually show performance comparable to typical controls with large overlaps. This lack of universality, together with a lack of specificity, for instance seen in the common patterns across all reviewed developmental disorders of increased timing variability, makes interval timing abnormalities unsuitable for predictions of group membership.

In summary, time processing abnormalities are a characteristic of developmental dyslexia, ADHD, and ASD. They may only affect a subgroup of individuals and can be found in different domains, timescales, and tasks. Although patterns of abnormalities show some differences between disorders, these are at this time not clear enough to allow their use as markers for specific developmental disorders. In contrast, these distinct patterns might become helpful in uncovering the role of time processing for diverse cognitive functions such as attention, memory, and impulsivity, and eventually they could inform our knowledge of the mechanisms of time processing in the brain.

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27 The Potential Link between Temporal Averaging and Drug-Taking Behavior

Allison N. Kurti, Dale N. Swanton, and Matthew S. Matell

The capacity to perceive time in the seconds to minutes range, or interval timing, allows organisms to develop temporal expectations about when significant events should occur, therein promoting the efficient organization of behavior. However, disruptions in temporal perception, such as those that have been seen following drug use, for example amphetamine (Eckerman et al., 1987), methamphetamine (Maricq, Roberts, & Church, 1981; Matell, Bateson, & Meck, 2006), cocaine (Matell, King, & Meck, 2004), marijuana (Mathew et al., 1998), MDMA (Frederick & Paule, 1997), and other drugs of abuse (Paule et al., 1999), can have dramatic impacts on the temporal organization of behavior. Furthermore, since it has been demonstrated that temporal expectations play a role in choice behavior (e.g., intertemporal choice based on delay discounting), alterations in temporal perception could lead individuals to pursue alternative goals. In the present chapter, we discuss the formation of a novel temporal expectation resulting from the averaging of temporal memories, and we end with the hypothesis that temporal memory averaging may play a role in drug abuse and addiction.

27.1 General Framework of Interval Timing

Prior to delving into the data obtained in our laboratory on temporal memory averaging, we provide a brief framework of an interval-timing model, which we refer to in subsequent presentations of our experimental findings. The large majority of interval-timing models can be broken down into three information-processing components: a clock, memory, and decision stage (Church, 1997). While there are important differences in the form of these stages across models, the basic framework is that the clock component provides an isomorphic representation of elapsed time; temporal memory is a storehouse of experienced clock values at biologically relevant times; and temporally controlled behaviors are produced when the decision stage registers that the current clock representation is “similar enough” to the value(s) stored in temporal memory. For example, in scalar expectancy theory (Gibbon, 1977), a popular model of interval timing, the clock component is instantiated as a pacemaker-accumulator system in which the subjective representation of elapsed time grows as a linear function of objective time. Upon occurrence of a biologically relevant event, such as reinforcement, the accumulated value of the clock is stored as an element in a distribution of temporal memories. Temporally controlled behaviors are emitted when the current accumulator value is similar enough to a value selected from temporal memory according to a proportional rule. Due to variability in these components across trials (i.e., clock speed, memory storage processes, and decision thresholds), temporal estimates are roughly normally distributed. Further, due to the proportional similarity rule of the decision stage, errors in estimation are directly proportional to the interval being timed, a characteristic of interval timing known as the scalar property (Gibbon, 1977).

27.2 Temporal Averaging

We have recently reported that simultaneously presenting rats with two stimuli, each specifying its own tone-food reinforcement delay, results in maximal response at a time midway between the conflicting intervals (Swanton, Gooch, & Matell, 2009). Specifically, rats were trained on a dual-duration, peak-interval procedure in which one modal stimulus (e.g., a 4 kHz tone) signaled probabilistic reinforcement on a fixed-interval 10 s schedule (i.e., on a portion of trials, the first nose-poke response after 10 s was reinforced, and the stimulus terminated), and a different modal stimulus (e.g., a house light) signaled probabilistic reward on a fixed-interval 20 s schedule. The stimulus-duration relations were counterbalanced across rats. On a proportion of trials, "probes" were provided in which one of the cues commenced, but no reinforcement was delivered, and the cue terminated independently of response after three to four times the duration associated with that cue. Plotting the rate of nose-poking on probe trials as a function of elapsed time following the onset of each cue resulted in the typical Gaussian-shaped "peak functions" in which maximal responding occurred at approximately the time of the criterion interval associated with each cue. In order to keep peak response rates equivalent between the short (10 s) and long (20 s) cues, the reinforcement probability was twice as large for the long cue (50 percent) as for the short cue (25 percent). After sufficient training to establish reliable peak functions for the discriminative stimuli signaling each of the two anchor durations, rats were presented with a compound stimulus (i.e., simultaneous tone and light) and tested in extinction (i.e., responding was never reinforced in the presence of the compound cue). Remarkably, presentation of the compound stimulus resulted in a single, robust peak of responding with an average peak time that fell in between the average peak times of the anchor stimuli. Importantly, when normalized by their peak times, the compound peak functions were approximately scalar, as they superimposed on the peak functions of the anchor cues.

The fact that the presentation of the compound stimulus resulted in scalar timing suggested that rats combined the two temporal memories associated with each discriminative stimuli to produce a single temporal expectation, which was then "timed" using normal temporal processes. However, to further assess the nature of responding to the compound stimulus, single trial analyses (Church, Meck, & Gibbon, 1994) were performed to identify the times of response rate shifts on individual probe trials. This analysis allowed us to determine whether rats were somehow combining the anchor durations to generate a singular temporal expectation, or whether they were behaving in another manner that produced mean data that simply *appeared* as if an average was being computed (e.g., responding "short" on some trials and "long" on others, starting "short" and stopping "long," etc.). Inspection of the time and variability of the start and stop times was consistent with timing a single (combined) duration, and was incompatible with timing different durations within or between trials. Together, these data indicate that rats can synthesize incongruent temporal information from different sources to structure their behavior.

While these data were not the first to suggest some form of combinatorial processing in response to cues providing discrepant temporal information, they were the first to provide clear evidence of the computation of a singular value timed in a normal, scalar manner. Indeed, Cheng and Roberts (1991) used an experimental design similar to Swanton et al. (2009) described above; pigeons were trained on a peak procedure in which one visual cue signaled probabilistic reinforcement at 9 s, and another visual cue signaled probabilistic reinforcement at 30 s. On a proportion of trials, the two cues were presented as a simultaneous compound, and responses on these trials were not reinforced. Peak rates of responding on these compound trials tended to occur at a time in between the two criterion durations, suggesting combinatorial processing of the two cues. However, the response rate on compound trials was extremely low, and responding extinguished very rapidly, leading to difficulties drawing conclusions regarding the form of responding and the expected time of reinforcement.

Malapani and colleagues (1998) have also demonstrated some combinatorial processing of discrepant temporal information using the peak procedure in humans afflicted with Parkinson's disease. In this experiment, patients were both trained and tested while off their dopamine (DA)-replacement medication to respond after a visual stimulus had been on for 8 s. After a block of testing at this duration, they were trained and tested using a 21 s duration. While response to the 8 s duration was later than 8 s (consistent with a general slowing of cognitive and motor processes), response to the 21 s duration was significantly earlier than 21 s. In contrast, when participants were trained and tested on the 21 s duration alone (i.e., without experience with the 8 s duration), response was later than 21 s. These data suggested that the patients' temporal expectancies of 21 s were drawn toward the 8 s duration to which they had been previously exposed, a phenomenon referred to as the "migration effect." In contrast, control participants and Parkinson's patients on their DA-replacement medication timed the two durations accurately.

In a subsequent study (Malapani et al., 2002), Parkinson's disease patients were trained and tested with all combinations of on- or off-medication states, and the results indicated that the migration effect occurred when tested off-medication, irrespective of patients' medication states during training. In contrast, when tested on-medication, the migration effect was not obtained, irrespective of their medication state during training. These data were interpreted as showing that the diminished dopaminergic tone of Parkinson's patients when tested off-medication produces a failure to selectively retrieve the appropriate temporal memory. Consequently, some form of temporal memory synthesis must have occurred, leading to a response peak that reflected a contribution of both the 8 s and 21 s expectations. However, the migrated peaks were broader than would be expected given scalar timing, suggesting that patients were not timing a singular expectation in a normal manner. Nevertheless, and of direct relevance to the current chapter, these data suggest that being in a DA-depleted state increases the tendency to combine discrepant temporal memories.

In contrast, other work using multiple cues, each associated with different delays, did not show evidence of combinatorial processes at all. For example, Olton and colleagues (1988) trained rats that one signal (a light) was associated with a short duration, and another signal (a tone) was associated with a long duration. However, unlike the simultaneous onset used in the work described above, Olton et al. employed mixed-cue trials in which a long stimulus commenced initially, and after some time had elapsed, the short signal was turned on as well. Results showed that the rats produced two peaks, located at the times expected from each stimulus's onset, rather than a single peak at a midway point between the two durations. Similarly, Fairhurst et al. (2003) examined temporal control in pigeons in a serial compounding procedure in which a short duration cue commenced after a long duration cue was already on. Their results demonstrated that the pigeons based their responding solely on the short duration stimulus. Taken together, the data from Olton et al. (1988) and Fairhurst et al. (2003) suggest that the simultaneous onset of discrepant cues (or the simultaneous retrieval of temporal memories) may be a necessary factor in generating some form of composite expectation.

27.3 Stimulus Compounding Using a 5 s–20 s Duration Pair

As the scalar timing of a singular expectation seen in the work by Swanton et al. (2009) was surprising, we sought to assess whether these results were limited to the specific intervals utilized in that experiment. To this end, we tested rats using an identical experimental design as described above, but used novel durations of 5 s and 20 s (i.e., a duration ratio of 1:4).

27.3.1 Methods

Subjects: 10 male Sprague-Dawley rats, approximately 3 months of age at the beginning of the experiment.

Apparatus: 10 standard aluminum and Plexiglas operant chambers (30.5 × 25.4 × 30.5 cm, Coulbourn Instruments, Allentown, PA). Each chamber had 3 nose-poke response detectors (2.5 cm opening diameter) along the rear wall of the chamber and a food magazine that delivered 45 mg sucrose pellets (Bioserv) on the front wall of the chamber. Only the center nose-poke was utilized in this experiment. An 11 lux house light mounted at the top of the front wall served as one discriminative stimulus and a 95 dB, 4 kHz tone presented from a speaker at the top of the rear wall served as the other discriminative stimulus.

Training and testing: Following 3 sessions of nose-poke training using a fixed-ratio 1 schedule, rats were trained for 10 two-hour sessions on a dual-duration, fixed-interval procedure in which one discriminative stimulus (e.g., a 4 kHz tone) signaled a 5 s tone-food reinforcement delay, and the other discriminative stimulus (e.g., house light) signaled a 20 s tone-food reinforcement delay. The cue-duration relationship was counterbalanced across rats (tone short, light long: T_SL_L group; light short, tone long: L_ST_L group). All trials were separated by a variable, uniformly distributed 60–90 s intertrial interval. Subsequent to fixed-interval training, rats were trained on a dual-duration, peak-interval procedure in which a proportion of trials were nonreinforced probe trials that lasted 60–80 s and terminated independently of behavior. Initially, the probability of a reinforced trial for both cues was set at 80 percent. However, to generate equivalent levels of responding to each cue, the probability of a reinforced trial for the short cue was decreased slowly over the course of training until it reached 20 percent, at which point mean response rates for the two cues were not statistically different. Total peak-interval training lasted 50 sessions. Finally, rats received five sessions of compound testing, which were identical to peak-interval training, with the exception that nonreinforced, compound probes (i.e., simultaneous tone plus house light) lasting 60–80 s composed 20 percent of the total trials.

Analysis: Peak functions were generated by plotting the mean rate of response as a function of the time since signal onset using 1 s bins. Data were pooled across the 5 testing sessions. Due to the skewed pattern of response that was sometimes observed on compound trials, the pooled responses were fit with the dual asymmetric sigmoid function, $Y = Y_0 + A*(1/(1 + \exp(-1*((x - B + C/2)/D))))*(1 - (1/(1 + \exp(-1*((x - B - C/2)/E)))))$ [fitting by MATLab, Cambridge, MA; equation from PeakFit, Systat, San Jose, CA]. Peak time was taken as B: peak spread was taken as C; D and E are parameters that contribute to the shape of each sigmoidal half, A is a scaling factor, and Y_0 is the baseline response rate. The coefficient of variation (CV) was computed by normalizing peak spread by peak time. To determine the degree of skew of the peak functions, we computed the proportion of the area under the curve that fell to the right of the peak time.

Results: Mean peak functions (top) and superimposition functions (bottom) are displayed in figure 27.1 as a function of stimulus modality.

