Research in Developmental Disabilities 90 (2019) 41–50

Contents lists available at ScienceDirect

Research in Developmental Disabilities

journal homepage: www.elsevier.com/locate/redevdis

Modality and redundancy effects, and their relation to executive functioning in children with dyslexia

Carolien A.N. Knoop-van Campen[a,*], Eliane Segers[b], Ludo Verhoeven[a]

[a] Behavioural Science Institute, Radboud University, Netherlands
[b] Behavioural Science Institute, Radboud University, Department of Instructional Technology, University of Twente, Netherlands

ARTICLE INFO

Number of reviews completed is 2

Keywords:
Modality and redundancy effect
Multimedia learning
Dyslexia
Executive functions
Primary school

ABSTRACT

Children with dyslexia are often provided with audio-support to compensate for their reading problems, but this may intervene with their learning. The aim of the study was to examine modality and redundancy effects in 21 children with dyslexia, compared to 21 typically developing peers (5th grade), on study outcome (retention and transfer knowledge) and study time in user-paced learning environments and the role of their executive functions (verbal and visual working memory, inhibition, and cognitive flexibility) on these effects. Results showed no effects on retention knowledge. Regarding transfer knowledge, a modality effect in children with dyslexia was found, and a reversed redundancy effect in typically developing children. For transfer knowledge, written text with pictures supported knowledge gain in typically developing children, but not in children with dyslexia who benefited more from auditory-presented information with pictures. Study time showed modality and reversed redundancy effects in both groups. In all children, studying in a written text with pictures condition took longer than with audio replacing the text or being added to it. Results also showed that executive functions were related to learning, but they did not differ between the groups, nor did they impact the found modality and redundancy effects. The present research thus shows that, irrespectively of children's executive functions, adding audio-support for all children, can potentially lead to more efficient learning.

1. Introduction

Children with dyslexia have a phonological deficit and experience reading difficulties (Lyon, Shaywitz, & Shaywitz, 2003). They are often provided with audio supported texts to compensate for their reading problems. From a theoretical point of view, combining different media may interfere with children's learning process. The Cognitive Theory of Multimedia Learning (CTML; Mayer, 2005) states that, based on working memory overload, presenting the same information simultaneously as text and as audio hampers learning (i.e., the redundancy effect). Furthermore, people learn more from pictures with audio than from pictures with text (i.e., the modality effect). These multimedia effects have mostly been found in system-paced learning environments and directly after learning (Ginns, 2005), while in user-paced settings, where learners can determine their own pace, and on the long-term, no or even reversed effects have been found (Tabbers, Martens, & Van Merrienboer, 2004; Witteman & Segers, 2010). The role of working memory in explaining such effects has hardly been studied, even though it is fundamental to the CTML. While working memory is a central concept in the CTML, it is also part of the larger construct executive functioning. Executive functions control and regulate non-automatic behavior (Diamond, 2013) and are important predictors for academic success (Best, Miller, & Naglieri, 2011) and may

* Corresponding author at: Radboud University, Behavioural Science Institute, Montessorilaan 3, 6525 HR, Nijmegen, Netherlands.
E-mail address: c.knoop-vancampen@pwo.ru.nl (C.A.N. Knoop-van Campen).

https://doi.org/10.1016/j.ridd.2019.04.007
Received 4 July 2018; Received in revised form 1 April 2019; Accepted 9 April 2019
Available online 30 April 2019
0891-4222/

influence multimedia learning as learners have to switch between the different modalities and inhibit (redundant) information. Although children with dyslexia tend to have lower executive functions (e.g., Booth, Boyle, & Kelly, 2010), studies so far have not examined the role of executive functions related to their multimedia learning outcomes. Therefore, the focus of the present study was on modality and redundancy effects in multimedia learning in children with dyslexia in relation to their executive functioning.

1.1. Multimedia learning in children

The CTML (Mayer, 2005; Mayer & Fiorella, 2014) links cognitive resources to the impact of combining different media on learning. The CTML assumes that information comes through an auditory and visual channel and that each of these channels has a maximum capacity. More information can be processed, and thus learned, when presented visually and auditory at the same time (spoken text with pictures), compared to visual presentation only (written text with pictures). This is called the modality effect. A meta-analysis (Ginns, 2005) showed that this modality effect is robust. However, there are boundary conditions (Tabbers, 2002): the presence and strength of the effect depends on the type of learning environment. The modality effect tends to weaken or disappear in a user-paced learning environment where people can determine their own pace (Witteman & Segers, 2010) instead of a system-paced environment where the material is programmed to move on after a certain amount of time has passed. In addition, over time the modality effect also seems to disappear or reverse (Savoji, Hassanabadi, & Fasihipour, 2011; Scheiter, Schüler, Gerjets, Huk, & Hesse, 2014; Segers, Verhoeven, & Hulstijn-Hendrikse, 2008; Tabbers et al., 2004). So, in user-paced learning environments and on the long-term, learning from pictures with audio does not seem more effective than learning from pictures with written text; sometimes written text may even be better.

