Multimedia Learning and Dyslexia

Carolien A. N. Knoop-van Campen

Behavioural
Science
Institute

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Carolien A. N. Knoop-van Campen

Colofon

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“Leave this world a little better than you found it”

Robert Baden-Powell, Last Message to Scouts, 1941

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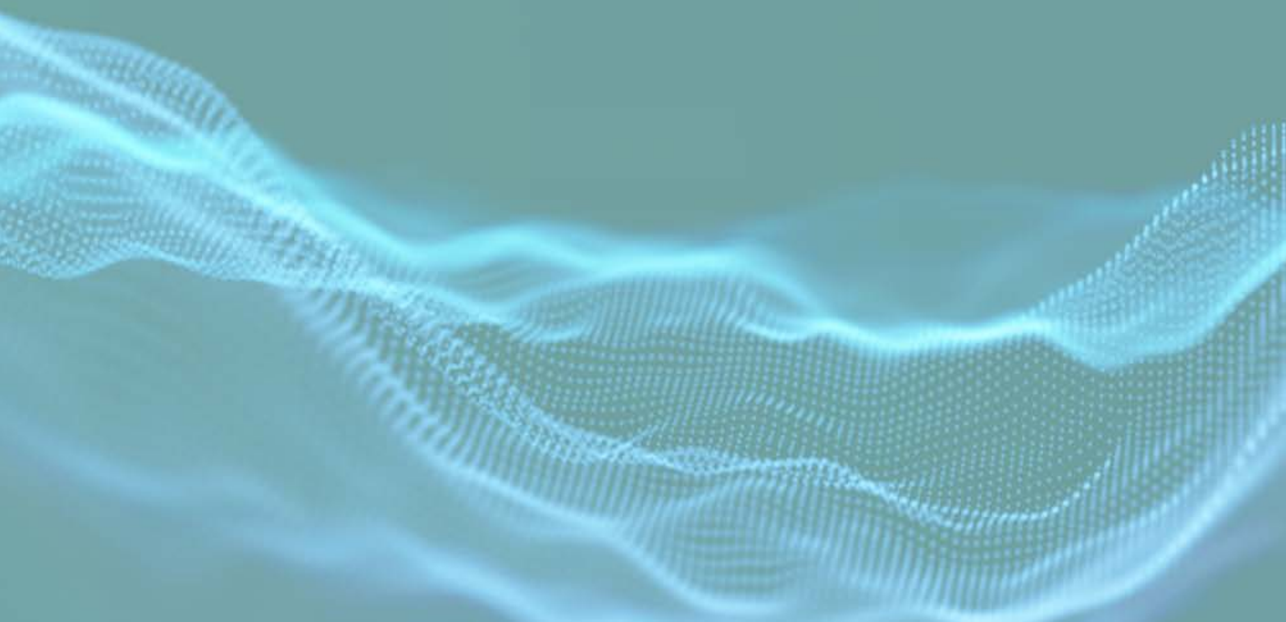


CHAPTER 1

GENERAL INTRODUCTION

General Introduction

Joris is a 21-year-old university student in Political Science who has been diagnosed with dyslexia in primary school. Reading has never been his favorite subject in school and he has always struggled with his textbooks. Luckily, ever since secondary school, he has been using software that reads his study books to him to compensate for his reading problems. Anneke - 5th grade primary school - loves animals but does not really enjoy the lessons on Nature. For this subject, she has to read a lot, which takes much effort as she is diagnosed with dyslexia. Recently, she has been allowed to read her school book on her laptop with headphones on. As the laptop reads the written text aloud, it enables Anneke to listen to the information and read along with the audio while learning the material.

More and more in the upper grades of primary school and in secondary and higher education, students with dyslexia learn with headphones on, listening to the written text in front of them (Ghesquière et al., 2010). Such multimedia environments, where written texts with illustrations are enhanced with audio (Mayer, 2002), are becoming more common due to technological possibilities in education. Whereas adults with dyslexia commonly use audio-support along with their written text (i.e., reading with narration), primary school children may also replace the written text with listening only.

From a theoretical point of view, audio-support - whether it replaces written text with audio or adds audio to written text – is thought to impact learning. Based on the Cognitive Theory of Multimedia Learning (CTML), replacing written text with audio in a multimedia environment has been shown to be beneficial for learning (modality principle), while adding audio to written text hampers learning (redundancy principle; Mayer, 2005), due to respectively offloading and overloading working memory. Especially for adding audio to written text, theory on one hand would suggest a negative effect on learning outcomes due to working memory overload. On the other hand, for students with dyslexia it can also be hypothesized that adding audio would enhance learning, since it compensates for their reading difficulties and, as such, relieves their working memory. Students with dyslexia differ in the way they process (multimedia) information from their typically developing peers (e.g., Heiman & Precel, 2003; Kim et al., 2014; Kirby et al., 2008).

Existing multimedia research mainly focuses on adults, and hardly focuses on long-term effects, while that is the ultimate goal of learning. Furthermore, research on multimedia principles is inconclusive, and learners with dyslexia have hardly been studied (but see Alty et al., 2006; Kim & Wiseheart, 2018; Wang et al., 2018). Children in primary school have a lower working memory capacity than adults and less reading experience. Both working memory and reading experience may have an impact on multimedia learning; even more so for children and especially in children with dyslexia. Thus far, the impact of audio-support on multimedia learning in children with dyslexia has not been studied.

In summary, it is by no means clear what the effect of audio-support is on how and what adults and children with dyslexia learn in multimedia environments. Therefore, the main aim of the present dissertation was to provide insight into the learning behavior and short- and long-term learning outcomes of adults and children with dyslexia as compared to their typically developing peers in multimedia learning environments. An effort was made to refine theory on multimedia learning especially in realistic learning environments and to provide empirical evidence for educational guidelines regarding the facilitation of audio-support in adults and children with dyslexia.

1

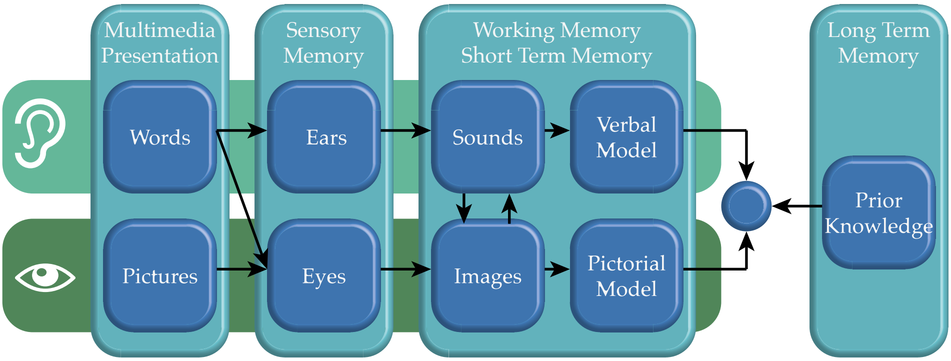
Theoretical Framework of Multimedia Learning

Multimedia learning refers to learning in environments in which is learned from words (written and / or spoken) and pictures (Mayer, 2005). These multimedia environments have become an integral part of education. Spoken material often exists of audio software (e.g., text-to-speech) or narration provided by educational publishers and is called audio-support. As a result of learning in a multimedia environment, learners must integrate different types of information and combine the entirety into one coherent mental model (Graesser, 2007).

The Cognitive Theory of Multimedia Learning (CTML; Mayer, 2005) provides a broad theoretical framework with various principles for creating efficient multimedia learning environments. These principles focus on minimizing the burden on the working memory so that working memory capacity can be used to process the information stored in long-term memory. Off-loading working memory capacity to enhance learning can, therefore, be regarded as the core of the CTML (Mayer, 2005). As such, it is closely related to the Cognitive Load Theory (CLT; Paas et al., 2003), which focuses on the process of reducing learners' cognitive load on working memory and long-term storage in order for learning to be most facilitated (Sweller, 1988).

The CTML (Mayer, 2005) is built on three assumptions. The first assumption, based on the dual-channel theory (Baddeley, 1986; Paivio, 1986), states that sensory information is processed through both an auditory channel and a visual channel in working memory, which can be seen as parallel and equal. The second assumption, based on the limited-capacity theory (Sweller, 1999), states that working memory can only process a certain amount of information at a time. The third one assumes that learners are actively building a mental model during learning (active processing assumption, Mayer, 1996). Combined, the CTML states that both the auditory and visual channels have a limited capacity and that an increased amount of information can be processed and stored in long-term memory when the two channels are combined (Mayer, 2005), as depicted in Figure 1.1. Several multimedia principles are derived from these assumptions. Two of those principles are particularly relevant when it comes to audio-support, namely the modality and redundancy principle.