As can be seen in figure 27.1, responding to the compound cue was robust in both groups, but the pattern of compound responding differed qualitatively between the two groups. A repeated measures analysis of variance (ANOVA; Greenhouse-Geisser corrected) on rats' peak times with duration as a within-subjects factor and modality as a between-subjects factor revealed significant effects of duration, $F(1.132,16) = 137.1$, $p < 0.001$; modality, $F(1,8) = 13.8$, $p < 0.01$; and a strong trend toward a duration x modality interaction, $F(1.132,16) = 4.4$, $p = 0.061$. A post hoc *t*-test of each cue separately revealed no significant differences in

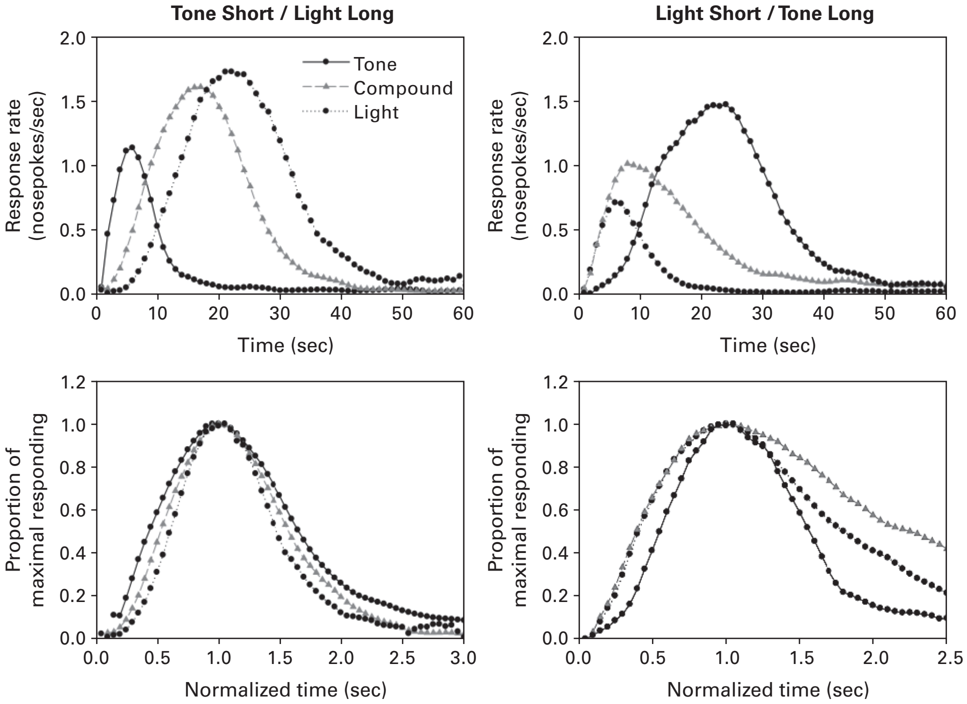

Figure 27.1

Top left: Peak functions for tone (short), light (long), and simultaneous compound cues in the T_SL_L group. Bottom left: Normalized peak functions in T_SL_L rats demonstrate superimposition, indicating scalar timing of all three cues, thereby indicating averaging of discrepant temporal memories. Top right: Peak functions for light (short), tone (long) and compound cues in the L_ST_L group. Bottom right: Normalized peak functions in the L_ST_L group fail to superimpose, indicating a failure to fully combine discrepant temporal expectations.

the peak times of the anchor cues between groups. Mean peak times for the short and long cues were 6.4 ± 1.3 s and 22.2 ± 1.0 s, respectively. Mean peak times differed significantly for the compound cue as a function of modality, $t(5.4) = 2.9$, $p < 0.05$. Mean peak time in the T_SL_L group was 17.0 ± 1.6 s, whereas in the L_ST_L group, it was 11.6 ± 3.8 s.

Similar results were found for CV. A repeated measures ANOVA (Greenhouse-Geisser corrected) on CV with duration as a within-subjects factor and modality as a between-subjects factor revealed a main effect of duration, $F(1.271,16) = 7.5$, $p < 0.05$; a duration x modality interaction, $F(1.271,16) = 5.8$, $p < 0.05$; and a trend toward an effect of modality, $F(1,8) = 4.3$, $p = 0.073$. Post hoc *t*-tests of each cue separately revealed no significant differences in the CVs of the anchor cues between groups. Mean CVs for the short and long cues were 1.05 ± 0.27 and 0.89 ± 0.13, respectively. Mean CVs differed for the compound cue as a function of modality, $t(4.8) = 2.8$, $p < 0.05$. The mean CV in the T_SL_L group was 0.96 ± 0.17, whereas in the L_ST_L group it was 1.66 ± 0.36.

The ANOVA for area under the curve asymmetry revealed a duration x modality interaction, $F(2,16) = 3.9$, $p < 0.05$; as well as main effects of both duration, $F(2,16) = 8.5$, $p < 0.005$, and modality, $F(1,8) = 9.4$, $p < 0.05$. Probing the interaction revealed significantly greater asymmetry on compound trials in the L_ST_L group as compared to the T_SL_L group, $t(8) = 4.9$, $p < 0.001$.

Discussion: Rats in the T_SL_L group showed compound responding consistent with a process in which the temporal "memories" of the anchor cues were combined and the resultant expectation was timed in an otherwise normal manner, as the compound peak showed close superimposition with the anchor peaks, thereby indicating scalar timing. As such, these data indicate that the combinatorial processes seen in Swanton et al. (2009) were not limited to the 10 s:20 s duration pair. One aspect of these data worth noting is that the compound peak time was closer to the long anchor peak time than the short anchor peak time. One explanation for this bias toward the long duration is that the rats may have taken into account the greater probability of reinforcement for the long duration (80 percent) as compared to the short duration (20 percent). In other words, because reinforcement was more likely at the long duration, the rats—presented with cues indicating possible reinforcement at both short and long durations—combined (i.e., "averaged"), the temporal memories of the two anchor durations but weighted this average by the reinforcement probabilities associated with each cue. We return to this possibility below.

In contrast to the T_SL_L rats, rats in the L_ST_L group showed a substantial rightward skew in responding and a failure of superimposition for the compound cue. In the peak functions for the L_ST_L group, the left tail of the 20 s response distribution overlapped the left tail of the 5 s response distribution, whereas the right tail came down at a time in between the right tails of the anchor distributions. As such, these data suggest that early in the trial, and/or when the decision to start responding was made, rats were timing the compound cue as though it was the short cue (see Brunner et al., 1997; Brunner, Kacelnik, & Gibbon, 1996). Conversely, later in the trial, and/or when the decision to stop responding was made, it appeared that both anchor durations influenced the response distribution.

Though the data presented above were obtained using a 1:4 duration ratio, similar results in terms of a bias toward the long duration in T_SL_L rats, as well as nonscalar, rightward-skewed responding in L_ST_L rats, were obtained using duration ratios of 1:3 and 1:6 (Swanton & Matell, 2011). As suggested above, one possible explanation for the bias toward the long duration in the T_SL_L rats is that they are factoring the differential probabilities of reinforcement for the short and long durations into their expectation, thereby weighting their combinatorial expectation by these probabilities. Indeed, as described in Swanton and Matell (2011), we attempted to predict the time of the compound peak by computing the average of the anchor peak times using data from five different duration pairs (10 s:20 s, Swanton et al. 2009; 4 s:12 s, 8 s:24 s, and 5 s:30 s, Swanton and Matell 2011; and 5 s:20 s, the present

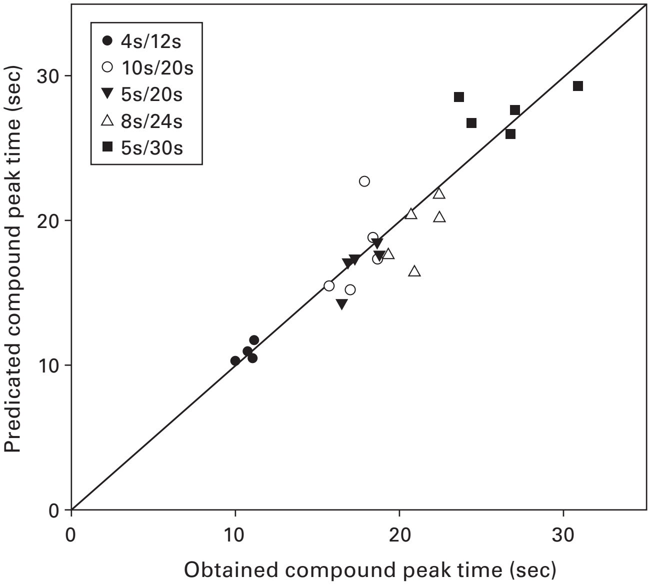

Figure 27.2

The obtained compound peak times in the T_SL_L rats from experiments utilizing five different duration ratios are accurately predicted (R = .99) by computing a reinforcement probability-weighted geometric average of the two anchor durations.

results]. We computed the arithmetic, geometric, and harmonic averages of the anchor peak times, either weighted equivalently (e.g., (short peak time + long peak time)/2), or weighted by the relative reinforcement probabilities of the anchor durations (e.g., 0.2 * short peak time + 0.8 * long peak time; weights from experiment reported above). The obtained compound peak times from the T_SL_L rats across the five experiments are plotted on the abscissa in figure 27.2 and are scattered against the predicted compound peak times (ordinate), as computed using a reinforcement probability-weighted geometric average of the anchor durations.

The line running through the data points is the best-fitting regression line, assuming zero intercept (in order to assess the absolute accuracy of prediction). Remarkably, the slope of the regression line is 0.99, indicating near-perfect predictability of the compound peak. Indeed, the only prediction in which the proportional differences between obtained and predicted peak times were not significantly different from zero was obtained by a geometric mean weighted by the relative reinforcement probability of the anchor durations. As such, these data provide strong evidence that under certain conditions, the presentation of cues leading to the retrieval of discrepant temporal memories does not simply result in a combinatorial process, but that the combinatorial process is a precisely computed weighted average.

Similar to the timing of the compound peak in these data, previous work using the bisection procedure (Church and Deluty 1977; Platt and David 1983; Allan and Gibbon 1991) has demonstrated that the point of subjective equality between two anchor durations occurs at the geometric mean (e.g., bisection of 2 s versus 8 s anchor durations occurs at 4 s). However, bisection at the geometric mean could be interpreted as resulting from a ratio-based comparison process on linearly scaled subjective times (e.g., 2 s/4 s = 4 s/8 s), or it could be interpreted as an arithmetically based comparison process on logarithmically scaled subjective times (e.g., the middle value of three values of the logarithmic series 1, 2, 4, 8, 16, 32, …), as these are computationally equivalent expressions. However, for a weighted average, as found necessary to account for the compound data, the computationally equivalent expressions are described below.

27.3.2 Log Scale

$R_S{*}D_S + R_L{*}D_L = D_C$, where D corresponds to the duration on a log scale, R corresponds to reinforcement probability, and the subscripts S, L, and C correspond to the short, long, and compound peak times.

27.3.3 Linear Scale

$D_S{}^{\wedge}R_S{*}D_L{}^{\wedge}R_L = D_C$, where D corresponds to durations on a linear scale.

To the extent that the latter equation (requiring exponentiation) is computationally more complex and therefore more difficult to instantiate in neural processes (Silver 2010), the current data provide a small piece of evidence in support of the logarithmic scaling of subjective time.

27.4 A Potential Link between Temporal Averaging and Drug Use

In this final section, we propose that temporal averaging may have implications for the development of drug abuse and addiction. Though different drugs have diverse mechanisms of action, the addictive potential of any abused drug is largely attributable to an increase in midbrain DA levels (Wise, 1998; Di Chiara, Loddo, & Tanda, 1999). While this increase in DA within the brain's reward circuitry (i.e., ventral tegmental area and nucleus accumbens) inevitably gives rise to the euphoric high that individuals experience while using drugs of abuse (Koob et al., 1994; Di Chiara, 1999), following metabolism of the drug, midbrain DA levels drop, producing symptoms such as dysphoria or anhedonia (Hodgins, el-Guebaly, & Armstrong, 1995). Some models of drug addiction have suggested that these negative emotional states, coupled with similarly caused physical withdrawal symptoms, serve as the basis for subsequent drug use (Shaham et al., 2003; Koob & Le Moal, 2008). Others (Robinson & Berridge, 1993) have argued that the time course of such withdrawal states does not necessarily parallel subsequent drug use, and that the neural changes resulting from drug use sensitize a system generating incentive salience, thereby producing an enhanced desire for the drug. While we believe that both of these mechanisms are likely to contribute to drug abuse and addiction, we propose that expectations of future reward value may also be altered through changes in temporal perception, and that these altered expectations will lead to choice behavior that facilitates drug use.

Our basic premise is as follows: (1) dopaminergic drugs increase clock speed, leading to the storage of longer temporal memories than would be experienced in a drug-naïve state for equivalent experiences. (2) Upon presentation of cues that relate to these experiences, temporal memories stored under the influence of drugs are retrieved and averaged with drug-absent temporal memories. These averaged temporal memories will thus be longer than "normal" drug-absent temporal memories. (3) Choice processes, based on expectations of future reward value, are derived in accordance with delay discounting mechanisms. As such, the utilization of longer than normal temporal memories in this expected valuation process leads to lower than normal expected values for future rewards. These lowered value expectations result in behaviors aimed at increasing expected reward value, such as taking drugs. We will briefly review data in support of these three premises.

27.5 Dopaminergic Involvement in Interval Timing

Pharmacological manipulations of DA have revealed a role for DA in timing, specifically in modulating clock-stage processes. Systemic administration of DA agonists, such as methamphetamine (Meck, 1996; Buhusi & Meck, 2002; Matell et al., 2006) or cocaine (Matell et al., 2004), causes peak times to occur earlier than normal. These immediate, horizontal, and proportional leftward shifts of the entire response distribution have been interpreted as resulting from an increase in the speed of clock-stage processing (Meck, 1983, 1996; Matell et al., 2006). In the terminology of scalar expectancy theory, DA agonists increase clock speed due to an increase in pacemaker rate or accumulation efficacy, resulting in decision-stage similarity processes reaching threshold levels earlier in real time. The magnitude of the leftward shift in the temporal response function resulting from methamphetamine administration is roughly linear with increasing dose (Matell et al., 2006), suggesting a tight relationship between synaptic DA levels and clock speed. Similar alterations in the perception of time are reported in human users of DA drugs (Goldstone & Kirkham, 1968). Identical effects, but in the opposite direction, are also seen in rats following DA antagonist administration (Meck, 1986; Buhusi &Meck, 2002; Drew et al., 2003), with the degree of clock speed slowing being correlated with the extent of D_2 receptor blockade (Meck, 1986).

Central to the current proposal's rationale, chronic exposure to the clock speed–altering effects of DA drugs can result in lasting alterations in temporal expectancy. Meck (1983, 1996) demonstrated that the acute, horizontal, proportional leftward shifts in peak time described above renormalize (i.e., timing becomes veridical) following repeated administration of these DA agents. Meck interpreted this effect as resulting from a constant impact on clock speed due to drug administration, but with the subjects relearning the relationship between the drugged brain state and reinforcement. Specifically, the increased clock speed leads to an immediate leftward shift, but upon repeatedly obtaining reinforcement at what subjectively appears to be a later time (due to the clock running at a faster rate, so that the accumulated clock value is larger at the actual time of reinforcement), the subject learns this new clock value and adjusts temporal expectancy accordingly. The gradual change in peak times over sessions is hypothesized to result from the competition (or averaging) between expected reward time due to the old, nondrug memories and the new drug memories. As more and more reinforcements are provided under the drug state, these new "fast clock" memories eventually dominate, and the organism begins timing in a veridical fashion. Consistent with this hypothesis is the rebound effect seen upon removal of the drug (i.e., in the drug-free state), such that a horizontal, proportional shift in the opposite direction of the initial drug effect occurs (i.e., temporal expectation is later than normal). Again, following continued training, this rebound shift renormalizes as the subject relearns to associate reinforcement with the drug-free pacemaker count (Meck, 1996).