In a similar vein, the CTML (Mayer, 2005) states that presenting the same information visually and auditory at the same time (written text with narration) would hamper learning due to causing cognitive (over)load. This is called the redundancy effect. The visual and audio channels have to process the same information, which requires working memory capacity, which is no longer available for learning. The redundancy effect can be showed in two ways: 1) comparing audio-only to written text with audio, or 2) comparing text-only to written text with audio. In both, pictures accompany the study material.

The redundancy effect has been clearly shown when audio-only is compared to text-audio. Higher learning gains have been shown in the condition in which learners only hear information (e.g., Jamet & Le Bohec, 2007; Kalyuga, Chandler, & Sweller, 1999; Mayer & Moreno, 2002). However, in schools, audio is often added to written text (for example, by read-aloud-support), in which the audio can be considered as the redundant information. Few studies investigated the redundancy effect in comparing text-only to text-audio, and the results of these studies are contradictory. Moreno and Mayer (2002) found a positive effect of the text-audio condition, while Diao and Sweller (2007), and Gerjets et al. (2009) found a negative effect of adding audio to written text. To our knowledge, no studies to date have examined redundancy effects on the long-term.

1.2. The role of executive functioning in multimedia learning

Working memory has been widely established to affect learning (e.g., Unsworth & Engle, 2007), but its influences on multimedia effects are hardly investigated. Working memory capacity theoretically drives both the modality and redundancy effect. It is therefore striking that the one study (Witteman & Segers, 2010) that examined the influence of working memory on multimedia learning in user-paced learning environments in typically developing children did not find a relation between working memory and modality effects. Another study in adults also did not find working memory to impact effects of multimedia learning (Gyselinck, Jamet, & Dubois, 2008). A study that compared university students with high and low working memory capacity on the redundancy effect (Seufert, Schütze, & Brünken, 2009), did not find differences on retention knowledge. On transfer of knowledge (quality of knowledge – the ability to apply knowledge to a new situation/problem), working memory mattered in a visual-only condition, while it did not impacted scores when audio was added. An explanation that can be put forward is that working memory is less important when learners can determine their own pace; when needing more time, they can slow down, which reduces their cognitive load. This may also explain the weaker or disappeared modality and redundancy effects in user-paced environments compared to system-paced environments.

Working memory is part of a larger umbrella term: executive functions. Executive functions entail various aspects of higher-order cognitive functions and are generally assumed to control and regulate non-automatic behavior (Diamond, 2013). Executive functions are important predictors for academic success (Best et al., 2011). Next to working memory, two other key components of executive functions are distinguished (St Clair-Thompson & Gathercole, 2006; Miyake et al., 2000): inhibition and cognitive flexibility. Inhibition refers to the ability to deliberately inhibit automatic responses, while cognitive flexibility is the ability to shift between mental states, rule sets, or tasks.

In the past decades, the focus in multimedia learning has been on working memory. This ignores the importance of inhibition and cognitive flexibility in learning in such environments. In multimedia environments, learners are presented with much information and need to be able to focus on the important aspects and inhibit the impulse to get distracted by other parts of the multimedia-learning environment. There is wide agreement that inhibitory skills are related to learning gain, as learners have to inhibit redundant or irrelevant information in multimodal environments (Kalyuga, 2007; Terras & Ramsay, 2012), and guide their attention to the most relevant information (Schmidt-Weigand, Kohnert, & Glowalla, 2010). To the best of our knowledge, no research on CTML has connected executive functioning to multimodal learning. Mayer (2005) does address inhibition and multimedia learning, however, and suggested that when inhibition declines with age, elderly should avoid redundant information to optimize their understanding of the information presented. In other words, even though inhibition seems important for multimedia learning, its role in multimedia learning has not yet been examined.

Next to inhibition, cognitive flexibility may affect multimedia learning. Learners need to be able to switch between the different multimedia aspects (written text, picture and/or audio, and integrate the provided information. Cognitive flexibility thus seems to become more important when more information is presented. Kieffer, Vukovic, and Berry (2013) showed that cognitive flexibility makes a unique contribution to reading comprehension, both directly, as well as indirectly via language comprehension. This suggests that although cognitive flexibility is important in learning from both written and spoken text, it may influence learning from written text differently than learning from spoken text; Kieffer et al. (2013) argued that it could play a role in real-time processing of oral language. When learning in a multimedia environment, switching between modalities can result in an increase cognitive load and thus lower knowledge gain (Sweller, 1988). An eye-tracking study revealed that in learning environments with pictures and written text compared with pictures, written text, and voice-over, students followed the voice-over in examining the picture. With the voice-over, their attention was drawn more to the pictures (Liu, Lai, & Chuang, 2011). Added audio reduces the necessity to constantly switch between the written text and pictures. Furthermore, Kalyuga (2000) suggested that switching between audio and picture is less demanding than between pictures and text, for it reduces the demand on one's cognitive flexibility.