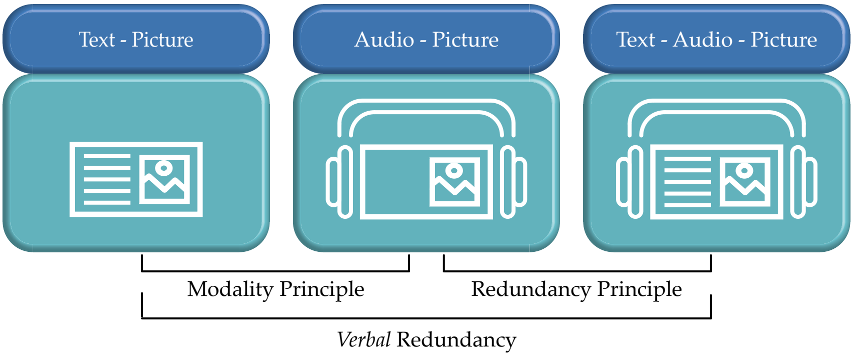
Figure 1.1
Cognitive Theory of Multimedia Learning (Mayer, 2005)



The **modality principle** compares written text with pictorial information to auditory information with pictures. According to the CTML (Mayer, 2005), cognitive load is distributed over two channels when learning from audio with pictures. Audio is processed via the auditory channel and pictures processed via the visual channel. When pictures are accompanied by written text, both sources of information have to be processed via the visual channel with the risk of overloading this channel. Therefore, the CMTL claims that audio-with-pictures is more efficient than written-text-with-pictures as more information can be processed at a single time, which would lead to better long-term storage and thus enhanced learning.

Whereas the modality principle revolves around changing the modality of the main information (written to audio and vice versa), the **redundancy principle** focuses on presenting these sources of information simultaneously. The CTML states that instead of enhancing learning, redundant information hampers the learning process. As visual and audio channels have to process the same information, the unnecessary processing of the information twice requires additional working memory capacity, which is no longer available for learning (Mayer & Fiorella, 2014). By presenting both written words and pictures, the visual channel becomes overloaded (similar as in the modality principle), and double information (words in written and spoken form) must be processed. To facilitate learning, the instructional design should contain as little duplicated information as possible (Paas et al., 2003). The redundancy principle of the CTML focuses on visual redundancy effects, by comparing spoken text with pictures to spoken text with additional and identical written text and pictures. Verbal redundancy, however, refers to learning situations in which written text with pictures are complemented with audio (e.g., narration / voice-over) (see Figure 1.2). As verbal redundancy corresponds to educational practices in which learners are provided with additional narration next to existing multimedia environments (Ghesquière et al., 2010), this form will be central in the present dissertation.

Figure 1.2
Overview of the Multimedia Environments



Multimedia Learning Outcomes

The modality principle and redundancy principle have been investigated abundantly in adults during the last decades (Li et al., 2019). As results do not always align with the theory these principles are based on, questions arise on the generalizability, boundary conditions, and the true effects on learning outcomes.

The **modality principle** has been extensively researched in adults. A meta-analysis (43 studies; Ginns, 2005) showed that people indeed learned more from spoken-text-with-pictures than from written-text-with-pictures. Ginns (2005) showed a strong, robust effect. In this meta-analysis only four studies involved primary school children and no difference was found between children and adults. Although also confirming the modality effect, Reinwein's meta-analysis (86 studies; 2012) showed more modest effect sizes and the size of which decreased even more when corrected for publication bias. He included 12 studies with primary school children and found that, in contrast to adolescents and adults, children learned as much from spoken-text-with-illustrations as from written-text-with-illustrations (no modality effect).

The observed modality effects do seem to be constrained, amongst others by the pacing of the learning environment (Tabbers, 2002). When learners can determine the pacing of the learning environment, modality effect are smaller than when students have to keep up with a predefined pacing (Ginns, 2005; Reinwein, 2012; Wang et al., 2016). Indeed, many user-paced studies found no or even reversed modality effects: Higher learning outcome with pictures-with-written-text compared to pictures-with-narration (e.g., Van den Broek et al., 2014; Ruf et al., 2014; Scheiter et al., 2014; Tabbers et al., 2004). System pacing was also found to be more effortful for learners than user-paced learning materials (Rop et al., 2018).

Next to pacing, the timing of testing also seems to constrain the modality effect. On the long term -a day or more after the multimedia lessons- many user-paced studies found no or reversed modality effects (e.g., Van den Broek et al., 2014; Ruf et al., 2014; Segers et al., 2008; Savoji et al., 2011; Sweppe & Rummer, 2012; Witteman & Segers, 2010). These studies showed that on the long term, learning from written-text-with-pictures went equally well or even better than learning from narration-with-pictures.

Even though the modality principle strongly leans on an individual's working memory capacity and despite its established effect on learning (e.g., Unsworth & Engle, 2007), the impact of working memory on the modality effects has hardly been examined. In fact, the few studies who did, did not find working memory to impact the modality effect (Gyselinck et al., 2008; Seufert et al., 2009; Witteman & Segers, 2010). Students' working memory capacity did not affect learning differences between written and spoken text in multimedia environments, which is difficult to align with the CTML (Mayer, 2005).

Although there is a fair amount of research on the **redundancy principle** in adults (Li et al., 2019), most of these studies involved visual redundancy in which spoken-text-with-pictures was compared to spoken-and-written-text-with-pictures (meta-analysis, Adesope & Nesbit, 2012). The effects of visual redundancy, in which adding written text to audio hampers learning, were robust (meta-analysis, Mayer, 2017; Kalyuga & Sweller, 2014). Results on verbal redundancy are less straightforward.

In their meta-analysis Adesope and Nesbit (2012) did not prove a verbal redundancy effect: Students learned as much from written-text as from written-text-with-narration (voice-over). This was replicated in a more recent system-paced study, which showed no verbal redundancy effects (De Koning et al., 2017). Also, variation in the degree of verbal redundancy in user-paced multimedia environments did not affect learning gains (Roscoe et al., 2015). However, even though Adesope and Nesbit (2012) did not find differences between learning from written-text or from written-text-with-narration in multimedia environments, the overall mean effect size for system-paced studies was almost three times as large as for user-paced studies. This suggests possible differences between user-paced and system-paced environments, and thus pacing as a similar constraint to verbal redundancy as it is to the modality principle. In their meta-analysis, only two studies involved primary school children: the system-paced study showed better results without added audio (Leahy et al., 2003), while the user-paced study showed improved results with audio (Olson & Wise, 1992).

There are no studies on verbal redundancy that have taken consolidation of learning into account, though that is the ultimate goal of education. Also, no studies were found that investigate the possible impact of working memory on verbal redundancy. It is thus unknown whether timing of testing and students' working memory capacity affect verbal redundancy outcomes.

Multimedia Learning Processes

In addition to insight into which knowledge students gain (learning outcomes), understanding how they acquire this knowledge is important. Examining the process of multimedia learning, could potentially explain why empirical results on multimedia learning outcomes differ from what would be expected based on the CTML.

A distinction can be made between fine-grained and larger-grained learning processes (Barrios et al., 2004). More fine-grained learning processes may include monitoring learners' eye-movements to provide specific insights into reading (comprehension) in multimedia environments (Schroeder et al., 2015). Larger-grained information on multimedia learning processes entail more general learning behavior, like (mouse) clicks and log data of the multimedia slides (Barrios et al., 2004).

Regarding multimedia learning, there is an increasing amount of multimedia research that examines **fine-grained** learning differences between various multimedia environments. Eye-tracking on the modality principle showed that learners examine the illustrations more when written text is replaced by audio (Schmidt-Weigand et al., 2010). More specifically, replacing written text by narration in multimedia environments was found to elicit a higher number of fixations, higher fixation duration, and longer total inspection time in adults (She & Chen, 2009). Eye-tracking research shows distinct differences between the impact of audio on children's and adults' reading behavior. In contrast to adults, in primary school children learning with narration the number and duration of fixations were fewer and shorter (Molina et al., 2018).

In studies on the verbal redundancy principle in which narration was added to a multimedia environment, it was found that the audio affected students eye movements. In particular, it increased fixation duration, which may signal that narration reduces processing time of the text (Liu et al., 2011), and more fixations with shorter saccades, which could indicate an increased attention towards the illustrations (Krejtz et al., 2012; Wiebe & Annetta, 2008). However, multimedia learning with additional narration was found to be text-directed, as in general most attention focused on the written text and not to the (informative) illustration (Schmidt-Weigand et al., 2010).

Multimedia research into **larger-grained** learning processes did not focus on specific multimedia principles related to audio-support. Nevertheless, how learners move through such environments might be profoundly different than through plain written text. There are multiple ways to navigate through multimedia environments, but not all are equally successful for learning (Paans et al., 2020). By moving through a multimedia environment, learners create a mental model of the text, which is necessary to store the information into long-term memory (Caccamise et al., 2015; Juvina & Van Oostendorp, 2008). Such active involvement and regulation of one's own by using certain strategies in multimedia environments, has been found to contribute to learner's comprehension of the material (Amadieu et al., 2009; Madrid et al., 2009; Salmerón et al., 2006; Van den Broek & Helder, 2017). However, navigating multimedia environments can also be challenging as the increased amount of information may have a negative impact on regulating their learning process (Lajoie & Azevedo, 2006). In addition, when learners gain more experience in creating mental models of the text, they move from constructing a more or less linear representation - children-, towards a more networked based situation model - adults (Klois et al., 2013). As regulation skills develop as a function of age and experience (Pintrich & Zusho, 2002), one would expect larger-grained differences between children -with little reading and learning experience- and adults - with much reading and learning experience. In other words, both replacing written text with audio (modality effect) or adding audio to written text (verbal redundancy effect) may challenge learners in navigating through these learning environments, especially children.