27.6 Temporal Memory Averaging

We have already documented the existence of temporal memory averaging when subjects are presented with multiple cues that indicate different intervals until reward. However, multiple cues may not be required for temporal memory averaging to occur. For example, Matell and Meck (1999) examined the temporal control of behavior in rats on a multiple-duration peak procedure, in which reinforcement was sometimes available at 10, 30, and 90 s after tone onset on three different response levers. In contrast to other similar procedures with multiple reinforced durations (e.g., Fetterman & Killeen, 1995; Leak & Gibbon, 1995; Gallistel et al., 2004; Matell et al., 2004), reinforcement at the shorter durations (i.e., 10 s and 30 s) did not terminate the stimulus, and reinforcement could be earned again on the same trial at a later duration (i.e., 30 s and 90 s). Analysis of peak responding on the 30 s lever showed that the peak occurred at 25 s when no reinforcement occurred at 10 s, but at 35 s when reinforcement was provided at 10 s. Similar results were found for responding on the 90 s lever as a function of reinforcement provided at 30 s. These data were interpreted as suggesting that the rats reset their clock-stage accumulation processes upon reinforcement, and therefore learned that reinforcement was available on the 30 s lever after 30 s (when no reinforcement-induced resetting occurred) or after 20 s (when 10 s reinforcement led to accumulation reset). As a result of these incongruent pieces of temporal information, they further suggested that the two durations associated with the 30 s lever (20 and 30 s) were averaged to produce an expected reinforcement time of 25 s. However, it is unclear whether such averaging occurred during memory storage or during memory retrieval.

In a different study, Meck et al. (1984) trained rats on a peak procedure in which reinforcement was available either 10 s or 20 s after trial onset (duration counterbalanced between groups). After achieving steady state performance, the interval was switched (i.e., 10 s rats were now reinforced after 20 s, or vice-versa), and the median time of responding on individual trials was tracked until the rats were correctly timing the new duration. These investigators found that the time of responding did not jump abruptly from one criterion time to the other, nor did it move in a smooth and gradual manner. Instead, the median response time jumped first to an intermediate duration for a brief run of trials, and then jumped again to the new reinforced duration. The peak time of the intermediate duration fell at approximately 14 s, the geometric mean of the reinforced durations, and this time was not modulated by the direction of the shift. Meck interpreted these data as suggesting that when confronted with uncertainty regarding the time at which reinforcement could be earned, the rats computed the geometric average of the previously reinforced and most recently reinforced times, and responded at that average time. In a similar study by Lejeune et al. (1998), rats were tested on a peak procedure in which the time of reinforcement transitioned after every session on a triangular schedule (10, 20, 30, 20, and 10 s) for 24 consecutive sessions. They found that subjects tended to time the 10 s duration as longer than 10 s (with a mean of 12 s), and the 30 s duration as shorter than 30 s (with a mean of 28 s), indicating an influence of the other durations on temporal reproductions and suggesting some degree of temporal information synthesis. In all of these studies, the cues were identical on all trials. Thus, these data indicate that multiple cues are not a necessary condition for temporal averaging to occur.

27.7 Choice Behavior: Delay Discounting

The subjective value of a commodity (e.g., money, drugs, food) diminishes as a function of the anticipated delay before receipt of the commodity. Consequently, individuals from a variety of species, including humans (Rachlin et al., 1991), rodents (Bradshaw & Szabadi, 1992), and pigeons (Mazur, 1988), often choose a smaller immediate reward over a larger reward that is delivered after a delay. The diminishment in value as a function of delay is well described by a hyperbolic decay curve (Mazur, 2001), and an individual's rate of discounting has been shown to be stable over at least several months (Ohmura et al., 2006). Of importance to this chapter, the rate of discounting has been shown to be augmented in drug-abusing populations, including individuals using alcohol (Petry, 2001), nicotine (Bickel & Marsch, 2001), opioids (Madden et al., 1997), cocaine (Coffey et al., 2003), and methamphetamine (Hoffman et al., 2006). It remains unclear whether this difference in discounting between drug-using and drug-naïve human populations reflects a trait, predisposing one to drug abuse, or a state resulting from chronic drug use (Reynolds, 2006). However, empirical work in rodents has found support for both trait-based (Perry et al., 2005) and state-based (Helms et al., 2006) explanations, suggesting that some individuals may be in "double jeopardy."

The hyperbolic delay discounting curve is defined as [$V= A/(1 + kD)$], in which V is the subjective, expected value of the commodity, A is the "actual" value of the commodity (i.e., its instantaneous value), D is the expected delay until the commodity is obtained, and k is a free parameter that indexes the rate of discounting (Mazur, 2001). There are two important points to notice about this discounting equation. First, because k and D are multiplicatively related, changes ascribed to k (i.e., alterations in discounting rate due to drug use) may be equivalently understood as scalar changes in expected delay, D. Second, D is the expectation of delay, which is presumably based upon temporal memories, which are likely to differ between drug-present and drug-absent states as a result of drug-induced alterations in the speed of internal clock processes (Meck, 1983). The general view within the discounting field is that the increased discounting seen in these drug users contributes to their continued drug use by making future rewards (e.g., health through abstinence) less valuable than immediate rewards (e.g., the hedonic effects of the drug). Alternatively, a change in the rate of discounting may simply decrease the anticipated value of future rewards as compared to previous drug-naïve assessments, leading individuals to attempt to enhance the expected value of these rewards by potentiating their experienced value through drug use. In other words, whereas an individual's expectation of the value of a certain behavior may have been sufficient to engage in that behavior prior to drug use (e.g., going to a movie might be viewed as having relatively high expected value), alterations in expected value through changes in delay discounting may lead to future expectations that are insufficiently valuable to engage in these behaviors, leading to drug use as a means of enhancing reward value.

27.8 Averaging of Drug-Present and Drug-Absent Memories

The above premise demands that memories stored under the influence of a drug can be averaged with memories stored under a drug-absent state. However, a large number of drug discrimination studies have shown that the discriminative stimulus properties of a variety of substances can be used to guide behavior (e.g., Oberlender & Nichols, 1988; Kamien et al., 1993; McMillan & Li, 2000; McMillan & Hardwick, 2000; McMillan, Li, & Snodgrass, 1998; Jackson, Stephens, & Duka, 2005). As such, it remains unclear whether the temporal memories associated with two different drug states can be averaged together to form a singular expectation. To this end, we evaluated whether rats could be trained to generate different temporal expectations associated with the presence versus absence of amphetamine, and if so, whether exposure to an intermediate dose of amphetamine would generate an expectation in between the trained durations. Previous drug discrimination studies utilizing fixed-interval schedules have provided data suggesting that rats could associate specific intervals with different drug-induced interoceptive states (Krimmer, McGuire, & Barry, 1984; Kubena & Barry, 1969). However, given the interrelation between response rate and response time with fixed-interval schedules, this previous work does not provide indisputable evidence of specific temporal expectations as a function of drug state. As such, the experiment presented below, which utilized a peak-interval procedure, allowed us to identify whether temporal control could come under stimulus control by drug state.

27.8.1 Methods

Subjects: 10 adult male Sprague-Dawley rats (Harlan, Indianapolis, IN), approximately three months of age at the beginning of the experiment.
Apparatus: The same operant chambers as in the previously described stimulus compounding experiment. Animals in the present study were trained to respond only on the center nose-poke aperture. A 95 dB 4 kHz tone served as the discriminative stimulus.
Training and testing: After training rats to respond on the center nose-poke aperture using a fixed-ratio 1 schedule, rats were trained seven days per week on one of two single-duration, single-modality, fixed-interval procedures in which differing internal states signaled different tone-reinforcement delays. Specifically, an injection of 0.9 percent standard physiological saline (SAL, 1 ml/kg via intraperitoneal injection [i.p.]) prior to the session signaled that the first center nose-poke made after a 5 s delay following tone onset would be reinforced throughout the session. In contrast, an injection of amphetamine (AMP; 0.50 mg/kg, i.p.) prior to the session signaled that reinforcement could be earned after a 20 s delay following tone onset. All trials were separated by a variable, uniformly distributed intertrial interval of 60–80 s. The two drug-duration pairings were trained on different days in a pseudo-randomized order such that rats did not experience the same drug-duration pairing more than two days in a row.

After 8 days of fixed-interval training (4 days SAL, 4 days AMP), nonreinforced probe trials were added on 25 percent of the total trials. Additionally, 5 probe trials were added to the beginning of each training session, such that rats' capacities to discriminate saline from amphetamine could be tracked on a daily basis before rats received feedback about their performance in the form of fixed-interval trials. On probe trials, the tone was presented for 60–80 s on both saline and amphetamine days, and terminated independently of behavior. As with fixed-interval training, all trials were separated by a variable 60–80 s intertrial interval. All rats accurately discriminated the durations signaled by each respective cue (i.e., produced response functions with peak times occurring at approximately 5 s on saline days and 20 s on amphetamine days) after approximately 16 sessions (8 SAL, 8 AMP), and progressed subsequently to peak-interval testing.

During peak-interval testing, rats received an injection of saline, amphetamine, or an intermediate amphetamine dose (0.25 mg/kg, i.p.) in one of three randomly assigned orders. On saline and amphetamine days, rats were exposed to the same conditions (i.e., the same drug dose and tone-food delay) that are described above. In contrast, on the day in which each rat received the intermediate dose of amphetamine, they were run in extinction (all trials were probe trials). A variable 60–80 s intertrial interval followed each probe trial, and the total session length was two hours.
Data analysis: Histograms of the rate of nose-poking as a function of the time in a trial (peak functions) were constructed using 1 s bins. These data were collected from the first five probe trials of each test session. Peak functions for all injections types were fitted with a 5 parameter Gaussian curve, [a*exp((–1/2)*(((abs(x – b))/c)^d)) + e]. The first 3 parameters

related to the amplitude, the mean, and the width. The 4th parameter allowed the exponent of the function to vary in order to enable better fits given the low kurtosis (resulting from the low number of trials analyzed), and the 5th parameter accounted for a baseline rate of responding. Peak time was taken as [b], and peak spread was defined as the width of the function at half maximum as computed by [2*c*((2*log(2))^(1/d)]. The CV was computed by normalizing the peak spread by the peak time.

Results: Rats were able to generate specific temporal expectations in response to their interoceptive drug state.

Figure 27.3 (top panel) shows the average peak-interval functions following an injection of saline or the training dose of amphetamine from the first five trials of the testing sessions. As can be seen, the response functions peak around the respective criterion times associated with each drug's training durations, indicating the rats' ability to select a temporal memory based upon their interoceptive state. Also shown in this figure is the peak function in response to an intermediate dose of amphetamine. As can be seen, subjects responded at a time that was in between the times associated with the trained durations. Moreover, subjects responded in a manner that is consistent with the generation of an average of the times that are associated with each drug state. These impressions were confirmed with a repeated measures ANOVA comparing peak times from the three drug conditions, $F(2,18) = 58.1$, $p < 0.001$. Subsequent planned comparisons demonstrated that the peak time associated with the intermediate dose was later than that associated with saline ($p < 0.005$) and earlier than the peak time associated with the training dose of amphetamine ($p < 0.005$). The peak time on saline was also different than the peak time on the training dose of amphetamine ($p < 0.001$).

Normalizing the peak functions by their peak times revealed close superimposition, as shown in the bottom panel of figure 27.3. Consistent with this superimposition, a comparison of the CVs revealed no significant difference across drugs, $F(2,18) = 0.11$, $p > 0.05$. Further, planned comparisons revealed no differences between any conditions.

Discussion: These data suggest that the averaging of temporal memories associated with the different interoceptive states induced by amphetamine versus saline can occur. As stated above, our premise is that drug-experienced individuals in a drug-absent state will compute the expected value of a future outcome, but due to temporal memory averaging, these individuals utilize a "longer than drug-naïve" expectation, leading to an expected outcome value that is insufficient to generate drug abstinence. As such, the current data showing temporal memory averaging across drug-present and drug-absent experiences are consistent with our premise that temporal memory averaging may contribute to drug abuse and addiction. Nevertheless, there is undoubtedly a difference between (1) temporal memory averaging when presented with an intermediate dose of a drug, which may generalize to both previously experienced interoceptive states, and (2) temporal memory averaging upon presentation of a cue that has been present in both drug-present and drug-absent states, but is currently experienced while the individual is in a drug-absent state. Indeed, our data show

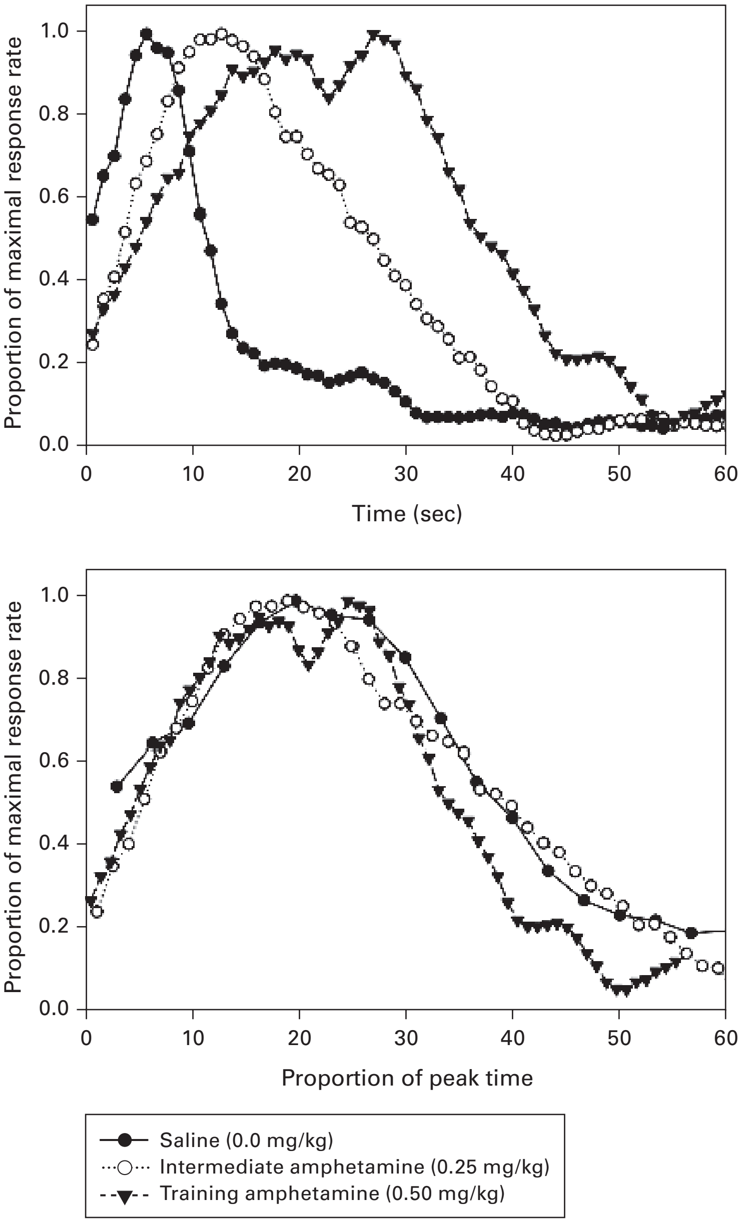

Figure 27.3

Top: Rats' peak functions following saline and amphetamine injections demonstrate maximal responding at approximately the trained durations, indicating that rats generate accurate temporal expectations based on interoceptive cues. In addition, rats generate a temporal expectation for an intermediate amphetamine dose that is in between the previously trained saline and amphetamine doses. Bottom: Rats' normalized peak functions for saline, amphetamine, and the intermediate amphetamine dose superimpose one another, indicating scalar timing of all three interoceptive cues.