In all, individual differences in executive functions may be important for multimedia learning. Higher executive functions may support learning in a multimedia environment and decrease modality and redundancy effects.

1.3. Multimedia learning in children with dyslexia

Children and students with dyslexia often use multimedia in the form of reading software (Ghesquière, Boets, Gadeyne, & Vandewalle, 2010) and/or text-to-speech software (Draffan, Evans, & Blenkhorn, 2007) both facilitating the computer to read the learning material out load. These children have phonological deficits and experience reading difficulties (Lyon et al., 2003). Consequently, extra cognitive capacity is needed for reading: working memory capacity that cannot be used for learning. In addition, a lower working memory was found in children with dyslexia (Berninger, Raskind, Richards, Abbott, & Stock, 2008; Swanson, Zheng, & Jerman, 2009) and also inhibition is generally assumed to be hampered (Reiter, Tucha, & Lange, 2005; Wang, Tasi, & Yang, 2012). Existing literature on cognitive flexibility in children with dyslexia is ambiguous. Some studies found children with dyslexia performing more poorly on cognitive flexibility (Helland & Asbjørnsen, 2000; Moura, Simões, & Pereira, 2015), while others did not find differences between children with and without dyslexia (Reiter et al., 2005; Van der Sluis, De Jong, & Van der Leij, 2004). A meta-analysis on executive functions in children with reading difficulties (including children with dyslexia) showed that these children have impairments on tasks of executive function (Booth et al., 2010).

Children with dyslexia are often provided with audio to support their reading (Ghesquière et al., 2010). However, presenting information in different modalities may hamper their learning according to CTML. People with dyslexia have more difficulties processing verbal and audio presented information simultaneously (Lallier, Donnadieu, & Valdois, 2013) and with switching their attention from visual information to audio-presented information, leading to more or faster cognitive (over)load (Harrar et al., 2014). With regard to multimedia learning, Alty, Al-Sharrah, and Beacham (2006) showed that university students with dyslexia learned more from written text only, than from text and diagrams or from audio and diagrams. A recent study on multimedia learning and dyslexia showed similar results (Wang et al., 2018). They did not find modality effects on recall and recognition, but students with dyslexia did learn more from written text with pictures than from audio with pictures (reversed redundancy effect: Wang et al., 2018). Research in primary school children with dyslexia also showed no modality effects on retention and transfer when comparing multimedia conditions, but there were modality effects in learning efficiency (Knoop-van Campen, Segers, & Verhoeven, 2018). Children with dyslexia in this study were much slower in the condition that combined text with pictures, and comparable to their typically developing peers in the condition that combined audio with pictures. The Authors thus concluded to have evidenced a modality effect on efficiency of studying.

To conclude, research on modality and redundancy effects in typical and atypical learners so far can at best be called contradictory. This may be (partly) be due to the varying ways of measuring knowledge gains. In the classical CTML, open-ended questions were used to assess children's retention knowledge (Mayer, 2005), which taps unto retrieval abilities, while others used recognition tasks, for example multiple choice (Knoop-van Campen et al., 2018; Segers et al., 2018). To keep close to the theoretical paradigm, in the present study we examined modality and redundancy effects with open-ended questions following Mayer (2005). Furthermore, the role of inhibition and cognitive flexibility on modality and redundancy effects in children with dyslexia have not been studied before. Executive functions can be considered important for multimedia learning, especially for students with dyslexia who often show problems in executive functioning, but have not been rigorously examined in light of the CTML.

1.4. The present study

The aim of the present study was to examine modality and redundancy effects on study outcomes and study time in user-paced learning environments in children with dyslexia, compared to typically developing peers, and to examine to what extent children's executive functions influences these effects. Therefore, we examined children with dyslexia and a control group of typically developing peers in user-paced learning environments who all were presented with three different types of multimedia lessons: pictorial information presented with (i) written text, (ii) audio, and (iii) combined text and audio. Directly after completing the learning task and one week later, children were tested on retention and transfer knowledge. Log-files recorded children's study time. Children's verbal and visual working memory, inhibition and cognitive flexibility were examined.

Based on the CTML, we expected modality and redundancy effects, especially on transfer knowledge and study time, which would be stronger in children with dyslexia (hypothesis 1). Further, higher executive functions were expected to support learning in a multimedia learning environment, and decrease modality and redundancy effects (hypothesis 2).

2. Method

2.1. Participants

Seven schools in the Netherlands participated. Informed active consent was obtained from parents and schools. This study was approved by the Ethics Committee of the Faculty of Social Sciences of our university.

All children with dyslexia in this research were officially diagnosed with dyslexia and in possession of an official dyslexia statement according to the clinical assessment of the Protocol Dyslexia Diagnosis and Treatment (Blomert, 2005). The control group was selected from the same classrooms to diminish group influence and were matched on gender. In total, 21 typically developing children (13 boys) aged 10.87 years (SD = .30), and 21 children with dyslexia (13 boys) aged 11.01 years (SD = .54) participated. The children with and without dyslexia did not differ on age, $t(40) = 1.08$, $p = .287$, Cohen's $d = .32$. Only monolingual children were included.