Multimedia Learning and Dyslexia

As multimedia learning has become an integral part of education, the opportunities for students with a learning disability to receive support and compensation are increasing. In fact, audio-support - adding narration to written text - is a very popular aid for students with reading problems (Ghesquière et al., 2010; Gregg & Banerjee, 2009).

A specific group of learners who uses this audio-support to compensate for their reading problems are students with dyslexia. **Dyslexia** is a learning disability characterized by severe and persistent reading problems that are not due to external factors such as poor education or low intelligence (Lyon et al., 2003). These genetic-based impairments in reading and spelling are in particular associated with a phonological core deficit. During their reading development, their decoding problems may also cause difficulties in reading comprehension as decoding continues to be effortful (De Jong & Van der Leij, 2003).

Next to these decoding problems, learners with dyslexia often -but not always- experience working memory problems (e.g., Berninger et al., 2008; Menghini et al., 2011; Swanson et al., 2009). Studies showing lower working memory capacity in dyslexia mostly focus on verbal working memory (e.g., Beneventi et al., 2010; Berninger et al., 2008; Menghini et al., 2011; Swanson et al., 2009; Tijms, 2004) and less on visual working memory (Reiter et al., 2005; Smith-Spark, & Fisk, 2007). There are some indications that these working memory differences are at least partly due to their phonological core deficit (Schuchardt et al., 2008). It has been argued that students with dyslexia especially struggle with the phonological aspects of working memory (Pickering, 2012; Tijms, 2004).

As both decoding and working memory capacity impact cognitive load, learning in a multimedia environment could be particularly challenging for students with dyslexia. However, since audio-support lowers the necessity to decode every single word and increases reading speed (Draffan, 2002), audio could also lessen the cognitive load. In other words, audio-support could both hinder as well as aid learners with dyslexia.

Studies examining multimedia learning in **adult students with dyslexia** are scarce. Two studies investigating the modality principle in students with dyslexia indicated that -even when a modality effect was found in typical developing learners- students with dyslexia performed better with written-text-with-pictures than written-text-with-audio-and-pictures (Alty et al., 2006; Wang et al., 2018). This result is remarkable given their established decoding problems. In a study under strict time pressure, Kim and Wiseheart (2018) did find a modality effect on retention knowledge in students with dyslexia. Students recalled more facts from the lesson when learning from audio-with-illustrations than from written-text-with-illustrations, but there was no difference on transfer knowledge (Kim et al., 2018).

The only study specifically investigating the verbal redundancy principle in students with dyslexia (Kim, Wiseheart, & Walden, 2018), showed that these learners scored lower than their typically developing peers when learning from written text, but not so when audio was added. These results point towards a reversed redundancy effect in students with dyslexia (positive effect of added audio). Related multimedia research shows that by listening to information, students with dyslexia can compensate for their poor reading skills (Casalis et al., 2013). Fidler and Everatt (2012) suggested that the comprehension in students with dyslexia could be increased by means of supportive technology to tap into their listening comprehension skills.

Regarding both modality and redundancy effects, Beacham and Alty (2006) indicated that they could not identify one specific multimedia condition that was more beneficial for all students with dyslexia. In light of this study, more research on multimedia learning processes in students with dyslexia should be proformed.

Various differences in learning processes can be observed between students with and without dyslexia. Regarding **fine-grained** learning processes, clear differences between eye-movements of learners with and without dyslexia were already established twenty-five years ago (Hyönä & Olson, 1995). More recent research even shows that differences in eye-movements can support detection of students with dyslexia by means of machine learning (Rello & Ballesteros, 2015). With the addition of audio to written text, students with dyslexia fixated more on the pictures than their typically developing peers and made fewer transitions between text and picture area (Kim & Wiseheart, 2018). Students with dyslexia also need more time for processing both text and graphs (Kim et al., 2014). Integrating information from different modalities was challenging for them (Kim et al., 2018; MacCullagh et al., 2017), even though they were found to strategically process information to improve their learning (Andresen et al., 2019).

With respect to **larger-grained** learning processes, studies on academic strategies indicated that students with dyslexia approach learning materials differently than their typically developing peers (Bråten et al., 2010; Heiman & Precel, 2003; Kirby et al., 2008). In example, they select fewer main ideas and test taking strategies and use more study aids and time management strategies (Kirby et al., 2008). As reading skills predicted navigation strategies (Salmerón & García, 2011) and knowledge of metacognitive strategies (Wu, 2014), students with dyslexia may be disadvantaged in that respect too.

Not only adults with dyslexia learn in multimedia environments. Next to university students with dyslexia who use audio-support (sometimes for many years), primary school **children with dyslexia** are also increasingly provided with a laptop and reading software. As shown above, the few studies that examine multimedia learning in adults with dyslexia, provide indications that the impact of audio-support on learning outcomes and learning processes differs from the impact in typically developing adults.

Children have, in contrast to adults, less reading experience and less experience in learning in multimedia environments. Reading ability increases as reading becomes more automatic (De Jong & Van der Leij, 2003 Perfetti & Hart, 2002) and basic language skills (involving decoding) as well as comprehension abilities - both necessary for multimedia learning – develop, partly independently, over time (Helder et al., 2015). Working memory capacity in children is also lower than in adults as it develops until early adolescence (Diamond, 2006; Schneider, 2011). As children with dyslexia have lower reading experience and working memory capacities, it raises the question how audio-support affects children with dyslexia. These primary school children are provided with audio-support to compensate for their decoding problems. However, it is unknown how this affects their learning. All studies on the modality and verbal redundancy principle together with dyslexia focus on adults.

The Present Dissertation

Adding audio to multimedia environments may seem promising in some cases, however, there also seem to be many ambiguities and pitfalls. By combining multimedia learning outcomes with learning processes, a more complete overview of such research can be presented. This will help refine theory on multimedia learning and benefit children in need of audio-support in schools. Therefore, the aim of this dissertation was to provide insight into the multimedia learning behavior and (long-term) learning outcomes of **adults and children with dyslexia** as compared to their typically developing peers. The following three research questions were addressed:

RQ 1 To what extent does audio-support impact **what** these learners learn?
RQ 2 To what extent does audio-support impact **how** these learners learn?
RQ 3 What are **boundary conditions** for efficient multimedia learning?

An overview of the current state of research on the impact of audio-support in multimedia learning is presented in Table 1.1, showing the scope of this dissertation in relation to previous research.

Research in the present dissertation was carried out in the Netherlands. In the Netherlands, most children have access to digital devices at home (Gubbels et al., 2016) and many use a laptop or tablet at school on a daily basis. Having these digital opportunities establishes multimedia learning as an integral part of everyday life and today's education system. Being able to have text read aloud is becoming more common as well. Internet pages of, for example, the Dutch government offer this automatically, and there are also various speech-to-text apps that -whether or not linked to written onscreen text- read texts out loud. In the Netherlands, children with dyslexia, which comprise approximately 7.5% of children in primary education (Onderwijsinspectie, 2019), can use available support software and audio textbooks, which are produced by a government foundation (Dedicon Rijksoverheidsdienst, 2020).

Overview of the Chapters

To address these research questions, four experimental studies were conducted of which two in university students and two in primary school children (plus one pilot for each age group). These studies had a similar set-up: Learners were presented with two or three multimedia learning environments after which they received a posttest directly after learning and a week later.

Chapter 2 addresses multimedia learning processes in university students with dyslexia. In this chapter, eye-tracking provides insight in the fine-grained learning behavior during learning with audio-support. Learning processes are connected to learning outcomes directly after learning.

Chapter 3 examines learning behavior on a larger-grained level, both in university students as well as in primary school children. It provides insight in the impact of audio-support on the navigation strategies of learners with and without dyslexia, and highlights differences in multimedia learning between children and adults.

Chapter 4 and 5 focus on primary school children with and without dyslexia. In Chapter 4 it was examined whether modality and redundancy effects would affect learning outcomes in multimedia learning in children with dyslexia to the same extent as their typically developing peers while taking into account children's working memory capacity. Chapter 5, a replication study of the earlier chapter, focuses on a broader range of executive functions and their impact on the modality and redundancy effect. Both chapters include learning outcomes directly and a week after learning, and thus allow for examining possible constrains of time of testing and working memory. As they also include study time, they support conclusions on learning efficiency.

Chapter 6 is the only chapter with solely typically developing learners, and examines the impact of pacing, time of testing, and working memory on verbal redundancy effects on students' cognitive load and learning outcomes directly after learning and a week later. The previous chapters all concerned user-paced learning environments, while this chapter also examines learning in a system-paced learning environment allowing to investigate pacing effects.

To conclude, a summary and discussion of the main findings of this dissertation are provided in Chapter 7. Limitations, directions for future research, and guidelines for educational practice are given.