that in response to a tone cue signaling reinforcement at a future time, rats used their current interoceptive state to select which temporal memory to utilize for temporal control. As such, the current data implicate the necessity of some failure in retrieval processes as a result of chronic drug use and as a prelude to an averaging of temporal memories. Intriguingly, as described above, such memory-retrieval errors have been found to occur in Parkinson's patients in a dopamine-depleted state (Malapani et al., 2002). Importantly, profound decreases in dopaminergic tone, as well as in D_2-receptor availability, are found in drug-addicted individuals (reviewed in Volkow et al., 2004). While drug abuse has been associated with a variety of memory deficits (see Fernández-Serrano et al., 2011 for review), it remains to be seen whether memory-retrieval processes in particular are altered in drug-addicted individuals.

Finally, we would be remiss if we did not point out that while the current data, as well as the evidence reviewed above, are consistent with enhanced discounting in drug-using individuals resulting from altered temporal perception, direct evaluation of discounting following amphetamine administration in both healthy humans (de Wit, Enggasser, & Richards, 2002) and animal subjects (Richards, Sabol, & de Wit, 1999; Isles, Humby, & Wilkinson, 2003; Winstanley et al., 2003), has demonstrated decreases, rather than increases, in impulsivity. As these results are in the opposite direction to the anticipated effects resulting from an increase in clock speed, these reports indicate that additional psychological processes above and beyond changes in temporal perception are impacted by DA and contribute to choice behavior. However, given the increased impulsivity seen in drug-abusing populations tested during drug-free states (Robbins & Everitt, 1999; Self & Nestler, 1995; Field et al., 2006), the current data suggest that alterations in time may play a role in the maintenance of their addiction.

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28 The Perception of Time in Hypnosis

Peter Naish

28.1 Introduction

It would be understandable for a reader to wonder why, out of all the situations that might reasonably have an influence upon time perception, something as esoteric as hypnosis has been chosen as a topic. As might be guessed, it is because hypnosis has a rather special impact upon temporal judgment, and trying to discover why has the potential to add to our understanding of both hypnosis and time perception.

It has been recognized for a long time (Bowers & Brenneman, 1979) that when people are roused from a session of hypnosis and asked how long they believe it lasted, they are liable to produce a considerable underestimate. It is not unusual for the participant to suggest as little as half the true duration. In terms of an inner clock, it is as if the system has slowed; in terms of the widely cited scalar expectancy theory (Gibbon, 1977), possible explanations would include the tick rate of the pacemaker being reduced by hypnosis or ticks being missed from the accumulator.

From time to time in this account, it will be necessary to describe something of the nature of hypnosis. An important observation is that people vary in their responsiveness to the procedure. In research settings, scales of hypnotic susceptibility are used; they typically comprise of the order of a dozen test suggestions, ranging from motor effects (e.g., "Your arm is getting light and will float up") to sensory experiences (e.g., "You will begin to hear music playing"). The distribution of susceptibility, i.e., responsiveness to suggestion, is approximately normal, with only a few people able to pass every item in the test, but equally few passing none. If hypnosis were responsible for causing time distortion, it would be reasonable to suppose that participants with higher susceptibility would experience more distortion. Although a few early reports suggested that this was indeed the case, subsequent research was unable to find a simple correlation (see St. Jean et al., 1994 for a review).

In the period of St. Jean's studies, hypnosis was regarded with a growing sense of realism, if not complete skepticism. It was very clear that none of the earlier, almost magical beliefs about hypnosis was tenable, and it was equally apparent that all the items in the susceptibility tests could either be faked (lifting a "light" arm) or were unverifiable (hearing music). Some researchers (e.g., Wagstaff, 1981) were inclined to believe that much so-called hypnotic behavior represented simple compliance: people acted out what was expected of them by the experimenter. A somewhat less skeptical approach (e.g., Spanos, 1991) proposed that a willingness to "go along with" the suggestions enabled some people to convince themselves that the effects they achieved were occurring automatically. Crucially, these accounts were ascribed to simple psychological processes, so the notion that hypnosis represented a distinct state of consciousness, different from normal, appeared to be unsupported. If this was correct and hypnosis did not produce any significant, distinctive changes in the brain, it would seem to follow that it was unlikely to have any consistent impact upon timing: if any effect were observed at all, it must come about through some side effect of the situation.

28.2 Things That Do Not Cause Time Distortion

Although not an essential ingredient of a hypnotic induction, it is traditional to begin a session with suggestions for relaxation. It is conceivable that the resultant sense of heaviness reported by many people could be accompanied by a slowing of neural activity, including that which underpins the clock. Fatigue is known to affect neural response times, and this has been demonstrated in air traffic controllers, whose critical flicker fusion frequency (CFF) is depressed at the end of a shift. Conversely, CFF is raised by the consumption of stimulant drinks (Hindmarch et al., 1998). The CFF is measured using a flashing light and adjusting the frequency to determine the transition point at which the flashing appears to change to continuous illumination. This procedure has been used with people both in and out of hypnosis, and no shift in CFF was found (Naish, 2001). It would seem that a fatigue-like effect is unlikely to be the time-distorting element of hypnosis.

Following hypnosis, some participants may exhibit a degree of amnesia for the events that took place, or for the suggestions that were given during the session (especially if these included suggestions for amnesia). It had been proposed (Ornstein, 1969) that one of the factors that influences our judgment of how long a period lasted is the number of activities that took place within it. Someone who, through amnesia, could remember only a few activities might conclude that the period had been rather brief. St. Jean, a prolific researcher in this field, tested this proposal (St. Jean et al., 1982) and failed to find any correlation between the extent of hypnotic amnesia and the degree of time distortion. Amnesia cannot be the element of hypnosis that accounts for the foreshortening of retrospective time judgments.

A common cause of missing the passage of time is through being completely absorbed in some situation. People who are more hypnotizable tend to exhibit higher levels of absorption; for example they readily become "lost" in a book or film (Tellegen & Atkinson, 1974). St. Jean and MacLeod (1983) tested the absorption/missed time proposal by reading subjects absorbing stories, following which the subjects judged the story's duration. The procedure was carried out, both within and outside hypnosis. Substantial underestimation was found only when two conditions applied: (a) the subjects were highly susceptible, and (b) they were hypnotized. In other words, this study showed hypnosis producing its traditional timing effect, but in particular with those who scored high on susceptibility. The effect was not found if the material listened to was not involving, suggesting that the absorption component of hypnosis was indeed the dimension associated with the timing effects. This study looked as if it may finally have established a link with susceptibility, but St. Jean soon rejected the absorption account (St. Jean & Robertson, 1986). It was shown in this latter study that the attentional demands of the task, rather than the involving nature of the story, determined the degree of time underestimation. The temporal effect of having to pay close attention to a task has been well known for some time. Thus, outside the hypnosis context, it has been shown that high attentional demand leads to time underestimation (e.g., Brown & Boltz, 2002). It is assumed that attention is a finite resource, and that an increase in mental workload, such as occurs when a task is difficult, makes more demands upon the resource, leaving less available to monitor the passage of time (e.g., Zakay, 1989). This observation is pertinent to two of the possibilities for noncorrelation raised earlier. First, it suggests a plausible, varying, nonhypnotic influence upon time judgments, which might dilute any hypnotic effects. Second, mental workload may actually be a varying element of hypnosis itself, and thus be the component that gives rise to the timing effects. This latter was the claim of St. Jean et al. (1994), who developed what they called the "busy beaver" hypothesis.

Based upon the recognition that high mental workload situations produce shortened time estimates, the busy beaver proposal suggested that being in hypnosis is mentally demanding, and so inevitably causes time distortion. In one of their experiments, St. Jean et al. (1994) had participants judge the durations of stories, both in and out of hypnosis, and also in both a low-workload condition (merely listening to the story) and in a high-workload condition (counting target words and solving puzzles). In spite of the conclusion of the authors that the results supported the busy beaver hypothesis, they do not in fact appear to do so. Under low workload, the duration estimates were 92 percent of the true duration outside hypnosis and 80 percent in hypnosis. Thus, hypnosis appeared to be having the usual effect of reducing the perceived duration. However, under high workload the situation was different: no hypnosis, 45 percent and hypnosis 64 percent of true duration. That is, in hypnosis the time distortion was actually *less* pronounced. This puzzling interaction just missed statistical significance ($p = 0.08$), and the only significant main effect was of the nonhypnotic workload manipulation. If being hypnotized were truly a high-workload situation, adding it to a condition where workload was already heightened should result in even larger duration underestimates. The failure of St. Jean et al. to observe this effect severely undermines the suggestion that hypnotic time distortion is a workload phenomenon.

28.3 Unpacking Factors That Do Lead to Time Distortion

If hypnosis behaves as if it is slowing an internal clock, then as well as resulting in underestimates of periods judged retrospectively, it should lead to *over*estimates in prospective judgments. As an analogy, consider using a slow-running stopwatch either to time a race, or to take a predetermined period of exercise. In the former case the stopwatch would read a shorter time than the race had actually taken, whereas in the latter the user would exercise for longer than had been intended. Mozenter and Kurtz (1992) tested for the prospective "overshoot," and did indeed find the effect. It was explored further (Naish, 2001) using both long periods (in the minutes range) and shorter (a few seconds). This manipulation was used in an attempt to rule out the possibility that the timing distortions were the result of inattention. When longer times are used, it is not easy to control for the mental processes taking place in the interim; some of these may well impair accurate time keeping. However, if the participant is set a timing task of a few seconds' duration, it is reasonable to suppose that this remains the focus of attention throughout. In addition to these prospective estimates, the Naish experiments also included retrospective tests, again in both the longer and shorter ranges. All the estimates were made both within hypnosis and in the waking state. As predicted, retrospective judgments were shorter in hypnosis than during waking, while prospective judgments were lengthened in hypnosis. These effects applied for both the minute- and second-range durations.

Having established that the hypnotic overshoot in prospective timing was as robust as the retrospective underestimate, Naish (2003) used a series of prospective timing studies in an attempt to determine the specific elements of hypnosis that produce the distortion. A typical hypnotic induction has the participant relax with closed eyes, then try to visualize a relaxing scene. Frequently a beach scene is chosen, and people are asked to imagine themselves on the beach experiencing the various sensory stimuli, such as the texture of the sand or the sound of the waves. There are a number of factors in this situation that might, in principle, have a distorting effect upon time estimation. The most obvious are trying to visualize vividly, having the eyes shut and, of course, "being hypnotized," whatever that implies. One of the experiments (Naish, 2003) explored the impact of trying to imagine being in a suggested scene. Participants were shown a sequence of projected photographs of an island location, the last of which showed a coastal scene; this final picture remained displayed throughout the timing phase of the experiment. The experimental subjects were asked to imagine that they had been walking on the island and ended their trip at the beach, where they were awaiting a friend. They were to keep looking at the picture and try to imagine themselves in the scene, doing whatever they liked while waiting. The experimenter suggested that the friend was due in exactly 5 minutes, and that the participant should indicate when they believed that time to have elapsed.

The mean waiting time produced by twelve participants was 3 minutes, 56 seconds; in other words, an undershoot of approximately 1 minute—certainly not an overshoot.

However, two of the subjects did produce considerably longer times of over 5 and over 7 minutes respectively; perhaps significantly, both had shut their eyes, rather than continuing to look at the picture, although they reported visualizing it very vividly. To test the importance of visualizing with eyes closed, a further group of participants was tested. An identical procedure was used, except that after being told to visualize being in the scene depicted by the final picture subjects were asked to close their eyes, "So that you can visualize better." This manipulation resulted in a mean time of 4 minutes 49 seconds: over 20 percent longer than the eyes-open condition, but still not an overestimate.

A further experiment repeated the procedures, but this time with hypnosis. Thus, after looking at the final picture and listening to an explanation about trying to be "in" the scene while awaiting a friend, participants were given a brief hypnotic induction, using progressive relaxation and ending with a brief verbal reminder of the depicted scene. At this point they were told the friend was due in 5 minutes and the experimenter ceased speaking. In this condition the mean estimate was 5 min 36 s.

It would appear that hypnosis is required to experience the time distortion effect, although clearly some people were able to achieve this merely by shutting their eyes and visualizing vividly. Subjective reports confirmed successful visualization as the key factor; the greatest overshoots were achieved by those who described the beach experience as highly realistic, and at the same time lost awareness of their actual surroundings. It seems likely that hypnosis amplified the timing effect by facilitating the visualization.