In line with their diagnosis, children with dyslexia (M = 43.20, SD = 6.07) did not differ on general nonverbal intelligence compared to the typically developing children (M = 44.14, SD = 6.05), $t(39) = .48$, $p = .635$, Cohen's $d = .16$. As expected, children with dyslexia did score significantly lower on word reading (M = 55.67, SD = 10.75) and pseudo word reading (M = 26.24, SD = 9.04) than typically developing children (resp. M = 72.91, SD = 11.29 / M = 39.57, SD = 11.22), resp. $t(40) = .5.07$, $p < .001$, Cohen's $d = 1.60$ for word reading, $t(40) = 4.24$, $p < .001$, Cohen's $d = 1.47$ for pseudo word reading.

Two children were removed from further analyses. One child with dyslexia attained very high (pseudo) word reading scores (outliers) compared to the dyslexic group. These scores were comparable with the top sores of the control group. In the typically developing group, one child had a negative outlier on pseudo word reading, comparable to the scores of the children with dyslexia.

2.2. Procedure

Testing was done in an individual setting in school. Children were provided with the lessons on day one, with a direct post-test to measure the learning effect on the short-term. A week later they filled in the posttests. All children were provided with all three multimedia lessons. The three lessons, three modalities and two posttest were offered in a randomized-block-design. Tests were performed on executive functioning.

2.3. Measures

2.3.1. General nonverbal intelligence

The Raven's Progressive Matrices General was used to measure nonverbal intelligence (Raven, 1998) and administered according to its assessment instructions. Sixty visual patterns of increasing difficulty were presented (A-E). In each pattern, children had to choose the missing piece of information from six or eight alternatives. The number of correct answers was used for analysis.

2.3.2. Word reading and pseudo word reading

The *Een-Minuut-Test* (EMT) [One-Minute-Test] and the Klepel (Verhoeven, 1995), was used to measure word decoding and pseudo word (non-existing words) decoding. Both are standardized tests and consists of a reading card with 116 different (pseudo) words in increasing difficulty level. Children have to read out aloud as many items correctly in one minute as possible. The number of correct read items was used for analysis.

2.3.3. Verbal working memory

The subtest Digits-backwards of the WISC-III-NL (Wechsler, 1992) was used to measure verbal working memory and administered according to its assessment instructions. Children had to recall a sequence of spoken digits (between two and nine). Children were asked to recall the sequence backwards, for example when the sequence 5-4-7 was provided, children had to recall 7-4-5. The number of digits in a list increased, until two sequences of the same length were incorrect. The score given was the number of correct recalled lists.

2.3.4. Visual working memory

An N-backwards working memory task with N = 2 (a variant of the 'n-back' procedure, Gevins & Cutillo, 1993) was used to measure visual working memory. This task is commonly used in literature as a visual working memory measure (Baddeley, 2003) and useful in experimental research (Jaeggi, Buschkuehl, Perrig, & Meier, 2010). On a laptop screen, children were presented with numbers (one at a time) and had to press a key whenever they saw a number that repeated after two intervening stimuli (N-2). For example, children saw the sequence 4-5-4, and had to press the key at the second '4'. Stimuli were presented 600 ms with 645 ms in between. Children were presented with 225 stimuli (32 were an N = 2 item). The score given was the number of correct responses.

2.3.5. Inhibition

A Stop-Signal task was used to measure inhibition. On a laptop screen, children were presented with numbers (one at a time) and had to press a key anytime they saw a number, except when they saw ‘3’. Stimuli were presented 600 ms with 645 ms in between. Children were presented with 225 stimuli, (32 were ‘3’). The score given was the number of times they refrained from pressing the key when seeing ‘3’ (a.k.a. number of correct responses).

2.3.6. Cognitive flexibility

The Trail-Making-Test-B (Reitan & Wolfson, 1985) was used to measure cognitive flexibility. Children saw 12 numbers and 12 letters on a paper sheet and had to connect them, while alternating between numbers and letters (1, A, 2, B, etc.). Children were provided with an example sheet to practice. Instructions were according the manual. The score given was the time needed to finish the task.

2.4. Multimedia lessons

All children made three multimedia lessons (balance in nature, motion, and global warmth) in different types of learner-paced multimedia lessons: pictorial information presented with (i) written text, (ii) audio, or (iii) combined text and audio. Lessons and set-up were taken from Knoop-van Campen et al. (2018) and were based on three lessons for a textbook of Grade 6 (1 year above children's school year) to enable the possibility of learning gain. The lessons were comparable in set-up and complexity, and they each involved approximately 530 words. One lesson consisted of 12 slides and every slide showed a picture with written text and/or audio. The children were able to move back and forth through the pages.