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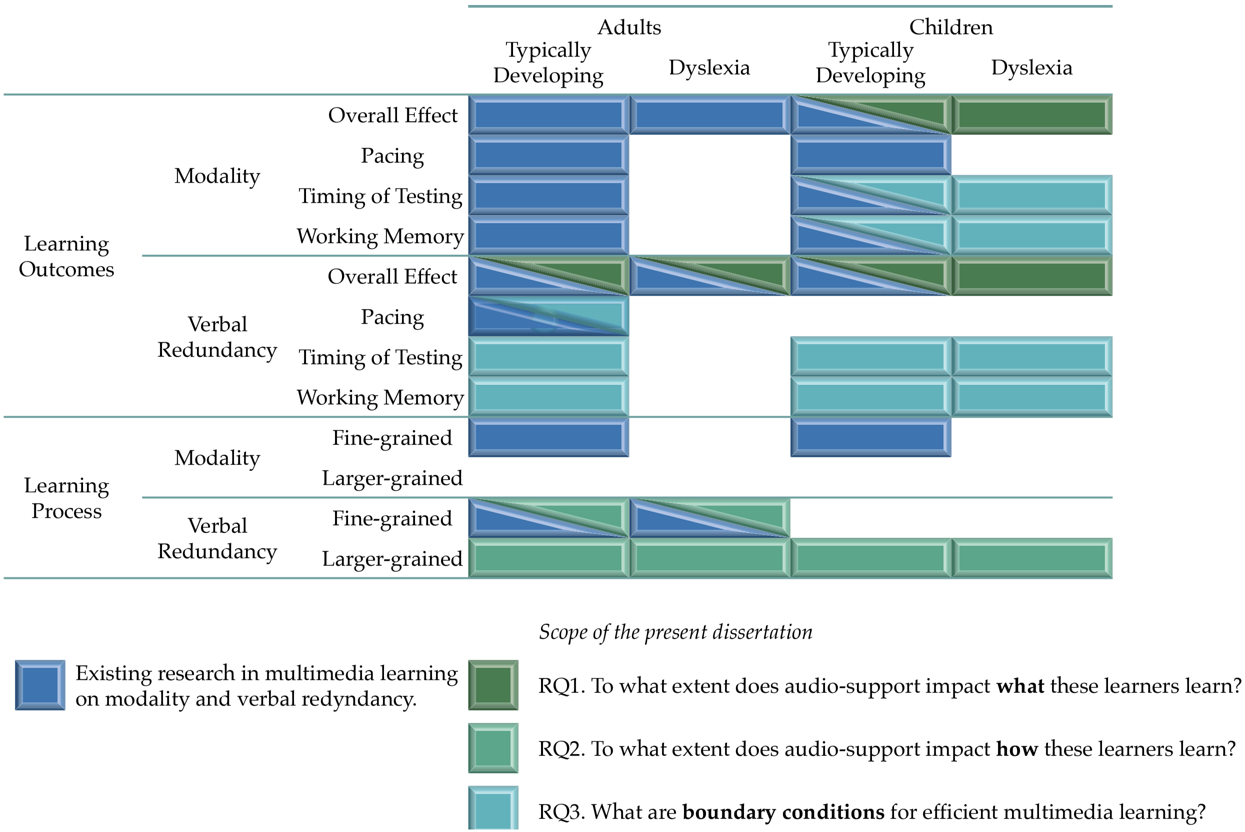
Table 1.1
Overview of Current State of Research in Multimedia Learning and the Scope of Present Dissertation



References

Adesope, O. O., & Nesbit, J. C. (2012). Verbal redundancy in multimedia learning environments: A meta-analysis. *Journal of Educational Psychology*, *104*(1), 250. http://doi.org/10.1037/a0026147

Alty, J. L., Al-Sharrah, A., & Beacham, N. (2006). When humans form media and media form humans: An experimental study examining the effects different digital media have on the learning outcomes of students who have different learning styles. *Interacting with Computers*, *18*(5), 891–909. https://doi.org/10.1016/j.intcom.2006.04.002

Amadieu, F., Tricot, A., & Mariné, C. (2009). Interaction between prior knowledge and concept-map structure on hypertext comprehension, coherence of reading orders and disorientation. *Interacting with Computers*, *22*(2), 88-97. https://doi.org/10.1016/j.intcom.2009.07.001

Andresen, A., Anmarkrud, Ø., Salmerón, L., & Bråten, I. (2019). Processing and learning from multiple sources: A comparative case study of students with dyslexia working in a multiple source multimedia context. *Frontline Learning Research*, *7*(3), 1-26. https://doi.org/10.14786/flr.v7i3.451

Baddeley, A. D. (1986). *Working memory*. Oxford University Press.

Barrios, V. M. G., Gütl, C., Preis, A. M., Andrews, K., Pivec, M., Mödritscher, F., & Trummer, C. (2004). AdELE: A framework for adaptive e-learning through eye tracking. *Proceedings of IKNOW*, 609-616.

Beacham, N. A., & Alty, J. L. (2006). An investigation into the effects that digital media can have on the learning outcomes of individuals who have dyslexia. *Computers & Education*, *47*(1), 74–93. https://doi.org/10.1016/j.compedu.2004.10.006

Beneventi, H., Tønnessen, F. E., Ersland, L., & Hugdahl, K. (2010). Executive working memory processes in dyslexia: Behavioral and fMRI evidence. *Scandinavian Journal of Psychology*, *51*, 192–202. https://doi.org/10.1111/j.1467-9450.2010.00808.x

Berninger, V. W., Raskind, W., Richards, T., Abbott, R., & Stock, P. (2008). A multidisciplinary approach to understanding developmental dyslexia within working-memory architecture: Genotypes, phenotypes, brain, and instruction. *Developmental Neuropsychology*, *33*, 707–744. https://doi.org/10.1080/87565640802418662

Bråten, I., Amundsen, A., & Samuelstuen, M. S. (2010). Poor readers-good learners: A study of dyslexic readers learning with and without text. *Reading & Writing Quarterly*, *26*(2), 166-187. https://doi.org/10.1080/10573560903123684

Caccamise, D., Friend, A., Littrell-Baez, M. K., & Kintsch, E. (2015). Constructive theory as a framework for instruction and assessment of reading. In S. R. Parris & K. Headley (Eds.), *Comprehension instruction: Research-based best practices* (3rd ed., pp. 88-104). Guilford Press.

Casalis, S., Leuwers, C., & Hilton, H. (2013). Syntactic comprehension in reading and listening: A study with French children with dyslexia. *Journal of Learning Disabilities*, *46*(3), 210–219. https://doi.org/10.1177/0022219412449423

Dedicon Rijksoverheidsdienst (2020).

De Jong, P. F., & Van der Leij, A. (2003). Developmental changes in the manifestation of a phonological deficit in dyslexic children learning to read a regular orthography. *Journal of Educational Psychology*, *95*(1), 22-40. https://doi.org/10.1037/0022-0663.95.1.22

De Koning, B. B., van Hooijdonk, C. M., & Lagerwerf, L. (2017). Verbal redundancy in a procedural animation: On-screen labels improve retention but not behavioral performance. *Computers & Education*, *107*, 45-53. https://doi.org/10.1016/j.compedu.2016.12.013

Diamond, A. (2006). The early development of executive functions. In E. Bialystok & F. I. M. Craik (Eds.), *Lifespan cognition: Mechanisms of change* (pp. 70–95). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195169539.003.0006

Draffan, E. A. (2002). Dyslexia and technology. In L. Phillipa, A. Sutherland, & J. Seale (Eds.), *Access all areas: disability, technology and learning* (pp. 24-48). Jisc TechDis.

Fidler, R., & Everatt, J. (2012). Reading comprehension in adult students with dyslexia. In N. Brunswick (Ed.), *Supporting dyslexic adults in higher education and the workplace* (pp. 91–100). London: John Wiley & Sons. https://doi.org/10.1002/9781119945000.ch10

Ghesquière, P., Boets, B., Gadeyne, E., & Vandewalle, E. (2011). Dyslexie: een beknopt wetenschappelijk overzicht. In A. Geudens, D. Baeyens, K. Schraeyen, K. Maetens, J. De Brauwer, & M. Loncke (Eds.), *Jongvolwassenen met dyslexie: diagnostiek en begeleiding in wetenschap en praktijk* (pp. 41-58). Acco Uitgeverij.

Ginns, P. (2005). Meta-analysis of the modality effect. *Learning and instruction*, *15*(4), 313–331. https://doi.org/10.1016/j.learninstruc.2005.07.001

Graesser, A. C. (2007). An introduction to strategic reading comprehension. In D. S. McNamara (Ed.), *Reading comprehension strategies: Theories, interventions, and technologies* (pp. 3-26). Lawrence Erlbaum Associates Publishers

Gregg, N., & Banerjee, M. (2009). Reading comprehension solutions for college students with dyslexia in an era of technology. In G. Reid (Ed.), *Dyslexia: A handbook for Research and Practice* (pp. 265–285). Routledge. https://doi.org/10.4324/9780203549230

Gubbels, J., Netten, A., & Verhoeven, L. (2016). *Vijftien jaar leesprestaties in Nederland: PIRLS-2016*. Expertisecentrum Nederlands. https://www.iea.nl/publications/study-reports/national-reports-iea-studies/vijftien-jaar-leesprestaties-nederland

Gyselinck, V., Jamet, E., & Dubois, V. (2008). The role of working memory components in multimedia comprehension. *Applied Cognitive Psychology, 22*(3), 353–374. https://doi.org/10.1002/acp.1411

Heiman, T., & Precel, K. (2003). Students with learning disabilities in higher education: Academic strategies profile. *Journal of Learning Disabilities, 36*(3), 248–258. https://doi.org/10.1177/002221940303600304

Helder A., Kraal A. & Van den Broek P.W. (2015). De ontwikkeling van begrijpend lezen: Oorzaken van succes en falen vanuit een cognitief perspectief. In: Schram D. (red.). *Hoe maakbaar is de lezer* (nr. 25, pp. 59-78). Eburon, Stichting Lezen Reeks.