28.4 Consciousness and the Clock

In a general sense, it is clear that conscious awareness is inextricably bound to an awareness of the passage of time, but it has also been suggested that an inner clocking mechanism is at the heart of consciousness. Gray (1995) proposed the existence of a "consciousness cycle." He suggested that sensory inputs were polled at a regular rate, rather as a computer polls peripherals such as a mouse and keyboard. The new, updated information, Gray suggested, was compared with what was predicted for the sample, the prediction being based on what had been learned from previous samples. The test-and-predict cycle was presumed to continue, with attention being captured by the mismatches caused when aspects of the current epoch did not correspond with predictions; in fact, Gray's proposal was that the contents of consciousness would be determined largely by that which had not been predicted. As will be seen later, it is of particular interest that Gray developed these ideas in an attempt to explain the hallucinations of schizophrenia. He proposed that these patients had a problem in the comparator stage, so that sensory information, which should have been anticipated, was registered as unexpected. For example, their own inner speech would come as a "surprise" and hence be attributed to an external agency, so giving rise to the well-known symptom of hearing voices.

Gray's cycle was supposed to run at a more or less constant rate, the period he proposed being of the order of 100 ms. It is possible that such a fundamental cycle could underpin the system for making time estimates, and in that context it is significant that Treisman et al. (1994) found evidence that the base period of an inner clock was around 80 ms. Gray's own description of his proposal was a "conjecture," but building upon this, it is possible to suggest why hypnosis might slow the clock (Naish, 2001, 2007). Perhaps the proposed cycle rate can vary to suit the demands of the situation; for example, it may speed up at times of heightened arousal. Thus, survivors of car accidents frequently describe events as having seemed to unfold in slow motion. If their sample rate had increased, the changes from one sensory sample to the next would be smaller than normal, giving the impression that a moving object, such as an oncoming car, was moving unusually slowly. The situation in hypnosis is quite the reverse. A person who can successfully reduce awareness of outside reality to a minimum, while generating a convincing "reality" of their own, does not need frequent sample updates. Reality has become largely self-generated, little can happen that is unpredicted, and consequently the sample rate can be reduced. If this rate and the inner clock really were one and the same, it would follow that people who visualized vividly would also experience time distortion.

28.5 Distorting Reality and Time

Although the Naish (2003) findings linking time distortion to vividness of visualization offer some support to the notion that the effects may be a function of sensory sampling rates, no firm conclusion can be drawn. Nevertheless, there does appear to be a clear link between the modification of reality through hypnosis and a concomitant modification to timing. These hypnotic changes are of course entirely voluntary, but there are also conditions that produce an involuntary distortion of reality. Schizophrenia is an obvious example. Consistent with the account being developed here, it has been claimed that the major cognitive deficit associated with schizophrenia is an impairment to timing ability (Elvevåg et al., 2004).

Intriguingly, there are several other parallels between hypnosis and schizophrenia, including the fact that people who score high on a scale of schizotypy tend to be more hypnotically susceptible (Gruzelier et al., 2004). Schizotypy measures the tendency to spontaneously experience some of the phenomena associated with schizophrenia, such as thinking one has heard a voice although no one else was present.

A number of studies have suggested that there is some level of "disconnect" between brain regions in schizophrenia. Thus, Lawrie et al. (2002) deduced that there was a reduction in the effective connectivity between the frontal and more posterior regions of the brain in schizophrenic patients, and Shergill et al. (2007) employed diffusion tensor imaging (a form of fMRI) to reveal abnormalities in the neural tracts linking these parts of the brain. No neural abnormalities of this nature have been associated with hypnosis, but since hypnotic effects are reversible and do not come unbidden, no structural problems would be expected. Nevertheless, Fingelkurts et al. (2007) used EEG techniques to reveal that, during hypnosis, a highly hypnotizable subject's brain *behaved* as if there were poor connectivity between the regions. The procedures entailed the examination of neural oscillations at various brain sites. It is believed that normally, when the frontal regions direct the assembly of information from across the brain to form a unified experience, the oscillations in contributing regions become phase-locked. This is analogous to having a large gathering of musicians, among whom a certain subset is involved in producing a piece of music, and these follow the conductor. Meanwhile, those not involved play at different, unsynchronized tempi. The Fingelkurts et al. (2007) data revealed reduced phase-locking in hypnosis, as if the long-range assembly process were breaking down. Haig et al. (2000) reported analogous findings when using EEG with schizophrenia patients, concluding that the data were consistent with a deficit in the integration of relevant information.

There is one characteristic of schizophrenia that is not paralleled in hypnosis; whereas hypnosis behaves as if slowing the clock, schizophrenia seems to increase the rate (e.g., Densen, 1977). In contrast, patients with Parkinson's disease (PD) do generally appear to exhibit a slowed clock (Harrington, Haaland, & Hermanowicz, 1998). Moreover, PD patients are also vulnerable to hallucinations (Fénelon and Alves, 2010). Although the processes giving rise to these experiences are not fully understood, there is support for the idea that there is a failure to properly mesh bottom-up, data-driven information with top-down hypothesis-testing signals (Koerts et al., 2010). Taken together, the PD and schizophrenia observations lend strong support to the notion of a link between impairment to timing processes, on the one hand, and aberrations in conscious experience on the other. It is tempting to assume that a similar link exists in hypnosis.

28.6 Variability in Time Judgment

It is not obvious that a simple, moderate slowing or speeding of an inner timekeeper should be associated with quite dramatic changes in conscious experience. In fact, the clock changes of schizophrenia and PD are not limited to the "simple"; in addition to the basic rate changes, there appear to be decrements in the *reproducibility* of time keeping. This lack of precision might be attributable to memory failures, where stored representations of intended intervals become corrupted or are inaccurately accessed, but for the time being and for the sake of exposition it will be assumed that the deficit stems from variability in the "tick" rate. It seems more plausible that instability of this sort might lead to the kind of mismeshing that results in hallucinations.

A well-established technique for assessing impairments to timing precision is the temporal bisection task (e.g., Wearden & Ferrara, 1995). In the auditory domain, participants learn two "anchors"—a short duration tone and a longer one. Subsequently they are presented with a range of stimuli, comprising the anchors and other tones of intermediate durations. To each of these a short or long decision is required, with the participant attempting to classify the intermediate stimuli as being nearer to the short or the long. Typically, the anchors are judged with almost 100 percent consistency, while other stimuli receive increasing proportions of "long" assessments as they become closer in duration to the long anchor. Plotting the probability of deciding "long" against stimulus duration yields a characteristic sigmoid curve, with the slope of the straight central section giving an indication of the ability to make consistent decisions. If the system were perfect, a vertical step function would result.

It has been demonstrated that for both Parkinson's patients (Smith et al., 2007) and for those with schizophrenia (Carroll et al., 2008), the bisection task yields shallower probability plots than are produced by healthy controls. In other words, patients who are liable to experience distortions to reality show an impaired ability to make consistent time judgments. Whether or not a similar (but presumably temporary) impairment occurs during hypnosis was unclear, but the author has now tested the possibility.

Ten participants were selected on the basis of their hypnotic responsiveness, five of high susceptibility (referred to as "Highs") and five of low ("Lows"). They were taught anchor durations of 450 ms and 900 ms, then tested with these, plus further stimuli of 525, 600, 675, 750 and 825 ms. Each of the seven stimuli was presented eight times, giving a total of 56 stimulus presentations. These were delivered in random order, participants being required to make push-button responses indicating whether a stimulus appeared to be long or short. The testing was repeated with and without hypnosis, with three participants of each group carrying out the test in the waking state first, then in hypnosis; the other four participants were tested in hypnosis first. The data showed no impact of order of testing, so were combined.

There were indeed differences in the slopes of the functions between the different groups and conditions. To present the data more meaningfully, difference limens were calculated from the slopes. This was done by finding the two stimulus durations at which the probabilities of giving a "long" response were 0.25 and 0.75, respectively. Halving the difference between these two durations yields the difference limen. A steeper slope gives rise to a smaller difference limen, thus showing a greater sensitivity to duration changes. The results are shown in table 28.1.

To place these data in context, Carroll et al. (2008), using stimuli of similar durations, obtained difference limens of 40 ms for controls and 67 ms for schizophrenic patients. As can be seen, far from becoming less sensitive in hypnosis (as might have been expected by analogy with patient populations) the Highs actually improved their ability to discriminate stimuli. The Lows, in contrast, do appear to do worse in hypnosis. Individual slopes were derived for each participant in each condition, and the data were tested with a two-way (group x state) ANOVA. The interaction was significant ($F_{1,8} = 11.3$, $p = 0.01$). Pair-wise comparisons using *t*-tests revealed that the change with hypnosis for Lows was nonsignificant ($t = 2.18$, d.f. = 4, $p = 0.10$), whereas in Highs the increase in steepness of slope with hypnosis was significant ($t = 3.59$, d.f. = 4, $p = 0.02$, 2-tailed).

The tendency for hypnotic Lows to show opposite effects to Highs in a timing study has been reported before (Naish, 2007). In that study, when Highs were showing the traditional

Table 28.1

Mean (and s.d.) difference limens for participants of high and low hypnotic susceptibility, tested either when hypnotized or waking (values in milliseconds)

	Waking	Hypnosis
High hypnotizable	45 (9.4)	36 (3.8)
Low hypnotizable	33 (9.1)	46 (9.6)

"slow clock" effect, Lows were behaving as if their clocks were ticking faster. It was suggested that this might be an attentional effect, and parallels were drawn with the findings of Gruzelier, Gray, and Horn (2002), who recorded evoked potentials in an "oddball" experiment. A series of low-pitch tones was presented, with just the occasional, unexpected high-pitch tone inserted in the sequence. Outside hypnosis, both Highs and Lows produced the typical N100 and P300 wave responses to the odd tones. When hypnotized, Highs produced a response to oddballs that was dramatically reduced, but in Lows it became even more marked.

It should be pointed out that in the kinds of study reported here, hypnotic Lows are people chosen for their failure to pass any (or at least, very few) items in a susceptibility test; by any reasonable definition they are nonhypnotizable. Thus, when one reports that they were tested in hypnosis, what this really means is that they were taken through the same induction procedure as was used with the Highs. The consequences are, of course, very different for the two groups. It may be conjectured (Naish, 2007) that, while the Highs move effortlessly into whatever neural state is implied by "being hypnotized," the Lows strive actively to attain it—and fail. This striving may lead to a greater clock speed and, in the light of the temporal bisection data, perhaps a less constant speed too. In contrast, as a result of hypnosis, the Highs appear to have reduced the jitter in their timing system. One way in which jitter might be reduced would be to reduce general levels of neural activity. McGeown et al. (2009) have used fMRI to monitor the "default mode" regions of the brain, the frontal regions that become active when no formal task is being undertaken. These researchers have demonstrated that in hypnosis, highly hypnotizable subjects reduce levels of activity in these regions. Perhaps this finding is indicative of a general ability of Highs to reduce neural noise, one result of which is to facilitate finer discriminations in time judgments.

28.7 Hemispheric Effects

Koch et al. (2005) tested for hemisphere-specific effects in the timing deficits of PD patients. A distinctive deficit is apparent in these patients when they are required to remember and reproduce two intervals, one short, the other long. Whereas the short interval tends to be reproduced too long (the typical "slow clock" effect), the longer interval is reproduced shorter than the true duration, so that the two intervals are in effect judged as more similar than they really are. The phenomenon has been termed migration and appears to be the result of faulty retrieval processes (Malapani, Deweer, & Gibbon, 2002). Koch et al. looked for this effect in hemi-Parkinson's patients, whose symptoms were confined to one side; only right hemisphere–impaired patients demonstrated migration. The authors hypothesized that malfunctioning of the right basal ganglia may induce dysfunctions in the right dorsolateral prefrontal cortex (rDLPFC) to which they project. Lewis and Miall (2006) have identified the rDLPFC as a key region in temporal tasks.

There is evidence that hypnosis involves changes of hemispheric asymmetry. Naish (2010) used a temporal-order judgment task in order to determine relative hemispheric processing speeds. A light was positioned in each visual hemifield and the two were flashed sequentially, the participant's task being to decide which light flashed first. When the interstimulus interval (ISI) was sufficiently brief that decision became impossible, ISIs were adjusted separately for left-right and right-left sequences, to determine the critical values at which the order could just be detected. For hypnotic Lows a slightly shorter ISI was possible for left-leading sequences, implying a modest right-hemisphere advantage. This pattern was not changed following a hypnotic induction, although there was a general tendency for ISIs to lengthen. The pattern of results for Highs was very different. When tested during waking, they showed a strong left-hemisphere advantage, but this was reversed to an equally strong right-hemisphere advantage during hypnosis.

The physiological underpinning of these results is not clear. If we imagined that it was possible to carry out coincidence detection in the middle of the corpus callosum, then the data would point unequivocally to differences in processing speeds in the two hemispheres. In reality, the order judgment must be made in one hemisphere or the other and, while different speeds of processing remain a possible explanation for the asymmetries, the abrupt switch demonstrated by Highs may reflect a change in the hemisphere where the judgment is made. Whichever the situation, there is in some sense greater activation in the right hemisphere when Highs are hypnotized, and the changes in time-estimation performance associated with hypnosis may reflect an impact of this shift upon the rDLPFC timing circuitry.

The results of a study currently in preparation are of relevance here. Participants suffering from posttraumatic stress disorder (PTSD) were tested with the same temporal-order judgment technique. PTSD sufferers experience vivid flashbacks (effectively hallucinations) of the precipitating trauma and also display considerable foreshortening in retrospective time estimates, particularly when judging the length of time since the trauma event. The pattern of ISIs for this group, tested without hypnosis, was indistinguishable from that of Highs when hypnotized. It is known that these patients show increased right-hemisphere responsiveness (Asbjørnsen, 2010) and also that they are more than averagely hypnotizable (Yard, DuHamel, & Galynker, 2008).

The status of hemispheric differences in schizophrenia is less clear-cut, with some researchers implicating a weakness of hemispheric dominance in the etiology of the disease.