2.5. Knowledge gain

The post-tests consisted of both retention and transfer questions. Following Mayer and Moreno (2002) the retention knowledge was measured by asking: ‘Tell me as much as you remember from the lesson’. Answers were recorded and written out. From every lesson 60 words where identified that reflected the content. Children received one point per correctly named item (max is 60 points). The 4 transfer questions were open-ended questions, e.g. “What would happen if the bones of a bird were not hollow inside?”. These questions triggered children to apply the knowledge from the lesson, to a related but new situation/problem. For example, they learned about the greenhouse effect, and were asked to imagine a machine that would counteract the enhanced greenhouse effect. The questions were scored with 0, 1, or 2 points by the first Author according to the scoring-card from Knoop-van Campen et al. (2018). Children could receive max 8 points. The alpha’s of the transfer knowledge were > .80, indicating good reliability.

2.6. Study time

Study time was defined as the time children spent studying a multimedia lesson, as was extracted from the log data of the lessons.

2.7. Data-analyses

GLM repeated measures ANOVA analyses were conducted on both retention and transfer test as well as on study time. First, the modality effect was examined, with time (short-term/long-term) and condition (text/audio) as within-subject-factors, and group (dyslexia/typically developing) as between-subject-factor. Second, a similar analysis was conducted for the redundancy effect, but with the conditions text, audio, and text & audio. Simple contrasts were performed with the text & audio condition as reference category, since we compared text vs. text & audio, and audio vs. text & audio. Both the modality as the redundancy analysis was performed separately for retention and transfer knowledge.

To examine the influence of executive functions on the modality and redundancy effect (retention knowledge/transfer knowledge/study time), in follow-up analyses verbal and visual working memory, inhibition and cognitive flexibility were added as covariates to examine their influences on the modality and redundancy effects.

3. Results

3.1. Descriptives

The means and standard deviations for executive functions and study time, separately for children with and without dyslexia, are provided in Table 1. Children with dyslexia did not differ significantly from the control group on all executive functions. The means and standard deviations for retention and transfer knowledge are provided in Table 2.

Correlations between executive functions and knowledge per group are presented in Table 3. In children with dyslexia, more inhibition correlated with less transfer knowledge in the combined condition. Better cognitive flexibility correlated with more knowledge in the audio condition (retention) and combined condition (transfer). In typically developing children, better visual working memory correlated with less knowledge in the audio condition. Better verbal working memory was correlated with more knowledge in the combined condition. Better inhibition was correlated with less knowledge in the written text condition. Better cognitive flexibility was correlated with more knowledge in the audio condition.

Table 1
Descriptives for Childrens' Study Time and Executive Functions per Group.

	Dyslexia			Typically developing			
	N	M	SD	N	M	SD	*d*
Study time							
Text condition	20	6.82	2.05	19	6.04	2.46	.47
Audio condition	20	5.73	2.03	20	5.36	1.19	.22
Combined condition	20	5.68	1.73	19	5.43	1.12	.17
Executive functions							
Visual working memory	20	9.00	4.97	20	7.90	2.94	.27
Verbal working memory	20	4.55	0.94	20	5.30	1.49	.60
Inhibition	20	12.85	4.92	20	12.20	5.00	.13
Shifting	20	69.95	18.46	20	67.55	19.17	.13

Note: due to computer malfunction, learning time was not recorded in one child.

Table 2
Means and Standard Deviations over Time, per Condition and Group.

		Dyslexia						Typically developing						All children					
		Short-term		Long-term		Total		Short-term		Long-term		Total		Short-term		Long-term		Total	
	Condition	M	SD	M	SD	M	SE	M	SD	M	SD	M	SE	M	SD	M	SD	M	SE
Retention	Text	8.80	5.63	3.55	3.25	6.18	.86	9.90	4.85	4.65	3.80	7.28	.86	9.35	5.22	4.10	3.54	6.73	.60
	Audio	8.85	4.31	5.05	3.47	6.95	.74	9.50	3.75	4.50	3.32	7.00	.74	9.18	4.00	4.78	3.36	6.98	.53
	Combined	8.85	4.36	4.50	3.10	6.68	.72	1.35	3.63	4.55	2.93	7.45	.72	9.60	4.03	4.53	2.98	7.06	.51
Transfer	Text	4.55	1.76	4.55	1.57	4.55	.28	5.65	1.66	4.80	1.44	5.23	.28	5.10	1.78	4.68	1.49	4.89	.20
	Audio	5.50	1.85	5.10	2.02	5.30	.33	5.00	1.41	4.70	1.42	4.85	.33	5.25	1.64	4.90	1.74	5.08	.23
	Combined	4.70	1.42	4.85	1.81	4.78	.24	5.40	.99	5.60	1.19	5.50	.24	5.05	1.26	5.23	1.56	5.14	.17

Table 3
Correlations between Retention and Transfer Knowledge and Executive Functions per group.