Hyönä, J., & Olson, R. K. (1995). Eye fixation patterns among dyslexic and normal readers: Effects of word length and word frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*(6), 1430. https://doi.org/10.1037/0278-7393.21.6.1430

Juvina, I., & Van Oostendorp, H. (2008). Modeling semantic and structural knowledge in web navigation. *Discourse Processes*, *45*, 346–364. https://doi.org/10.1080/01638530802145205

Kalyuga, S., & Sweller, J. (2014). 10 The redundancy principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 247-262). Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.013

Kim, S., Lombardino, L. J., Cowles, W., & Altmann, L. J. (2014). Investigating graph comprehension in students with dyslexia: An eye tracking study. *Research in Developmental Disabilities, 35*(7), 1609–1622. https://doi.org/10.1016/j.ridd.2014.03.043

Kim, S., & Wiseheart, R. (2017). Exploring text and icon graph interpretation in students with dyslexia: An eye-tracking study. *Dyslexia*, *23*(1), 24-41. https://doi.org/10.1002/dys.1551

Kim, S., Wiseheart, R., & Walden, P. R. (2018). Do multimedia instructional designs enhance comprehension in college students with dyslexia? *Journal of Postsecondary Education and Disability*, *31*(4), 351-365.

Kirby, J. R., Silvestri, R., Allingham, B. H., Parrila, R., & La Fave, C. B. (2008). Learning strategies and study approaches of postsecondary students with dyslexia. *Journal of Learning Disabilities*, *41*(1), 85–96. https://doi.org/10.1177/0022219407311040

Klois, S. S., Segers, E., & Verhoeven, L. (2013). How hypertext fosters children's knowledge acquisition: The roles of text structure and graphical overview. *Computers in Human Behavior*, *29*(5), 2047-2057. https://doi.org/10.1016/j.chb.2013.03.013

Krejtz, I., Szarkowska, A., Krejtz, K., Walczak, A., & Duchowski, A. (2012). Audio description as an aural guide of children's visual attention: Evidence from an eye-tracking study. *Proceedings of the symposium on eye tracking research and applications* (pp. 99–106). ACM. https://doi.org/10.1145/2168556.2168572

Leahy, W., Chandler, P., & Sweller, J. (2003). When auditory presentations should and should not be a component of multimedia instruction. *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition*, *17*(4), 401-418. https://doi.org/10.1002/acp.877

Lajoie, S. P., & Azevedo, R. (2006). Teaching and learning in technology-rich environments. In P. A. Alexander & P. H. Winne (Eds.), *Handbook of educational psychology* (pp. 803–821). Lawrence Erlbaum Associates Publishers.

Li, J., Antonenko, P. D., & Wang, J. (2019). Trends and issues in multimedia learning research in 1996–2016: A bibliometric analysis. *Educational Research Review*, *28*, 100282. https://doi.org/10.1016/j.edurev.2019.100282

Liu, H. C., Lai, M. L., & Chuang, H. H. (2011). Using eye-tracking technology to investigate the redundant effect of multimedia web pages on viewers' cognitive processes. *Computers in Human Behavior, 27*(6), 2410–2417. https://doi.org/10.1016/j.chb.2011.06.012

Lyon, G. R., Shaywitz, S. E., & Shaywitz, B. A. (2003). A definition of dyslexia. *Annals of Dyslexia, 53*(1), 1-14. https://doi.org/10.1007/s11881-003-0001-9

MacCullagh, L., Bosanquet, A., & Badcock, N. A. (2017). University students with dyslexia: A qualitative exploratory study of learning practices, challenges and strategies. *Dyslexia*, *23*(1), 3-23. https://doi.org/10.1002/dys.1544

Madrid, R. I., Van Oostendorp, H., & Melguizo, M. C. P. (2009). The effects of the number of links and navigation support on cognitive load and learning with hypertext: The mediating role of reading order. *Computers in Human Behavior*, *25*(1), 66-75. https://doi.org/10.1016/j.chb.2008.06.005

Mayer, R. E. (1996). Learners as information processors: Legacies and limitations of educational psychology's second metaphor. *Educ. Psychol.*, *31*, 151-161. https://doi.org/10.1080/00461520.1996.9653263

Mayer, R. E. (2002). Multimedia learning. In B. H. Ross (Ed.), *Psychology of learning and motivation* (Vol. 41, pp. 85-139). Academic Press. https://doi.org/10.1016/S0079-7421(02)80005-6

Mayer, R. E. (2005). *The Cambridge Handbook of Multimedia Learning*. Cambridge University Press. https://doi.org/10.1017/CBO9780511816819

Mayer, R. E. (2017). Using multimedia for e-learning. *Journal of Computer Assisted Learning*, *33*(5), 403-423. https://doi.org/10.1111/jcal.12197

Mayer, R. E., & Fiorella, L. (2014). 12 principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (Vol. 279, pp. 279-315). Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.015

Menghini, D., Finzi, A., Carlesimo, G. A., & Vicari, S. (2011). Working memory impairment in children with developmental dyslexia: Is it just a phonological deficity? *Developmental Neuropsychology*, *36*(2), 199–213. https://doi.org/10.1080/87565641.2010.549868

Molina, A. I., Navarro, Ó., Ortega, M., & Lacruz, M. (2018). Evaluating multimedia learning materials in primary education using eye tracking. *Computer Standards & Interfaces*, *59*, 45-60. https://doi.org/10.1016/j.csi.2018.02.004

Olson, R. K., & Wise, B. W. (1992). Reading on the computer with orthographic and speech feedback. *Reading and Writing*, *4*(2), 107-144. https://doi.org/10.1007/BF01027488

Onderwijsinspectie. (2019). Dyslexieverklaringen: Verschillen tussen scholen nader bekeken. Retrived from https://www.onderwijsinspectie.nl/documenten/themarapporten/2019/04/10/dyslexieverklaringen-verschillen-tussen-scholen-nader-bekeken

Paas, F., Renkl, A., & Sweller, J. (2003). Cognitive load theory and instructional design: recent developments. *Educational psychologist*, *38*, 1-4. https://doi.org/10.1207/S15326985EP3801_1

Paans, C., Molenaar, I., Segers, P. C. J., & Verhoeven, L. T. W. (2020). Children's macro-level navigation patterns in hypermedia and their relation with task structure and learning outcomes. *Frontline Learning Research*, *8*(1), 76 – 95. https://doi.org/10.14786/flr.v8i1.473

Paivio, A. (1986). *Mental representations: A dual coding approach*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195066661.001.0001

Perfetti, C. A., & Hart, L. (2002). The lexical quality hypothesis. *Precursors of functional literacy*, *11*, 67-86. https://doi.org/10.1075/swll.11.14per

Pickering, S. J. (2012). Working memory in dyslexia. In T. P. Alloway, & S. E. Gathercole (Eds.), *Working memory and neurodevelopmental disorders* (pp. 161–186). Psychology Press.

Pintrich, P. R., & Zusho, A. (2002). The development of academic self-regulation: The role of cognitive and motivational factors. In A. Wigfield & J. S. Eccles (Eds.), *Development of achievement motivation* (pp. 249-284). Academic Press. https://doi.org/10.1016/B978-012750053-9/50012-7

Reinwein, J. (2012). Does the modality effect exist? And if so, which modality effect?. *Journal of Psycholinguistic Research*, *41*(1), 1-32. https://doi.org/10.1007/s10936-011-9180-4

Reiter, A., Tucha, O., & Lange, K. W. (2005). Executive functions in children with dyslexia. *Dyslexia*, *11*, 116–131. https://doi.org/10.1002/dys.289

Rello, L., & Ballesteros, M. (2015). Detecting readers with dyslexia using machine learning with eye tracking measures. *Proceedings of the 12th International Web for All Conference*, 1-8. https://doi.org/10.1145/2745555.2746644

Rop, G., Schüler, A., Verkoeijen, P. P., Scheiter, K., & Gog, T. V. (2018). The effect of layout and pacing on learning from diagrams with unnecessary text. *Applied Cognitive Psychology*, *32*(5), 610-621. https://doi.org/10.1002/acp.3445

Roscoe, R. D., Jacovina, M. E., Harry, D., Russell, D. G., & McNamara, D. S. (2015). Partial verbal redundancy in multimedia presentations for writing strategy instruction. *Applied Cognitive Psychology*, *29*(5), 669–679. https://doi.org/10.1002/acp.3149

Ruf, A. P., Seckler, M., & Opwis, K. (2014). Long-term modality effect in multimedia learning. *Proceedings of the 8th Nordic Conference on Human–Computer Interaction: Fun, Fast, Foundational*, 963-966. https://doi.org/10.1145/2639189.2670251

Salmerón, L., & García, V. (2011). Reading skills and children's navigation strategies in hypertext. *Computers in Human Behavior*, *27*(3), 1143-1151. https://doi.org/10.1016/j.chb.2010.12.008