A study by McCourt et al. (2008) used a line bisection task. Like the temporal-order judgment task described above, line bisection has been used as a tool for detecting visual neglect. Healthy (right-handed) participants display a tendency to divide a line left of center, but McCourt et al. reported that schizophrenia patients did not show a bias and interpreted this as revealing a deficit in right-hemisphere functioning. Taking a different approach, Caligiuri et al. (2005) used a range of tests of hemispheric function in patients, and from their (mixed) results speculated that decreased arousal in the left hemisphere might result in reduced inhibition of the right (via the corpus callosum) and hence lead to right hemisphere dysfunction. Whether results such as these should be interpreted as an underactive or as an inappropriately active right hemisphere, a reasonably consistent picture is preserved: conditions in which the right hemisphere behaves abnormally are associated with changes in perceived reality and changes in the perception of time. The one missing element in this picture concerns Parkinson's patients. Based on the data discussed so far, it would be predicted that one class of hemipatient would be more likely to develop hallucinations than the other. Currently there appear to be no data that address this issue.

28.8 Drawing Threads Together

As demonstrated in the previous section, there has been an attempt in this chapter to fit a wide range of data into some form of unifying model. Broadly expressed, this model states that aberrations in an internal timing system will be associated with aberrations in conscious experience, and that these effects are associated with changes in right-hemisphere processing. This may have served as a useful framework within which to present some disparate material, but that may be the full extent of its value. Certainly many subtleties (e.g., whether effects are linked to the clock rate itself, or to storage and retrieval of temporal information) have been glossed over. Moreover, it is entirely possible that in different conditions (e.g., hypnosis and schizophrenia) completely different processes are involved in the production of superficially similar outcomes.

An important consideration is whether the consciousness-clock link is in some sense a causal one, or whether each is an independent reflection of some other process. By analogy with a computer, in which it is essential that different processes yield up their results in precisely defined time windows, it is easy to imagine a faulty clock giving rise to erroneous output. However, it is far from clear that a single, central clock that was simply running slower would do the same; as long as all processes were driven by the same clock, nothing would get out of synchrony. It is true that in the timing literature, more than one clock is sometimes postulated, but that has never been suggested in the hypnosis field, and it is upon hypnosis that we must now focus. When hallucinations are generated in hypnosis they are well ordered and come about in direct response to suggestions; these are surely not the products of mis-meshing clocks. In any case, it is probably inappropriate to use a computer clock analogy to link timing with consciousness; such analogies have a poor record.

At the advent of the so-called cognitive revolution in psychology, computers were coming into widespread use, and it was natural to use their serial data processing as an analogy for the apparently serial processes of attention. However, subsequent research has revealed the enormously parallel nature of sensory processes and the inappropriateness of the serial analogy (Naish, 2005).

If a faulty clock does not generate hallucinations, perhaps there is a sense in which the reverse applies. One version of this is clearly not the case. It is the idea that the rate at which hallucinated events seem to unfold gives an impression of the passage of time. The St. Jean et al. (1982) study showed that there was no correlation between time estimation and the number of events remembered during hypnosis. Moreover, it seems implausible that the existence of a hallucination should have a direct impact upon the estimation of brief time intervals. However, if the production of hypnotic effects entails a shift of activity toward the right hemisphere, then a colocated component of the clock (e.g., Lewis & Miall, 2006) may well be impacted. Not only is the clock slowed, but from the data reported here it also appears to be more accurate. The McGeown et al. (2009) results imply a reduction of neural activity in a situation when there would normally be an increase. The finding applies to the rest period between tasks, but it is possible that during tasks, too, there is less inessential activity. Certainly there is good evidence that those who are able to achieve high levels of hypnosis have particularly effective strategic brain control (Naish, 2007). If Highs were able to reduce background neural activity to a minimum, then this might explain the ability to produce more consistent responses. It may also account for the slowing of the clock, since additional neural noise may sometimes be treated as part of the "tick train."

The literature has frequently identified the basal ganglia, and sometimes the rDLPFC, as two likely locations for the clock mechanism. Scanning studies in hypnosis have never implicated the basal ganglia as playing any special role, whereas prefrontal regions are frequently shown to be involved. One interpretation of this could be that the clock is located entirely frontally, rather than in the basal ganglia. However, this is probably too extreme a position to take. More plausibly there are different elements of the timekeeping mechanism, located in different regions, and these different components are affected in different brain states. The gross physiological changes of PD, for example, with their particularly heavy impact upon the basal ganglia, may well disrupt a clock component located in this region. Of course, this does not rule out the involvement of other regions, to which there are dopaminergic projections. In addition, although the primary effects are motor, it is not unreasonable to suppose that disruption at the level of the basal ganglia would impact sensory experience, resulting in the occurrence of hallucinations.

The situation in hypnosis, and perhaps in PTSD too, is clearly different. Unlike PD or schizophrenia, where the evidence concerning hemispheric effects is unclear, these two hallucination-supporting conditions show a clear shift of activity to the right hemisphere. In PTSD the bias has been associated with a leaning toward global rather than local processing, the latter being associated with the left hemisphere (Vasterling et al., 2004). A predisposition to respond preferentially to global information may well be adaptive in a high-arousal state where danger is anticipated. A global approach may also facilitate top-down processing, such that perceptions can be generated in the absence of matching stimuli. Arguably it is easier to maintain a hallucination generated in this way, if disconfirming local detail (analyzed in the left hemisphere) is ignored. This may explain why people who are successful in generating hypnotic experiences show the rightward shift. We may hypothesize that this shift then impacts the right-based timing system.

To the author’s knowledge, no formal research on time perception in PTSD has been carried out; it is certainly not known whether patients show any change in the slope of the bisection task function. Consequently it is not known whether the high arousal level would add noise to the system and lead to a more shallow slope. If we had that information, it would be possible to determine whether the clock rate and its consistency were impacted independently, but currently we know only that hypnosis both slows the rate and reduces the difference limen. These may both result from a slowing and steadying of the clock “tick,” but it is also possible that these two effects are independent. The slowing of the clock may be a result of employing some time monitoring structures for tasks not usually undertaken in the right hemisphere. At the same time, to facilitate the production of hallucinations, strategic inhibition would be required to avoid the production of disconfirming signals. The resultant general damping down of activity might then reduce variability in time estimation.

28.9 Conclusion

Hypnosis is a right-hemisphere phenomenon, and consequently its impact upon time perception most plausibly acts via timekeeping circuits in this hemisphere. Its action appears to be confined largely to frontal regions, so the most likely site for interaction with timing structures is the right dorsolateral prefrontal cortex. This does not rule out the possibility that there are other important elements in the timing circuitry, most likely located in the basal ganglia. Some conditions, such as Parkinson’s disease and schizophrenia, that bear at least superficial resemblance to hypnosis clearly differ from it in crucial ways. Importantly, the patient populations show a flattening of temporal discrimination curves, while highly susceptible people in hypnosis show the reverse effect. Whereas hypnosis is characterized by strategic and precise deployment of neural resources, the medical conditions are associated with an absence of full control. Many timing effects exhibited in patients can be ascribed to defects in the storage and retrieval processes associated with learned durations. In hypnosis there is no evidence of memory effects, so it is more likely that timing enhancements are the result of a reduction in general neural activity. Drawing stronger conclusions must await the results of further studies. Currently, the most promising research directions may involve posttraumatic stress disorder patients, who of all the patient populations may bear the closest resemblance to the highly hypnotizable participant in hypnosis.

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29 Time in the Psychopathological Mind

Melissa J. Allman, Bin Yin, and Warren H. Meck

Man is apparently almost unique in being able to talk about things that are remote in space or time (or both) from where the talking goes on.

—Charles Hockett, "The Origin of Speech"

What does "time" mean to you? Think about the Grand Canyon for a moment: try to imagine millions of years of erosion by the Colorado River, revealing billions of years of the Earth's geological history. It's hard to imagine all of that *time*. Time itself can bestow historical beauty and appeal, and like other aspects of psychophysics and perception, controls much of our interactions with events in our internal and external lives. We typically think about the consequences of our actions in hypothetical time, and these temporal dynamics influence our valuations of future rewards and past experience. It's as if the temporal sequence of events that we experience courses through our lives like a river, honing the rhythmical structure of our earliest social interactions and emotions (Eagleman & Pariyadath, 2009; Droit-Volet & Meck, 2007; Droit-Volet et al., 2007; Fortin et al., 2009; Gu & Meck, 2011; Jaffe et al., 2001; Meck & MacDonald, 2007; Stetson et al., 2007); our perception and production of speech (Kotz & Schwartze, 2010; Schirmer, 2004); the coding of memories (Brown et al., 2007; Malapani et al., 1998; Meck, 2002); as well as our ability for mental time travel—that is, contemplation of the past, present, and future (Boyer, 2008; Nyberg et al., 2010; Suddendorf et al., 2009; Wearden, 2002). At a more basic level, our ability to estimate absolute and relative durations on different timescales allows us to anticipate, learn, and adapt to temporal regularities and dynamics in the social and nonsocial environment (Hinton & Meck, 1997b; Agostino et al., 2011; Buhusi & Meck, 2005, 2009a, b). The question of how internal, subjective time corresponds to external, objective time is commonly assessed by psychophysical procedures that quantify how an internal sensory experience scales with an external stimulus. Indeed, such timing processes (e.g., prospective time estimation) have been argued to play an important role in multisensory integration and the monitoring of cognitive behavior (e.g., Holmes & Spence, 2005; Meck, 2002, 2003, 2005; Meck & Benson, 2002; van Wassenhove, 2009). If we are indeed all marionettes on this earth, time is surely one of the strings, and its accompanying patina shows how we have been shaped by the past.

Time, space, and number are fundamental dimensions of the world in which we live that have been incorporated into the brains and behaviors of virtually all species (Gallistel, 1990; Meck, 2003; Walsh, 2003). Interval timing, which refers to the ability to measure durations in the seconds-to-minutes range, has been intensively studied, both in humans (e.g., Brannon et al., 2008; Droit-Volet & Wearden, 2001; Rakitin et al., 1998) and other animals (e.g., Bateson & Kacelnik, 1997; Boisvert & Sherry, 2006; Brodbeck et al., 1998; Cheng et al., 2011; Roberts, 1981). These studies stem from earlier work on operant and classical conditioning (Pavlov, 1927; Skinner, 1938) as well as the law of effect (Thorndike, 1933) and Michel Treisman's "internal clock" hypothesis (Treisman 1963), and continuing with the efforts of mathematical psychologists and learning theorists (e.g., Balci et al., 2011; Gallistel & Gibbon, 2001; Gibbon and Church, 1990). More recently, the study of interval timing has entered the realm of neurobiological investigation both in humans and other animals (e.g., Coull et al., 2004, 2011; Lake & Meck, 2013; Lustig et al., 2005; Matell et al., 2003; Meck & Benson, 2002; Meck, 2006a, b, c; Merchant et al., 2013; Rao et al., 2001). However, the transition from the modeling of behavioral timing data to electrophysiological recordings and simulation of the patterns of neural firing that contribute to behavioral output has never been an easy undertaking (Matell & Meck, 2000, 2004). On the one hand, it is possible to adopt the core concepts of traditional timing models (e.g., Gibbon et al., 1984) and attempt to identify plausible brain areas and neural circuits that might satisfy the proposed information-processing stages of interval timing (Gibbon et al., 1997; Meck, 1983, 1996; Van Rijn et al., 2013—see Church & Broadbent, 1990 and Shi et al., 2013 for proposed guidelines).

The major goal of such attempts would be to identify the source of the scalar property of interval timing, which states that the variability of timing behavior is proportional to the mean of the target duration (Cheng & Meck, 2007; Gibbon et al., 1984, 1997). Such "time-scale invariance" is the hallmark of interval timing that most theoretical models have attempted to emulate (Almeida & Ledberg, 2010; Cheng & Meck, 2007; Van Rijn et al., 2013—but see Lewis & Miall, 2009; Wearden & Lejeune, 2008). On the other hand, "timing" is a broad and varied topic that may include estimation of event durations (e.g., how long an event lasts), temporal predictions (when an event is likely to occur), temporal-order judgment (whether event A occurs before or after event B), temporal ordinal comparison (whether duration A is "longer" or "shorter" than duration B), or simply the sense of time flow or chronesthesia as part of episodic memory (Nyberg et al., 2010; Tulving, 2002. It is still unclear whether all of the above can be explained and predicted by a single neurobiological model of "interval timing," and conflicts or discrepancies among a wide variety of reports may come from the inherent divergence in the experimenter's use of the term "timing" and "temporal control" of behavior (Grondin, 2010).

Specifically, the heterogeneity in the field of timing and time perception may come from the specific task requirements or goals that are used in timing research. One example is that the behavioral procedures used to study how participants sense the "flow of time" are very different from the behavioral procedures used to study duration estimation and temporal prediction. The sense of the flow of time may become part of episodic memory, which depends, in part, on the hippocampus (see Dickerson & Eichenbaum, 2010 for a review). MacDonald et al. (2011) recently provided evidence for so-called "time cells" in the hippocampus that mark the flow of time and may serve to distinguish between prospective and retrospective timing processes (MacDonald et al. 2014). In contrast, the anticipation of an event contributes to the formation of goal-directed behavior or stimulus-response habit learning. Such habit learning has been shown to rely on cortical-striatal circuits (e.g., Balleine & O'Doherty, 2010), which are also thought to support interval timing (e.g., Buhusi & Meck, 2005; Meck et al., 2008) and associative learning (e.g., Gallistel & Gibbon, 2000). Moreover, these different psychological processes likely interact with each other in most real-life scenarios (Goto & Grace, 2008), and distortions of time and temporal relationships are likely to be components of most psychiatric diseases (e.g., Allman & Meck, 2012; Del Arco & Mora, 2009; Harrington et al., 2011; Moustafa & Gluck, 2011; Schwartze et al., 2011). Consequently, it would be important to investigate the potential roles the hippocampus may play in cortico-striatal-dependent timing tasks (Harrington et al., 2010; Yin & Troger, 2011).

Because temporal processing is integrated with other psychological processes, such as attention, memory, and motivation, researchers focusing on interval timing need paradigms that are able to isolate timing factors from nontiming factors (Cheng & Meck, 2007; Roberts, 1981, 1987). These paradigms can be categorized into temporal estimation, temporal production, temporal reproduction, and temporal ordinal comparisons (Buhusi and Meck, 2005; Cordes & Meck, 2013; Gu & Meck, 2011; Wittmann and Paulus 2008). One classic paradigm that is being used to study interval timing both in humans and other animals is the peak-interval (PI) procedure, a reproduction task that measures temporal discrimination with response rate averaged over trials, usually ramping up toward the target duration and then ramping down when the subjective time has passed the target duration (Church et al., 1994; Levin et al., 1996, 1998; Meck, 2007; Paule et al., 1999; Rakitin et al., 1998).