			Dyslexia				Typically developing			
			vis-wm	ver-wm	inh	cogf	vis-wm	ver-wm	inh	cogf
Retention	Text	short	.08	−.08	−.24	−.40	−.17	.22	−.37	−.29
		long	−.06	.19	−.07	−.14	−.27	.16	−.36	−.32
	Audio	short	.11	.07	−.25	**−.52***	−.44	.04	−.23	.06
		long	.05	−.01	−.05	−.13	**−.47***	.10	−.20	**−.45***
	Combined	short	.03	.12	.01	−.06	−.13	.23	−.41	−.12
		long	.03	.35	−.07	−.21	−.33	.31	−.25	−.06
Transfer	Text	short	−.13	−.19	.19	.13	−.43	.24	**−.52***	.29
		long	.14	.35	.06	−.24	−.04	−.19	−.10	.29
	Audio	short	.05	.17	.17	−.22	**−.53***	.05	.10	.06
		long	.13	.03	.24	−.36	−.24	.10	−.24	−.36
	Combined	short	−.13	.01	.04	−.02	−.02	−.23	−.19	.03
		long	.39	.05	**−.48***	**−.61****	−.06	**.49***	−.04	−.15

*$p < .05$ ** $p < .01$.
Note. Vis-wm = visual working memory, ver-wm = verbal working memory, inh = inhibition, cogf = cognitive flexibility.

3.2. Modality effect

3.2.1. Modality effect – retention

Analysis of the retention knowledge showed a main effect of time, $F(1, 38) = 102.67, p < .001, \eta_p^2 = .730$. Children recalled less information after a week compared to directly after the lessons. There were no significant main effects for condition, $F(1, 38) = .26$, $p = .614, \eta_p^2 = .007$, or group, $F(1, 38) = .32, p = .576, \eta_p^2 = .008$. There were no interactions (p's > .10).

3.2.2. Modality effect – transfer

Analysis of the transfer knowledge showed no significant main effect of time, $F(1, 38) = 3.58, p = .066, \eta_p^2 = .865$, condition, $F(1, 38) = .68, p = .416, \eta_p^2 = .017$, or group, $F(1, 38) = .09, p = .761, \eta_p^2 = .002$. However, there was a significant interaction effect between condition and group, $F(1, 38) = 6.07, p = .018, \eta_p^2 = .138$. To interpret this interaction effect, the analysis was performed separately for children with and without dyslexia. These analyses showed an interaction effect only in children with dyslexia. They scored higher in the audio condition compared to the written text condition, $F(1, 19) = 5.45, p = .031, \eta_p^2 = .223$ (modality effect), while in typically developing children there was no effect; they scored comparable in both conditions, $F(1, 19) = 1.34, p = .262, \eta_p^2 = .066$. Further, there were no interactions (p's > .10).

3.2.3. Modality effect – study time

Analysis of the amount of time children spent on learning the multimedia lessons showed a significant main effect of condition, $F(1, 37) = 4.71, p = .036, \eta_p^2 = .113$. Children spent significantly more time in the written text condition compared to the audio condition (modality effect). There was no main effect of group, $F(1, 37) = 1.39, p = .245, \eta_p^2 = .036$, and no interactions ($p$'s > .10).

3.2.4. Modality effect – individual differences in executive functioning

Adding visual and verbal working memory, inhibition, and cognitive flexibility as covariates to the performed analyses, did not alter the above described modality effects.

3.3. Redundancy effect

3.3.1. Redundancy effect – retention

Analysis of the retention knowledge showed a significant main effect of time, $F(1, 38) = 159{,}70, p < .001, \eta_p^2 = .808$. Children recalled less information after a week compared to directly after the lessons. There were no significant main effects on condition: text vs. combined condition, $F(1, 38) = .42, p = .523, \eta_p^2 = .011$, or audio vs. combined condition, $F(1, 38) = .02, p = .881, \eta_p^2 = .001$. Further, there were no main effects on group, $F(1, 38) = .50, p = .484, \eta_p^2 = .013$, and no interactions ($p$'s > .10).

3.3.2. Redundancy effect – transfer

Analysis of the transfer knowledge showed no significant main effects of time, $F(1, 38) = 1.00, p = .323, \eta_p^2 = .026$, or condition: text vs. combined condition, $F(1, 38) = 1.15, p = .291, \eta_p^2 = .029$, or audio vs. combined condition, $F(1, 38) = .06, p = .804, \eta_p^2 = .002$. There were also no significant main effects for group, $F(1, 38) = 1.13, p = .294, \eta_p^2 = .029$.

There was a significant interaction between condition (audio vs. the combined condition) and group, $F(1, 38) = 5.54, p = .024, \eta_p^2 = .127$. To interpret this effect, the analysis was performed separately for the audio condition and the combined condition. This analysis showed no significant difference between children with and without dyslexia in the audio condition, $F(1, 38) = .93, p = .341, \eta_p^2 = .024$, but did show a significant difference between the groups in the combined condition, $F(1, 38) = 4.52, p = .040, \eta_p^2 = .106$. In the audio condition, children with and without dyslexia had similar gains, while in the combined condition, typically developing children had a higher transfer knowledge than children with dyslexia. Further, there were no interactions (p's > .10).