1

Salmerón, L., Kintsch, W., & Cañas, J. (2006). Coherence or interest as basis for improving hypertext comprehension. *Information Design Journal*, *14*(1), 45-55. https://doi.org/10.1075/idj.14.1.06sal

Savoji, A. P., Hassanabadi, H., & Fasihipour, Z. (2011). The modality effect in learner-paced multimedia learning. Procedia. *Social and Behavioral Sciences*, *30*, 1488–1493. https://doi.org/10.1016/j.sbspro.2011.10.288

Scheiter, K., Schüler, A., Gerjets, P., Huk, T., & Hesse, F. W. (2014). Extending multimedia research: How do prerequisite knowledge and reading comprehension affect learning from text and pictures. *Computers in Human Behavior*, *31*, 73–84. https://doi.org/10.1016/j.chb.2013.09.022

She, H. C., & Chen, Y. Z. (2009). The impact of multimedia effect on science learning: Evidence from eye movements. *Computers & Education*, *53*(4), 1297–1307. https://doi.org/10.1016/j.compedu.2009.06.012

Schmidt-Weigand, F., Kohnert, A., & Glowalla, U. (2010). Explaining the modality and contiguity effects: New insights from investigating students' viewing behaviour. *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition*, *24*(2), 226-237. https://doi.org/10.1002/acp.1554

Schneider, W. (2011). Memory development in childhood. In U. Goswami (Ed.), *The Wiley-Blackwell handbook of childhood cognitive development* (2nd ed., pp. 347-376). Wiley-Blackwell. https://doi.org/10.1002/9781444325485.ch13

Schroeder, S., Hyönä, J., & Liversedge, S. P. (2015). Developmental eye-tracking research in reading: Introduction to the special issue. *Journal of Cognitive Psychology*, *27*(5), 500-510. https://doi.org/10.1080/20445911.2015.1046877

Schuchardt, K., Maehler, C., & Hasselhorn, M. (2008). Working memory deficits in children with specific learning disorders. *Journal of Learning Disabilities*, *41*(6), 514-523. https://doi.org/10.1177/0022219408317856

Segers, E., Verhoeven, L., & Hulstijn-Hendrikse, N. (2008). Cognitive processes in children's multimedia text learning. *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition*, *22*(3), 375-387. https://doi.org/10.1002/acp.1413

Seufert, T., Schutze, M., & Brunken, R. (2009). Memory characteristics and modality in multimedia learning: An aptitude–Treatment–Interaction study. *Learning and Instruction*, *19*(1), 28–42. https://doi.org/10.1016/j.learninstruc.2008.01.002

Smith-Spark, J. H., & Fisk, J. E. (2007). Working memory functioning in developmental dyslexia. *Memory*, *15*, 34–56. https://doi.org/10.1080/09658210601043384

Swanson, H. L., Zheng, X., & Jerman, O. (2009). Working memory, short-term memory, and reading disabilities: A selective meta-analysis of the literature. *Journal of Learning Disabilities*, *42*, 260–287. https://doi.org/10.1177/0022219409331958

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive science*, *12*(2), 257-285. https://doi.org/10.1207/s15516709cog1202_4

Sweller, J., & Australian Council for Educational Research (1999). *Instructional design*. ACER Press.

Schweppe, J., & Rummer, R. (2012). Long-term multimedia learning. In E. de Vries & K. Scheiter (Eds.), *EARLI Sig2 Meeting 2012: Staging Knowledge and Experience: How to Take Advantage of Representational Technologies in Education and Training* (pp. 196-198). Laboratoire des Sciences de l'Education.

Tabbers, H. K. (2002). *The modality of text in multimedia instructions: Refining the design guidelines* [Doctoral dissertation, Open Universiteit]. Open Universiteit.

Tabbers, H. K., Martens, R. L., & Merriënboer, J. J. (2004). Multimedia instructions and cognitive load theory: Effects of modality and cueing. *British Journal of Educational Psychology*, *74*(1), 71–81. https://doi.org/10.1348/000709904322848824

Tijms, J. (2004). Verbal memory and phonological processing in dyslexia. *Journal of Research in Reading*, *27*(3), 300-310. https://doi.org/10.1111/j.1467-9817.2004.00233.x

Unsworth, N., & Engle, R. W. (2007). The nature of individual differences in working memory capacity: active maintenance in primary memory and controlled search from secondary memory. *Psychological review*, *114*(1), 104-132. https://doi.org/10.1037/0033-295X.114.1.104

Van den Broek, P., & Helder, A. (2017). Cognitive processes in discourse comprehension: Passive processes, reader-initiated processes, and evolving mental representations. *Discourse Processes*, *54*(5-6), 360-372. https://doi.org/10.1080/0163853X.2017.1306677

Van den Broek, G. S. E., Segers, E., & Verhoeven, L. (2014). Effects of text modality in multimedia presentations on written and oral performance. *Journal of Computer Assisted Learning*, *30*, 438–440. https://doi.org/10.1111/jcal.12058

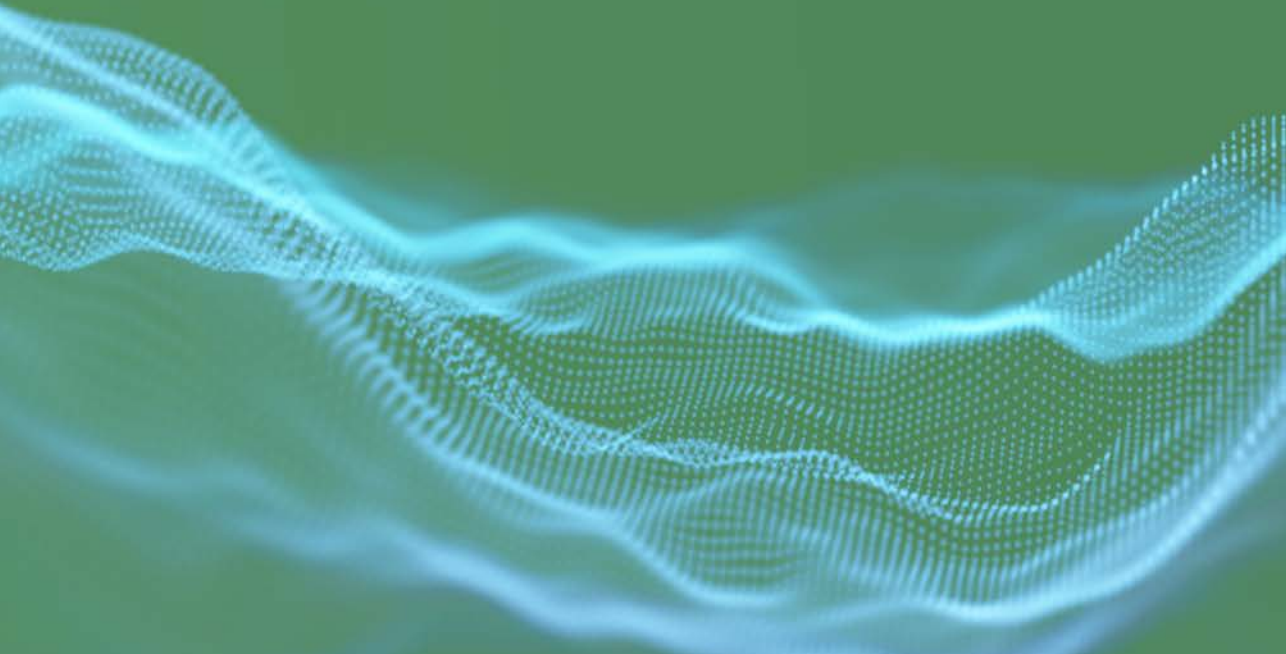
Wiebe, E., & Annetta, L. (2008). Influences on visual attentional distribution in multimedia instruction. *Journal of Educational Multimedia and Hypermedia*, *17*(2), 259–277.

Wang, J., Dawson, K., Saunders, K., Ritzhaupt, A. D., Antonenko, P. P., Lombardino, L., Keil, A., Agacli-Dogan, N., Luo, W., Cheng, L., & Davis, R. O. (2018). Investigating the effects of modality and multimedia on the learning performance of college students with dyslexia. *Journal of Special Education Technology*, *33*(3), 182–193. https://doi.org/10.1177/0162643418754530

Wang, F., Xie, H., & Li, H. (2016). Visual text or narration? Meta-analysis of the modality effect in multimedia learning. *Advances in Psychological Science*, *24*(3), 335-350. https://doi.org/10.3724/SP.J.1042.2016.00335

Witteman, M. J., & Segers, E. (2010). The modality effect tested in children in a user-paced multimedia environment. *Journal of Computer Assisted Learning*, *26*, 132–142. https://doi.org/10.1111/j.1365-2729.2009.00335.x

Wu, J. Y. (2014). Gender differences in online reading engagement, metacognitive strategies, navigation skills and reading literacy. *Journal of Computer Assisted Learning*, *30*(3), 252-271. https://doi.org/10.1111/jcal.12054



CHAPTER 2

IMPACT OF AUDIO ON LEARNING PROCESSES AND OUTCOMES IN ADULTS WITH DYSLEXIA

Abstract

Adding audio to written text may cause redundancy effects, but could be beneficial for students with dyslexia for whom it supports their reading. Studying both learning processes and learning outcomes in students with and without dyslexia can shed light on this issue and help to find out whether there are constraints to the redundancy effect as proposed in the Cognitive Theory of Multimedia Learning. We examined to what extent adding -redundant- audio affects multimedia learning in 42 university students with dyslexia and 44 typically developing students. Participants studied two user-paced multimedia lessons (text-picture, text-audio-picture) with retention and transfer post-tests. An SMI RED-500 eye-tracker captured eye-movements during learning. Regarding process measures, students had longer study times, with more focus on pictures, and more transitions between text and pictures in the text-audio-picture condition. Regarding learning outcomes, negative redundancy effects on transfer knowledge (deep learning), but not on (factual) retention knowledge were found across both groups. When relating learning processes to learning outcomes, longer study times predicted higher transfer knowledge in both groups in the text-audio-picture condition, whereas in the text-picture condition, more study time predicted lower transfer knowledge in typically developing students only. To conclude, adding audio seems to have a negative effect on the quality of knowledge and leads to less efficient learning across the two groups. Reading ability does not impact the universality of the redundancy effect, but students with dyslexia should only use audio-support when aiming to learn factual knowledge and should be aware that it increases study time.