Entering the PI procedure, the subject is initially trained with fixed-interval sessions, with each session containing dozens of trials and usually lasting for 1–2 hours. A signal comes on at the beginning of a trial; the first response after the target duration is reinforced, and the trial immediately ends with the termination of the signal. A new trial begins following a variable intertrial interval. Once the subject shows evidence of having learned the target duration, which is demonstrated by the production of a positively accelerated response function ramping up to the target duration, the second phase of training begins. During this phase, referred to as PI training, a random proportion of the trials are unreinforced probe trials, in which the signal stays on for at least three times the target duration and no reinforcement is given for responding. The subject typically learns to inhibit responding after the target duration has passed in unreinforced probe trials, thus displaying a "bell-shaped" response function that is typically centered around the target duration when averaged over trials.

Because of its shape, the mean response rate on unreinforced probe trials is referred to as the peak function and has three important parameters: peak time, peak rate, and the spread of the function at the 50th percentile. The peak time corresponds to the time window with the highest response rate, which reflects the accuracy of the remembered time of reinforcement, whereas the peak rate is the response rate associated with the time window used to determine peak time, which reflects the motivational state of the subject. The spread is typically defined as the distance in time between the first and last point that the peak function passes the 50th percentile of normalized peak functions, and reflects the precision in timing specific target durations. All these parameters can be calculated through a fitted function (Church et al., 1994; Buhusi and Meck, 2000), and the importance of establishing the independence of peak time and peak rate has been discussed by Cheng and Meck (2007) and Roberts (1981). A similar procedure is used for human participants, except that a change in the color of the "to be timed" signal is used as feedback during initial fixed-interval training, and later during the PI training feedback is provided by a histogram of responses displayed on the computer screen during the intertrial interval. This histogram provides feedback regarding the relative accuracy and precision of responses that occurred on the just-completed PI trial and is typically presented on 25 percent of the PI trials (Lustig & Meck, 2005; Rakitin et al., 1998).

During the PI phase of training, the participant is asked to reproduce the target duration by making multiple responses (e.g., keyboard presses) that center a window of responding around the previously trained target duration(s). In this way, the PI procedure can be used to study the three stages of interval timing that are typically described by scalar timing theory: clock, memory, and decision (Allman et al., 2014; Church et al., 1994; Gibbon et al., 1984; Rakitin et al., 1998). Briefly speaking, during training, the model suggests that the internal clock tracks the duration of the signal until its termination, at which time the clock output is stored in memory if it is associated with a significant event. Later, during probe trials, a sample of this target duration is retrieved from the distribution of remembered times learned on previous trials and compared with the current clock reading. If the ratio of this comparison surpasses a "Start" threshold, the subject will initiate the sequence of centering a window of responding around the target duration. If the ratio of this comparison surpasses a second threshold, referred to as the "Stop" threshold, the subject will terminate the response sequence (Agostino et al., 2013; MacDonald et al., 2012). One variant of the PI procedure called the "tri-peak" procedure, in which the subject is trained to simultaneously time three different target durations, is a powerful technique for studying effects on clock speed and memory as well as the independence of the timing processes associated with each of the target durations (Buhusi & Meck, 2009b; Cheng et al., 2006; MacDonald & Meck, 2005; Matell et al., 2004). Indeed, the temporal and motor components of response preparation and execution are frequently dissociable in preclinical studies (Cotti et al., 2011; MacDonald and Meck, 2004, 2005, 2006).

In clinical psychology and psychiatry, there is an attempt to better understand underlying gene-brain behavior and cognitive processes that may be malfunctioning in cases of psychological disturbance (Meck et al., 2012; Sysoeva et al., 2010; Wiener et al., 2011). The problem for modern psychiatry as a form of medicine is that it has a nomenclature of mental illness, but few known etiologies. The "mind" is considered an emergent property of the brain, not a "product" like urine from a kidney. The presence of mind is based on the interactions of elements in the brain, and the adequate organization of elements is fundamental for all conscious mental features (faculties, drives, and responses). One of the first psychiatrists to characterize *time* in psychopathological minds was Eugene Minkowski (1885–1972), whose book *Le temps vécu: Études phénoménologiques et psychopathologiques* was highly influential upon being translated into English. Minkowski wrote,

> the psychopathogical personality has lost, or has never achieved, the normal equilibrium which is constituted between interior and exterior forces. As a result, the psychopathologic personality conditions his world by "putting out of play" certain essential phenomena of life related to time and space, such as chance or the unexpected. The events and changes of the ambient world become profiled on this structure. (Minkowski, 1933/1970, xxii)

Minkowski proposed that schizophrenics lack a "vital contact with reality" and an appropriate "feeling of time" (Minkowski, 1970). At a general level, disorientation in time and inability to coordinate and orientate oneself temporally in the external world is routinely observed in the majority of neurological patients and those with states of mental confusion (e.g., intellectual disability, dementia), who also present with poorly developed abstract concepts of time. Moreover, time perception can be viewed as a fundamental aspect of consciousness because it allows us to detect space, time, and number relations (e.g., temporal order) and to derive meaning through the "binding" of events in terms of past, present, and future actions using a "self-referential" system (Chafe, 1994; Cordes et al., 2007; Fujisaki & Nishida, 2010; Hameroff & Penrose, 1996; Joliot et al., 1994; Moiseeva, 1988; Smythies et al., 2012; Vatakis et al., 2007; Wittmann et al., 2010).

Recently, there has been a burgeoning interest in the subjective experience of time in certain psychiatric disorders with a known neuropathology of the basal ganglia and other brain regions identified with timekeeping, such as Huntington's disease and Parkinson's disease (Allman & Meck, 2012; Beste et al., 2007; Harrington et al., 2011; Jahanshahi et al., 2010; Jones & Jahanshahi, 2013), or by virtue of diagnostic psychopathological distortions in the apparent temporal organization of cognition or behavior, such as attention-deficit/hyperactivity disorder (ADHD), autism, obsessive-compulsive disorder, and schizophrenia (Allman & Meck, 2012; Gu et al., 2011; Meck, 2005). Deviations from "normal" timing patterns have been obtained with a variety of targeted psychological, psychiatric, and neurological patient populations on both temporal-production and time-perception tasks (for reviews, see Allman & Meck, 2012; Coull et al., 2011; Cutting and Siler, 1990; Meck & N'Diaye, 2005; Meck et al., 2008; Melgire et al., 2005; Penney et al. 2005), as well as those assessing temporal perspective taking and internal notions of time (see Lehmann, 2006). These findings won't be reviewed here—instead, what follows is an attempt to link diagnostic features of certain disorders with descriptions of previously reported differences in the experience of *time* (e.g., see Allman, 2011; Allman et al., 2011, 2012, 2014; Balci et al., 2009).

Certain findings obtained from individuals with schizophrenia and autism have been discussed within the bounds of atypical experience of the "psychological present." Although the notion of the psychological present is somewhat woolly, it has a venerable history in the study of psychology. Harvard psychologist William James described it as "no knife-edge, but a saddleback, with a certain breadth of its own on which we sit perched, and from which we look into two directions of time [past and future]" (1890, 609). The "psychological present" has been much debated, and has been proposed to have a range of between 3 to 8 seconds (akin to a car headlight illuminating a limited amount of road only so far ahead). This likely corresponds to a putative temporal platform (possibly related to temporal capacities of attention, short-term/working memory, and segmentation of speech; e.g., see Pöppel, 1997). Accordingly, within this temporal platform, successive sensory inputs are "bound" together and integrated into a unified group. Thus, the "present" appears as a continuous flow (Delacroix, 1936). Certain findings from time-perception and timed-response tasks are consistent with the suggestion that the temporal breadth of this platform, or its ability to be "linked" to other temporal platforms in a sequence, may be disturbed in individuals with autism, although to date this has not been explicitly tested (see Allman & Meck, 2012; Allman et al., 2012).

It is widely believed that (within the bounds of the psychological present) people with schizophrenia experience an overload of sensory input and lack the executive functioning skills to compensate and "sift-through" information. Schizophrenics often produce "word salads" and lose track of a train of thought, failing to link different sentences appropriately. Theories of autism also propose a form of sensory overload, with certain senses tending to become highly arousing (visual) or aversive (auditory, tactile). It has been recently shown that children with autism "bind" sensory information over a longer extended time window than is typical, thus exhibiting a temporal binding deficit (Foss-Feig et al., 2010). At a general level, clinical disorders characterized by differences in sensory processing, sequencing and speed of thought, and behavior, might be expected to violate normal theoretical and modeling assumptions about *how* time is typically computed (Allman et al., 2014; Pronin & Jacobs, 2008; Pronin et al., 2008).

Minkowski proposed that certain psychiatric populations (schizophrenics) understand "before" and "after," but live very much in the present, and it has been claimed the "past, present and future may become telescoped together [in schizophrenia], or time may stand still or cease to exist all together" (Lehmann, 2006, 804; Minkowski, 1970). Duke University psychiatrist Frederick Melges (1935–1988) described paranoid psychiatric patients as having a form of "temporal disintegration"—memories of the past, perceptions in the present, and expectations in the future may be confused and appear to be happening at the same time, thus they may appear interconnected (Melges, 1982). By a similar account, depersonalization appears correlated with the confusion of past, present, and future: "as a person loses his sense of contiguity through time, he experiences himself as strange and unreal" (Melges et al., 1974, 855). According to Melges and his colleagues, changes in the temporal *form* of cognitive processes are likely related to the development of unusual thought content and delusions (Melges et al., 1974).

Temporal perspective taking, as it relates to a focus and awareness of events in the past and future, has the potential for interfering with goal-directed thinking: "If a person cannot keep a goal in mind and adjust his thinking accordingly, his thoughts are apt to wander in many different directions" (Melges et al., 1974, 855). Children with ADHD and adults with aberrant impulsive behaviors appear less tolerant to delays in the imagined future—as if they consider them too long. Feelings of sadness, as Minkowski noted, often accompany thoughts of the past, and people suffering from depression and compulsive neuroticism may tend to "live in the past," while neurotics in general tend to neglect the present (see Lehmann, 2006; Minkowski, 1970). It has been reported that children with autism experience difficulty imagining past and future changes to a current situation, understanding that things change over time but are still the same thing, and that successive events are part of a unitary process (Boucher et al., 2007).

Perhaps a universal strategy we share when trying to imagine millions of years of erosion in the Grand Canyon is to conceive the longest time we can, and multiply *n*-fold. By the same token, the length and complexity of an autistic individual's routines and repetitive units of behavior has been argued to index their ability to imagine extended amounts of time. It has been clinically noted that "most people with autism feel lost in a sea of time … they will often try to develop routines and rituals by way of compensation" (Peeters & Gillberg, 1999). This type of account is consistent with principles from behavioral theories of timing, in which sequences of behavioral states function to discriminate time (Killeen & Fetterman, 1988). Indeed, people with profound intellectual disability can reproduce durations as accurately as "normal" children only if they are allowed to engage in repetitive behaviors during the interval or are provided with an external rhythmical structure (e.g., Amos, 2013; Hardy & LaGasse, 2013).

Of course, if external timing supports are successful in ameliorating diagnostic features of a disorder, this may be an indicator that the disorder includes some form of temporal dysfunction. As highlighted in the movie *The King's Speech*, singing to music can make a stammer "disappear." Lionel Logue's interventions worked because speech requires the guidance of temporal cues generated internally, but this system is anomalous in those who stammer. Instead, external musical "beats" are required to activate the timing system (perhaps in the basal ganglia, cerebellum, and lateral motor circuit—see Allman et al., 2014), and provide the temporal cues that enable the speaker to appropriately initiate and maintain speech (Alm, 2004). In a similar vein, computer-based rhythm and timing training has been shown to improve attention capacity in children with ADHD, and motor (and depressive) symptoms in Parkinson's disease have been found to improve with rhythmical auditory stimulation (Thaut et al., 2001).

The brain-behavior basis of timing and time perception is consistent with the neurobiology of stereotypic behaviors—the repetitive, apparently functionless motor behaviors (such as rocking back and forth, spinning) often observed in persons with intellectual disability, and atypical sensory processing (e.g., autism, schizophrenia). In much the same way that external "beats" improve the temporal organization of speech (in those who stammer), the brain may attempt to compensate for inadequate perception of time by generating its own external "beat"—stereotypic behaviors are typically produced in regular repeating cycles, and may be separated by (often short) intervals in time. By this account, stereotypic behaviors (and "stimming" in autism) may serve to facilitate temporal processing of sensory information within the bounds of the psychological present, parse the passage of time, and link the passage of time with ongoing activities (much like the sound of a clock ticking indicates the expiration of a minute). It is interesting to note that during periods of waiting (another situation that poses a particular challenge for those with schizophrenia, autism, ADHD, or states of confusion) most "normal" people will often start tapping their fingers or rhythmically swaying their legs. This is usually attributable to behavioral disinhibition, but might function (or be a product of an attempt) to facilitate the endurance of time—if the sense of progression of self through time seems to be blocked.

The identification of a sheet of neurons, known as the claustrum, separating the neocortex from the more ancient basal ganglia has opened the door to the study of time and consciousness (Crick & Koch, 2003, 2005; Smythies et al., 2012). Because of its strategic location, the claustrum is able to correlate activity from widely distributed cortical regions representing a multitude of sensory inputs. Moreover, the ability of the claustrum to serve as a coincidence detector for thousands of convergent oscillatory inputs that are synchronized by stimulus onsets and modified by feedback-induced alterations of synaptic weights is exactly what one requires to simultaneous monitor the durations of multiple signals and to bind separate sensations into a unitary representation of time and space (see Allman & Meck, 2012; Coull et al., 2011; Kotz & Schwartze, 2011; Matell & Meck, 2000, 2004; Meck et al., 2008; Penttonen & Buzsáki, 2003; Van Rijn et al., 2011).