3.3.3. Redundancy effect – study time

Analysis of the amount of study time children spent on learning showed a significant main effect of condition for the written text condition vs. the combined condition, $F(1, 36) = 4.62, p = .038, \eta_p^2 = .114$, but not for the audio condition vs. combined condition, $F(1, 36) = .02, p = .884, \eta_p^2 = .001$. Children spent more time in the written text condition than in the combined condition (reversed redundancy effect). There was no significant main effect of group, $F(1, 36) = 1.45, p = .237, \eta_p^2 = .0$, and no interactions ($p$'s > .10).

3.3.4. Redundancy effect – individual differences in executive functioning

Adding visual and verbal working memory, inhibition, and cognitive flexibility as covariates to the preformed analyses, did not alter the above described redundancy effects, except for study time in the written text condition vs. the combined condition: after controlling for working memory, inhibition, and cognitive flexibility, condition was non-significant, $F(1, 32) = 4.10, p = .051, \eta_p^2 = .113$, instead of significant. This is probably due to the smaller amount of degrees of freedom: when adding the covariates separately, in pairs, or groups of three the effect remained significant.

4. Discussion

In this study, we examined modality and redundancy effects on study outcomes and study time in user-paced learning environments in primary school children with and without dyslexia, and the role of executive functions on these effects. Regarding study outcomes, no effects were found on retention knowledge. On transfer knowledge, there was on the one hand a modality effect for children with dyslexia: They benefitted more from audio-only compared to written text. On the other hand, typically developing children learned more from written text with added audio than students with dyslexia did. With regard to study time, modality and reversed redundancy effects were evidenced in all children. Learning from written text took longer than from audio-only or added audio. Children with or without dyslexia did not differ in executive functioning. Executive functioning was related to study outcomes, but did not impact the modality and redundancy effects.

4.1. Modality and redundancy effects in dyslexia

Our first hypothesis was that we would find modality and redundancy effects, especially on transfer knowledge and study time, which would be stronger in children with dyslexia. Regarding modality effects (hypothesis one), we indeed found that children with dyslexia benefitted more from audio than from written text (i.e., modality effect) on transfer knowledge and that learning in the written text condition took longer compared to the conditions with audio-only or added audio. Thus, learning from auditory-presented information with pictures in children with dyslexia is more efficient: they have higher study outcomes (knowledge) with less study time. These findings were in line with Knoop-van Campen et al. (2018) who showed that these children learned more efficiently when combining audio with pictures. In the present study, this effect was also found on the learning gain, and not just the study time. This may be due to the fact that we used a multiple-choice task (recognition) in the previous study, and asked for a summary in the present study (recall). In typically developing children, no modality effect on retention or transfer was found, but on study time, they also spent more time on learning in the written text condition compared to the audio condition. We expected this group to have smaller modality effects than the group with dyslexia. The fact that no modality effects were found in this group supports the idea that modality effects tend to disappear in user-paced conditions.

In both groups, we did not find modality effects on retention. In his meta-analysis Ginns (2005) shows that the effect sizes of multimedia effects in children are smaller than in adults. The absence of an effect on retention knowledge is line with previous studies in children (Savoji et al., 2011; Tabbers et al., 2004; She & Chen, 2009), and replicates the finding of the Knoop-van Campen et al. (2018), who also showed no modality and redundancy effects in primary school children on retention knowledge measured by multiple-choice questions. An explanation can be found in the work of Ainsworth (1999), who suggested that combining different modalities can foster deep processing of information (transfer). The fact that both ways of measuring retention knowledge (multiple choice in Knoop-van Campen et al. (2018), and free-recall in the present study) showed no effects and that the present study does find effects on transfer knowledge, supports the idea that decoding problems in a written text condition especially hinder deep processing of knowledge.

Regarding redundancy effects (hypothesis one), we did not find such effects on retention for both groups. For transfer knowledge, typically developing students learned more from written text with added audio than students with dyslexia did, while in the audio condition there was no difference in learning between the groups. On study time, all children spent more time in the written text condition than in the combined condition. This points to a reversed redundancy effect. When comparing the results of the children with dyslexia and typical developing children, we expected stronger effects in children with dyslexia. Since results of the present study showed that children with dyslexia indeed learn less when confronted with written text and audio compared to typically developing children, we could infer that in children with dyslexia the results are more in line with expectations. The need for written text to attain higher knowledge scores in typically developing children, is in line with Diao and Sweller (2007). This can be attributed to the transience of spoken language: although one can focus on the picture (visual channel) and listen to the spoken text (audio channel) (CTML: Mayer, 2005), it is not possible to gaze back to previous words or phrases. Typically developing children who have no difficulties with reading, can lean on the written word for remembering. This is supported by a hypermedia study, in which it was shown that students learned more from written text only than from spoken or combined written and spoken text (Gerjets, Scheiter, Opfermann, Hesse, & Eysink, 2009). Children with dyslexia, who have difficulties with reading (Lyon et al., 2003), learn less than typically developing students when confronted with written and spoken information, but obviously reading alone (without added audio) takes time. Adding audio seems more beneficial for compensating their reading in term of efficiency, but it also could disadvantage them compared to typically developing peers.