This chapter is based on Knoop-van Campen, C. A. N., Segers, E., & Verhoeven, L. (2020). Effects of audio support on multimedia learning processes and outcomes in students with dyslexia. *Computers & Education*, 150, 103858.

Introduction

On a daily basis, students with dyslexia are provided with audio-support to aid their reading (Ghesquière et al., 2010, pp. 41–58). Theoretically, this may have a negative impact on learning, as adding audio to written text causes a redundancy effect, as the working memory has to process the same information in two modalities, causing an overload (Mayer, 2005). However, a meta-analysis comparing learning outcomes on written-text and written-text-with-added-audio showed that while adding written redundant information does have a negative impact on learning outcomes, verbally redundant information does not (Adesope & Nesbit, 2012). To understand these differences in learning outcomes and to specify possible boundary conditions of the redundancy effect, there is a need to examine the online learning process. Previous studies showed that adding audio changes learning processes (Harrar et al., 2014; Liu et al., 2011; She & Chen, 2009). Nevertheless, how these learning processes affect learning outcomes is unclear. Applying this knowledge to students with dyslexia, theory on the one hand would suggest a negative effect on learning outcomes due to working memory overload, while it can also be hypothesized that adding audio would enhance learning in this specific group, since it helps to compensate for reading difficulties. In the current study, we aimed to find out whether there are constraints to the redundancy effect as proposed in the Cognitive Theory of Multimedia Learning (Mayer, 2005) by examining to what extent adding audio changes learning processes and outcomes in students with dyslexia as compared to their typically developing peers, and how these learning processes relate to learning outcomes. We seek to answer the question whether audio-support is beneficial for learning in students with dyslexia.

Redundancy Effect in Multimedia Learning

The Cognitive Theory of Multimedia Learning (Mayer, 2005; Mayer & Fiorella, 2014) states that learning is optimal when both the visual and the auditory channel in working memory are used to a similar extent. When, however, the same information is provided in two modalities simultaneously, this has a negative effect on learning. This negative effect is called the redundancy effect (Mayer & Fiorella, 2014). Mostly, the redundancy effect has been studied with the written information being redundant. When audio-only is compared to text-audio (and written text is thus redundant), clear redundancy effects have been found: people learn more when information is presented auditory (Jamet & Le Bohec, 2007; Kalyuga et al., 1999; Moreno & Mayer, 2002). Some studies, however, found reversed redundancy effects. For example, Ari and colleagues (2014) indicated that redundant on-screen text with auditory information supported learning in university students, especially when the learning material was complex.

Fewer studies examined the redundancy effect with audio being redundant, while this is most common in school materials in which students receive audio-support. A meta-analysis including 1480 participants comparing learning outcomes on written-text and written-text-with-added audio (Adesope & Nesbit, 2012) showed that verbally redundant information did not negatively influence learning. Students learned as much when presented with written-text as when they received written-text-with-narration; in other words, there was no redundancy effect. This was confirmed in more recent studies. In a study in primary school children, Knoop-van Campen and colleagues (2018) compared pictorial information with written text to pictures with written text and redundant audio in primary school children and did not find differences on retention or transfer knowledge. A study on adults comparing various forms of multimodal information, also did not find learning differences between participants in a written text condition compared to those who were presented with written text and narration (De Koning et al., 2017). When the degree of redundancy between written and narrated content was manipulated (Roscoe et al., 2015), this degree of redundancy did not affect learning gains. Also in the literature of software applications, studies on the effect of pedagogical agents on learning (Veronikas & Maushak, 2005) did not find differences between text and text with audio. When comparing students who were asked to listen to audio instruction in addition to using a laboratory manual to complete an exercise to students without the extra audio, no differences in the performance between the groups were found (Beccue et al., 2001).

It is important to note that the lack of the redundancy effect in the above-described studies is difficult to align with the Cognitive Theory of Multimedia Learning (Mayer, 2005), which explains the effects via working memory overload. The instructional orientated Cognitive Load Theory (Sweller et al., 2011) addresses this discrepancy from a slightly different angle and focuses on the limitations of the working memory. This theory indicates that there are three different ways to (over) load working memory: via intrinsic, extraneous and germane load (Sweller et al., 1998). The redundancy effect -with its two similar information sources- specifically involves increased extraneous cognitive load (Van Merriënboer & Sweller, 2010). As reducing one of these sources should result in lower extraneous cognitive load and higher learning gains, the Cognitive Load Theory implies that, when there are no redundancy effects, the material did not seem to burden learners' extraneous cognitive load to the point that the design principles of the learning material were problematic. There is thus a need to further study and understand the constraints to the redundancy effect.

Multimedia Learning Processes

One way to understand the differences between the theory and the observed results in multimedia learning and to examine possible boundary conditions, is to examine the learning process. What happens during learning could explain why students do or no do not benefit from added audio. Eye tracking is often used in multimedia learning to examine the learning process. Combined with offline knowledge measures, it provides new opportunities to examine how students learn in multimedia learning environments.

Within research on the processing of multimedia information, only a few studies have been conducted regarding the redundancy effect. Liu and colleagues (2011) used eye-tracking to investigate how adding audio to written text changed viewers' cognitive processes when examining webpages. They showed that students focus mainly on the written text instead of the accompanying picture for determining meaning. Their results showed that adding audio to written text did not change the number of fixations on the text and pictures, but the fixation duration did decrease. They argued that adding audio reduces processing time of the text (Liu et al., 2011). A study in primary school children examining the impact of added audio on movie clips, also showed that added audio changed children's viewing behaviour (Krejtz et al., 2012). Krejtz and colleagues (2012) showed that the audio-support guided students' attention towards the described objects, resulting in more fixations, and shorter saccades. A stronger fixation on pictures when audio was added to written text was also found in a study on the distribution of visual attention in multimedia learning (Wiebe & Annetta, 2008). Providing students with audio-support thus seems to affect the way they learn.

None of the above-described studies, however, related their processing results directly to learning outcomes, while Hyönä (2010) emphasized the importance of connecting process (eye-tracking) data to offline measures that examine the end product of learning (learning outcome). Doing so can facilitate a new understanding in multimedia learning and by combining online and offline measure "the researcher is in a position to tease apart, for example, the extent to which a learning failure is a result of inadequate intake and encoding of relevant features of the learning materials" (Hyönä, 2010, p. 176). In line with this notion, She and Chen (2009) propose that there is a direct correlation between eye fixation behaviour and learning, even though they do not examine this relation. There are studies that examined both processing and outcome measures, but these merely compared outcome measures based on a high versus low processing group or the other way around instead of directly relating the two to each other (e.g., Koć-Januchta et al., 2017; Mason et al., 2016; Ponce et al., 2018; Tsai et al., 2016). The field is thus in need of studies that make the direct link between process measures and outcomes.

Multimedia Learning in Dyslexia

In education, multimedia learning environments often contain audio in addition to written text and pictures. A specific group that uses this audio-support even more frequently are students with dyslexia. These students have phonological deficits and experience reading difficulties (Lyon et al., 2003). Even though they can acquire reading comprehension skills, their grapheme-phoneme-connection remains poorly over time (De Jong & Van der Leij, 2003). Reading written text costs extra effort and burdens the working memory. In addition, some students with dyslexia also experience working memory deficits (Beneventi et al., 2010), which potentially also increases the problems of the extraneous cognitive load due to redundant information. However, to compensate for their reading problems, students with dyslexia are often provided with audio-support, like reading software (Ghesquière et al., 2010). For university students with dyslexia, written text presented with an additional audio format is the most commonly used assistive technology (Gregg & Banerjee, 2009).

As audio-support is widely used in education, there is a clear need to understand how this audio-support affects students learning process and in turn their learning outcomes. Practitioners and educational-software developers need evidence-based information on how and when to provide audio-support. This is not only relevant for the educational field, but also helps to shape theory on multimedia learning, as such research supports the possible identification of boundary conditions to certain hypotheses (in the case of the current paper, to the redundancy effect). Based on the Cognitive Load Theory, this audio-support may hamper their learning by an extraneous cognitive overload but also decrease intrinsic cognitive overload by relieving their decoding issues.