Although there is no psychological disorder characterized solely as a disorder of time estimation, Minkowski argued that "in all psychopathologic cases, some distortion of lived time or lived space has occurred … although in normal life lived time and lived space can never be separated, certain mental disorders can be characterized in terms of a distortion in time" (Minkowski, 1970, xxii). A complete loss of a sense of time is perhaps protected by the notion of "degeneracy"— time perception is such a basic and critical process that other brain mechanisms will likely take over this function if the main timekeeper fails (Lewis

& Meck, 2012; Price & Friston, 2002). Normal subjective variations in temporal experience ("time flies when you're having fun"), coupled within individual differences, add color to our daily existence, and allow us to appropriately adapt to current environmental demands (Avni-Babad & Ritov, 2003; Droit-Volet & Meck, 2007; Hinton & Meck, 1997a; MacDonald & Meck, 2003). These variations may also be artifacts of how our brains process information under different conditions. According to this account, individuals may produce maladaptive behaviors through insensitivity to variations in time, differences in the intensity of experiencing them, or the overload of simultaneous temporal processing (Buhusi & Meck, 2009b; Lustig & Meck, 2009; Meck & MacDonald, 2007). Of course, if we really want to ponder what it might be like to be lost in a sea of time, we can always return to thinking about the Grand Canyon or consider the ancient question of "What then is time?," proposed by Saint Augustine more than 1,600 years ago in his attempt to define time as a set of reference points between events (Augustine, 1961, Book XI, p. 123).

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XI Reflections

30 The Disunity of Time

Dan Lloyd and Valtteri Arstila

In our mundane terrestrial pursuits, local clocks unite to give the one and only current time, fixing orders and intervals. Since physics follows the clock, we are obliged to be aware of time and timing in order to act effectively and perceive accurately in the real world. Our sensitivities to orders and intervals fall under the general concept of subjective time. In its primary meaning, subjective time is the *experience* of temporality, the phenomenology of duration and passage explored in the first two sections of these volumes. But time is nonetheless experienced in the experiments surveyed in the remaining sections. The responses tracked in all of them are conscious and deliberate (at least for the humans involved). A button press is as good as a verbal report in establishing that two intervals seem—subjectively—to be of equal duration.

Nonetheless, a sharp methodological divide separates the phenomenology and the psychology, and with it two core senses of subjective time emerge. In the opening chapters of this volume, philosophers of temporality drew our attention to the fundamental and pervasive (if paradoxical) presence of past and future in our conscious lives. Every object of experience is surrounded by some sort of awareness or remembrance of what just happened, and some sort of anticipation of what is to come. Because this apprehension is nonsensory, idiosyncratic, and ubiquitous, it does not lend itself to experimental study. At best, we "confirm it for ourselves." In these discussions we encounter temporality as *embedded* in the totality of conscious life.

Meanwhile, humans and many other animals can learn a variety of behaviors and judgments hinging on time itself. Down to certain thresholds, we can detect simultaneity, order, and duration. We can also make secondary judgments of the rate of passage. Binding all these tasks together is time, but time under a certain description, namely, the quantized progression of a single magnitude—clock time. With the clock as a measure, all of these judgments and behaviors are open to lab study. In these experimental settings, time moves to center stage. Intervals and durations are attended targets, and responses are signals of an awareness of passing time as such. The time of these experiments we might call "explicit temporality."

Subjective time, then, comprises both embedded temporality and explicit (conscious) timing. Even in the lab, our time experience is embedded in a fabric of perception and action from which we can never be disconnected. Likewise, walking down the street we are surrounded by events and objects with temporal properties that we are explicitly tracking, drawing on the cognitive capacities measured by experiments. We might therefore think of the experiences of explicit temporality as a special subset of the ubiquitous embedding of time in life.

As with cognitive science overall, we use the stripped-down and controlled experimental environment as a playground for examining fundamental cognitive capacities. Hundreds of experiments have been described in the pages above. As the clock of this book strikes twelve, what can be concluded (however tentatively) about subjective time, beginning with explicit time and timing? Putting it broadly, the message of the experimental review is that subjective time is subject to a broad and unruly relativity. The metaphorical flowing river might be replaced by a sputtering fireworks display. Timing is multifaceted, inconsistent, and variable.

30.1 Dyschronicity

The concert hall has gone quiet. The conductor raises the baton, and Mahler's First begins with a sustained chord. You can see it—the bows of all the strings digging in—and you can hear it—a majestic, austere minor opening. If you know the symphony well, you might anticipate its duration and even notice a deviation from its expected length, a first hint of how the conductor will interpret the work. You might notice these things, but what you won't notice is that the sound of the chord lasts longer than the sight of it (the bowing string section). Yet in the lab, a tone of duration *x* will be judged to last longer than a steady light of the same length. If this conflict were noticed in the concert hall, we should experience a paradox. The same opening chord should seem to have two durations, a "heard duration" longer than its "seen duration." The embedded timing of the symphonic experience and some aspect of its explicit timing should diverge.

The psychology of time is full of dissociations like the divergent judgments of heard and seen durations. Nontemporal differences of many kinds have subjective temporal effects. For example, filled intervals (continuous lights or tones) are judged to last longer than empty intervals (intervals whose endpoints are signaled by a brief tone or light). Context matters: a click train preceding a target interval will affect the judged duration of the interval. Action matters: the brief interval of each saccade is erased from awareness and from the accumulated sensibility of duration; causation and agency compress intervals. Modality matters: simultaneity has very different thresholds for different senses. Within modalities, detection of different features occurs on different timelines: changes in motion seem to occur at different times than concomitant changes in color. Attention matters: time judgments alter when attention is directed to a certain anticipated interval; even attention to a region in the visual field can alter time judgments for events at that location. Time judgments are also surprisingly plastic. Inserting a delay between a button press and its effect (a light flash or tone) can quickly adjust perceived simultaneity.

These are just some of the many bends in time. As in the example of the opening chord, these dissociations are surprising because our naïve, prescientific experience of time gives no hint of the asynchrony of the component psychological processes of time perception. Contrast this complacency to the experience of "impossible objects" such as the Penrose triangle, the blivet (or "devil's tuning fork"), impossible cubes, stairs that both ascend and descend—familiar props in the work of M. C. Escher. The pleasure in all of these lies in our immediate awareness of incongruity among visual cues. Yet we seem oblivious to the rampant incongruities among temporal cues. There is no double take when it comes to time.

Embedded time is thus surprisingly uniform in its appearance to us. How is this to be explained? The possible answers provide different paths for future study in the science of subjective time. Here are two possibilities.

1. The successive spotlight of temporal attention excludes conflicting time judgments by limiting the number of concurrent processes. One way to resolve two conflicting items of information is to ignore one of them. Attention in its normal function could perform this service for temporal judgment. We might experience a sequence of attended timer outputs; the asynchrony of these timers would not appear in the absence of a direct comparison between them.
2. Lowering the thresholds of temporal acuity increases tolerance for contradiction. Where magnitudes are approximate, so are comparisons. It may be that the peaks of explicit timing found through experiments are not so precise in temporal experience. So, in the symphony example, the different detected durations of sight and sound may be qualified by "more or less." Being used to discrepancies, we have a range of tolerance for all temporal judgments that allows the temporal dissociations to pass without notice.

Temporal attention and temporal acuity are not exclusive. Certainly, the bottleneck of attention limits the number of cognitive processes that can effectively occur, and this would presumably include timing processes. But there are some temporal judgments in which timing comparisons are seemingly unavoidable. These are judgments of simultaneity and time order, often involving the timing of different events mediated by different modalities and subject to different thresholds. The preceding chapters have made it clear that simultaneity and order are no less multifarious than intervals and durations. In the face of these dissociations, embedded time seems to tolerate discrepancy. The two loopholes could enable a stable impression of a single uniform subjective time.

The notions of temporal acuity and temporal tolerance provide a slightly different interpretation of the well-known scalar property of timing. The scalar property essentially states that variance in time judgments increases as intervals and durations increase. It implies that at every scale, there is some variation in repeated time judgments. In embedded contexts, then, a time judgment will fall somewhere in a range, which broadens as durations and intervals increase. Two judgments may differ in comparison, but without contradiction—if each falls within the scalar tolerance of the other. The price of tolerance is precision, but the reward is a smooth experience of embedded time, where time itself is always a single, continuously advancing magnitude.

One domain where local time is smooth and unified is the physical world, the scaffold for subjective time and everything else. It is an elaborate scaffold indeed. Our temporal coordination with the world is a complex and continuously updated amalgam of perception and judgment of all sorts. An interval between two events might feel too long or too short on a scale comprising many other physical and behavioral sequences and processes that are "just right." When we put a pot on the stove, all we expect is that it will boil—eventually—and that we have time to make a sandwich and set the table meanwhile. We don't expect to have enough time to do those things and read the paper too. Each of these component sequences decomposes into stages, some long and some short. The time line is really no more than a series of events in an expected sequence—it is just one thing after another. Once the series is dense enough with events, the rate of passage begins to look like an incrementing parameter, an approximation of clock time. Meanwhile, in a laboratory setting, all this folk wisdom of sequence and duration is set aside. What remains is a thin residue of temporal cues (respiration, heart rate, saccades, etc.), which can only inform a rudimentary capacity to estimate the abstracted quantities of elapsed time.

In short, the real world may provide a bridge between the dissociations of explicit timing and the stability of embedded time. This, together with the loose and limited aggregation of internal timers, may provide the foundation for a good-enough edifice of subjective time.

30.2 Many Mechanisms

Subjective time, we suggest, is a complex structure built of many parts. It is embodied and embedded in the world. Nonetheless, it is not wholly comprised of perceptions of external events. Can we conjecture about its cognitive component, the time-giving mechanisms of the brain? If there are many dissociable tasks of timing, then it seems less likely that a single central time-giver lurks in the brain. Rather, there are many time-dependent processes. The sensitivity of timing to nontemporal factors in turn suggests state-dependent timing processes. Embedding supports and expands this possibility. Subjective time is dependent not just on the state of the brain but on all the time cues of the world, second by second. These considerations militate against a localized center for time processing in the brain. Indeed, in this book several brain areas have been mentioned, and other contenders can be found in the research literature. Table 30.1 lists some of these. Far from being an exhaustive list, the table indicates the variety of brain areas proposed as correlates of temporality.

The regions highlighted in the table certainly share timekeeping with other cognitive functions. Moreover, their temporal functionality may be confounded with task difficulty (Livesey, Wall, & Smith, 2007), further challenging the idea of "time centers" in the brain. For other discussions of distributed timing mechanisms and nonspecialized timing mecha-

Table 30.1

Brain regions involved in timing and temporal awareness

Left frontal lobe (temporal binding)	Pöppel and Bao, chapter 12
Posterior parietal cortex (time-order judgments)	Jaśkowski, chapter 19
Insula (duration, attention to time)	Wittmann, chapter 24
Supplementary motor area, basal ganglia, cerebellum (short intervals)	Wittmann, chapter 24
Right prefrontal and parietal cortex (intervals of seconds)	Wittmann, chapter 24
Right supplementary motor area (reproduction of suprasecond intervals)	Noreika, Falter, and Wagner, chapter 25
Right frontal cortex (duration storage, recall)	Naish, chapter 28
Right dorso-lateral prefrontal cortex (interaction between timing mechanism)	Naish, chapter 28
Claustrum (coincidence detection)	Allman, Yin, and Meck, chapter 29
Hippocampus (incremental passage of time)	MacDonald et al., 2011
Basal ganglia (interval timing)	Buhusi & Meck, 2005; Meck et al., 2008
Right inferior parietal cortex (duration as magnitude)	Walsh, 2003
Right prefrontal cortex (interval comparison)	Lewis & Miall, 2006
Medial prefrontal cortex, lateral temporal cortex, hippocampus	Lloyd, 2012

nisms, see Mauk and Buonomano (2004), Buonomano (2007), and Eagleman and Pariyadath (2009).

30.3 Toward a Future Time

At every scale, the brain asks: What's next? Likewise, the big book of subjective time appropriately closes with a look toward the future. Arguably, it is an unnecessary addendum, since the researchers assembled here all express a clear direction in the work they review. But if we were to offer our own gentle suggestions, we might highlight three broad areas:

1. Ecologically situated timing. The studies of embedded time and explicit time need not be mutually exclusive. Several authors here have used realistic stimuli (like film clips, observed speech, and naturalistic sounds) as the basis for generalization. Not surprisingly, these naturalistic stimuli engage a wider range of responses, particularly emotional responses (like interest or boredom), along with cognitive discrimination and evaluation—and all of these seem to affect timing judgments. Similarly, several authors have advocated embodied conceptions of temporality, drawing attention to the action-orientation of cognitive life, and to the physical body as the field on which time works and as a frame for its representation. These strands can be brought together through more studies in which time is explored in realistic settings involving subjects enmeshed in meaningful environments, settings requiring attentive action and choice. Such real-world scenes will likely include external

time cues, but this is to be welcomed, as our review of human timing capacities suggest that external temporal scaffolding is important. The worldly time-givers need to be folded into the total picture of subjective time. "Ecological realism" certainly poses methodological problems for experimental design, but in these chapters we've seen several examples of effective yet realistic experiments.

2. Basic neural mechanisms of timing and temporality. As noted above, there is as yet no consensus on brain areas involved in time, and there are reasons to doubt that timing is a central dedicated function of any particular brain area. In any case, at the neural level there is mystery where time is concerned. In at least some situations, time passes in settings where nothing (else) is changing, and yet we detect its passage. How does that work? There will likely be many answers at different timescales and possibly mediated by different mechanisms altogether in different regions. This volume has had quite a bit to say about possible mechanisms, but even proponents of particular theories would probably agree that this pervasive sensitivity must emerge from an equally pervasive underlying circuitry.

3. Temporality in psychopathology, developmental disorders, and altered states of consciousness. Another kind of diversity emerged in the reviews in the last section of this volume. Some psychologically disordered states and diseases are typically accompanied by fairly specific deficits in timing abilities. As with disorders in general, these deficits and what is known of their physiology offer clues to the typical operation of the temporal brain. However, time may be more than just a side effect of other cognitive problems; in the previous chapters, we see suggestions that disordered subjective time is constitutive of some conditions and diseases. Subjective time could provide an explanatory link among conditions that may not otherwise seem similar (Lloyd, 2007).

30.4 Subjective Time without End

Our active engagement with the future and the past is the foundation for caring and daring, and the source of intelligence, ethics, and (sometimes) wisdom. For each of us, subjective time will come to an end. Likewise, *Subjective Time* (the book). Collectively, however, subjective time and research thereon flows toward an indefinite and open future. We conclude the book in a subjective mood of hopeful anticipation.

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