4.2. *Executive functions in multimedia learning*

The second hypothesis was on executive functioning. We expected higher executive functions to lead to decreased modality and redundancy effects. In contrast to our expectations, executive functions did not influence these effects. Perhaps this is due to the fact that learning was user-paced, as previous studies also did not find working memory impacting the modality (Witteman & Segers, 2010) and the redundancy effect (Gyselinck et al., 2008) in user-paced conditions. In these learning environments, students can relieve their executive functioning by slowing down or take a break.

Another explanation is that in primary school children, executive functions are still in a state of flux (Davidson, Amso, Anderson, & Diamond, 2006). Diamond (2006) even argues that although the development of cognitive flexibility starts early, it continues for almost twenty years. While Seufert et al. (2009) did show working memory influencing the redundancy effect, it was in (high achieving) adults. In the present study, executive functions may not be developed enough to matter in such learning environments. In addition, multimedia learning was examined in young children in which executive functioning varied greatly. Due to the robustness of the modality and redundancy effects, executive functions was perhaps not able to impact the effects strong enough to show an influence in this population.

Finally, children with different cognitive abilities may learn and process information in a different way. For example, Smith and Woody (2000) showed that multimedia benefits students with a high visual orientation. In addition, Riener and Willingham (2010) argue that students have different abilities that -logically- also influence students' learning. The fact that executive functions were related to learning but did not influence the modality and redundancy effects, argues for a more complex model than examined in the present study. Individual differences in executive functions may still be important for learning, but more on a general level as a charger for interest, prior knowledge and ability (Riener & Willingham, 2010) rather than stand-alone factors.

4.3. *Limitations*

Several limitations apply to the present study. Group sizes were relatively small, which increases the risk of type II error. However, the experimental and control group were matched on school, class, and gender, which allowed for sound comparisons between the two groups. Second, it would have been interesting to be able to compare our results in a user-paced environment with the results in a system-paced learning environment, by including such a condition. When future research includes both system-paced as well as user-paced environments, the role of executive functions may become clearer. In the present research, we examined the outcome measures of multimedia learning, the processing of the multimedia information was not taken into account. By examining the learning behavior, for example by the means of eye-tracking, it would be possible to study to what extent the learning pattern between the conditions and groups differs. In the combined text and audio condition, we currently do not know whether children read at all. Children with dyslexia are expected to differently process (multimedia) information (Bellocchi, Muneaux, Bastien-Toniazzo, & Ducrot, 2013), and including process measures could shed light on differences in children's' learning behavior.

4.4. Practical implications

The present research has implications for education. Theory of redundant information (Mayer, 2005) clearly does not apply to user-paced systems. The way children are presented information does not matter for their retention knowledge. In education however, teachers want children to understand and process information in a way they can transfer their knowledge to new situations. Since written text with pictures supports transfer knowledge in typically developing children, but not in children with dyslexia who benefit more from auditory-presented information, audio as replacement of written text seems useful for this specific group. However, since in Western society written text is inevitable, it is advisable to not refrain children with dyslexia from written text completely. Added audio can then relieve their cognitive load and support their learning in certain situations. Providing multimedia support has to be implemented with care as adding audio to written text may also disadvantage their learning compared to typically developing peers. The costs of adding audio should be weighted carefully against the time-saving feature of it.

Due to technological developments in the field of education and the development of personalized learning within existing and new to develop school methods, there is increasing interest by publishers and creators of educational materials to add multimedia to their materials. In light of the present finding, publishers and creators should be motivated to include the possibility of audio-support in their materials. This would provide teachers with the opportunity, as suggested above, to support their students at an individual level. Kester, Kirschner, and Corbalan (2007) argued that a powerful learning environment is multi-model. Multi-modality is more than only providing text with pictures, as educational technology offers many possibilities for a rich learning environment. It is important to note that when providing -especially young- students with audio-support, these students have to learn to use this support effectively. Teachers play an important role in this respect. Despite their crucial role in implementing educational technologies, teachers often have little knowledge on how audio can effectively be implemented for these specific students (Koehler & Mishra, 2005). We therefore argue for implementing audio-support but also for incorporating educational technologies and its possibilities in teacher training.

4.5. Conclusion

To conclude, for children with dyslexia it is more efficient (higher study outcomes with less study time) to learn from auditory-presented information with pictures, while for typically developing children learning is most efficient when next to the audio, also written text is available. Adding audio-support for all children, can potentially lead to more efficient learning, however, the costs of adding audio have to be weighted carefully against its time-saving feature in children with dyslexia. Executive functions do relate to learning in multimedia environments but not differentially between children with and without dyslexia.

Sponsor

N.A.

Grant number

N.A.

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