Despite this growing need for information, research on effects of compensatory audio-support on learning outcomes in students with dyslexia is scarce. Only two studies specifically investigated the redundancy effect on outcome measures in primary school children with dyslexia. Knoop-van Campen and colleagues (2018, 2019) showed that there was no learning difference in children with dyslexia between learning from multimedia consisting of images with text, or images with text and audio. Both children with and without dyslexia learned as much in learning environments with and without added audio. This implicates that even though information is presented in two different modalities at the same time, this design principle may not hamper young learners. The information that is redundant for typical readers, may not (at least not in a problematic way) be redundant for children with dyslexia. However, these studies were conducted in young children, who have less reading experience than adults.

Other research related to multimedia learning seems to be promising regarding audio-support in students with dyslexia. A study which examined both reading and listening comprehension in children with dyslexia, showed that the difficulties in comprehension were only related to poor reading skills and not to listening capacities (Casalis et al., 2013). Poor decoding hampered their reading comprehension, while after listening to oral information, these students scored equally well as typically peers. When providing students with dyslexia with enough time to carefully decode, their reading comprehension reaches similar levels compared to their typically developing peers (Jackson & Doellinger, 2002). Fidler and Everatt (2012) thus suggest that to improve learning situations for students with dyslexia, one could increase comprehension by means of supportive technology. Students with dyslexia may need to rely more on their listening comprehension skills to understand information. In Draffan's (2002) chapter on assistive technologies in supporting students' learning, he argues that listening to written text helps students with dyslexia in their reading tasks. This added audio is often faster than students own reading pace, and it may aid understanding. Audio-support lowers the necessity to decode every single word and thus more attention can be given to understanding the content and building an integrative model (Schnotz, 2005). The latter two studies emphasize the possible positive effects of audio-support on reading -and especially decoding- but did not include the effects on learning outcomes.

Aside from these differences between students with and without dyslexia on learning outcomes, students with dyslexia also seem to differ in the way they process learning materials. Studies on general academic strategies indeed argued that students with learning disabilities, like dyslexia, used different learning strategies to attain the required level (Kirby et al., 2008), and that they preferred to use more oral and visual strategies (like using oral explanations) compared to typically developing students who would use more written techniques (like rewriting or summarizing) (Heiman & Precel, 2003)). In several studies, an attempt was made to examine the processing of multimodal information in this specific group of students. Regarding the processing of auditory information, Lallier and colleagues (2013) showed with a dichotic listening task -syllables sequentially presented in the right ear and different syllables in the left ear-that children with dyslexia could recall less correct syllables than typically developing peers, indicating that the former had more problems processing auditory material. As to processing of visual stimuli, an eye-tracking study into graph-text comprehension, showed that students with dyslexia needed more time for processing both text as well as graphs (Kim et al., 2014). In addition, Schmidt-Weigand and colleagues (2010) showed that the distribution of visual attention in multimedia learning in typically developing students is largely guided by written text and not by the images. Since students with dyslexia have reading difficulties, this may impact their multimedia learning differently than that of typically developing peers.

When examining the combination of visual and auditory input, university students with dyslexia showed audio-visual integration problems (Harrar et al., 2014). Based on a reaction time study with motor responses, Harrar et al. (2014) showed that students with dyslexia had longer reaction times and that their reaction was especially slower when de modus of the stimuli changed (between visual, auditory and combined stimuli). They state that students with dyslexia find it harder to shift their attention away from visual stimuli towards auditory and vice versa than typically developing students. Finally, the two studies on the redundancy effect in primary school children with dyslexia (Knoop-van Campen et al., 2018, 2019) both showed differences in the time children spent on a lesson. When children with dyslexia were provided with audio in addition to the written text and pictures, these children learned as fast as their typically developing peers: audio-supported them to decrease study times (Knoop-van Campen et al., 2018; 2019). This decrease in study time is likely due to the compensatory effect of adding audio. However, results cannot be interpreted fully given the fact that it is unknown whether the children would read at all when audio was added.

It seems evident that students with dyslexia experience general problems in processing multimodal information. The nature of these problems is still under debate as process measures in multimedia environments are inconclusive. On top of that, although (some of) these studies investigated both learning processes and learning outcomes, typically process and outcome are put next to each other, instead of using process measures as predictors for learning outcomes and in such a way truly connect both aspects of multimedia learning. Doing the latter would provide the opportunity to identifying possible boundary conditions to the redundancy effect and in turn foster changes in the educational field. As such, it sheds light on the question whether audio-support is or is not supportive in students with dyslexia.

The Present Study

In the present study, it was examined to what extent adding -redundant- audio affects multimedia learning in university students with dyslexia as compared to typically developing students. This study is among the first to address this issue, both from a theoretical and educational point of view. All students were presented with two user-paced multimedia lessons: i) text with pictures and ii) text with picture and added audio. During the lessons, their eye-movements were captured with a SMI RED-500. Areas of interest (text vs. picture) and transitions were compared between the conditions (with or without added audio) and groups (with or without dyslexia). After the lessons, students' retention and transfer knowledge was measured. Students' process measures could therefore be related to their learning outcomes. Research questions were:

RQ 1 What are the differences in learning processes and outcomes in multimedia environments with or without added audio, in students with dyslexia compared to typically developing peers?

RQ 2 How are processes and outcomes in multimedia learning related in the two groups?

Regarding the first research question, it was hypothesized that there would be no redundancy effects on knowledge in typically developing students (Adesope & Nesbit, 2012), but in students with dyslexia adding audio was expected to positively influence learning (first hypothesis). Even though theory would suggest a negative effect on learning outcomes in students with dyslexia, it can be hypothesized that adding audio would enhance learning due to its compensatory capacities regarding their reading problems (Fidler & Everatt, 2012). Secondly, differences in processing multimodal information were expected. It was expected that students would spend more time on the images in the multimedia environment when audio was added. Also, a higher number of transitions between the written text and the images was expected when audio as added (Krejtz et al., 2012; Liu et al., 2011). Due to their reading problems and modality integration difficulties, it was expected that in students with dyslexia, the process differences with adding audio would be stronger (second hypothesis): they are expected to examine the image even more and also show more transitions than their typically developing peers (Harrar et al., 2014; Kim et al., 2014).

As no previous research has connected learning processes to learning outcomes and as the nature of (difficulties in) processing information in multimedia environments is still under debate, no specific hypotheses were made on how processing multimodal material would predict learning outcomes.

Method

Participants

Participants were 86 students (42 students with dyslexia; 44 typically developing students) from a Dutch university and applied university, who participated for a monetary reward (30 Euro) or course credit and gave active consent (ethical approval for the study was granted by the Ethics Committee). The students with dyslexia were all officially diagnosed with dyslexia (mostly during primary school) by a certified child psychologist following to the clinical Protocol Dyslexia Diagnosis and Treatment (Blomert, 2005), which is a guide to diagnosing, indicating, and treating clients with dyslexia. To be eligible for this clinical assessment during primary or secondary school, children have to score in the lowest 10 percent of reading (or lowest 15% reading and the lowest 15% on spelling) for three test measurements in a row. During the diagnostic procedure, children have to fail at least 2 out of 6 aspects of the test (phonological awareness speed & accuracy, grapheme-phoneme association speed & accuracy, rapid naming letters & numbers) to be diagnosed with dyslexia.

Only monolingual raised students were allowed to participate. Students of all types of studies participated, but due to the content of the multimedia lessons (biology lessons), biology and medicine students were excluded from participation.

Of the initial 86 participants, five participants had to be excluded due to a tracking ratio of less than 70% (N = 4 dyslexia, N = 1 typically developing). The tracking ratio was determined by dividing the amount of recorded eye movement time to the total time of the lesson (similar to Van Wermeskerken, Grimmius, & Van Gog, 2018). Tracking ratio of the included group was 93.98% (SD = 4.04) for the first lesson and 92.86% (SD = 4.79) for the second lesson. The tracking ratio of the excluded group was 54.16% (SD = 14.52) for the first lesson and 66.92% (SD = 21.45) for the second lesson. In addition, one participant (dyslexia) was excluded due to extreme outliers in eye-tracking data in combination with too much missing data on the other variables.

The remaining 80 students were included in the data analyses: 37 students with dyslexia (M_{age} = 21.59, SD = 2.37; 31 female) and 43 typically developing students (M_{age} = 21.58, SD = 2.10; 35 female). Of the students with dyslexia, four students (11%) had a double diagnosis. Two students indicated having ADHD for which they effectively took medication, one other had ADD, and one an autism spectrum disorder. All four university students indicated that they did not experience any learning problems due to these comorbidities. One can only be diagnosed with dyslexia when any co-morbidity is treated in such a way that it is no longer an obstacle for learning. The students with and without dyslexia did not differ in age, $t(78) = 0.03$, $p = .979$, $d < 0.01$. In line with their diagnosis, students with dyslexia scored significantly lower on word reading fluency (M = 80.49, SD = 10.86) and pseudo word reading fluency (M = 71.51, SD = 18.89) than their typically developing peers (resp. M = 96.02, SD = 14.70 and M = 97.72, SD = 12.33), word reading, $t(78) = 5.30$, $p < .001$, $d = 1.20$, pseudo word reading, $t(60.29) = 7.22$, $p < .001$, $d = 1.64$.

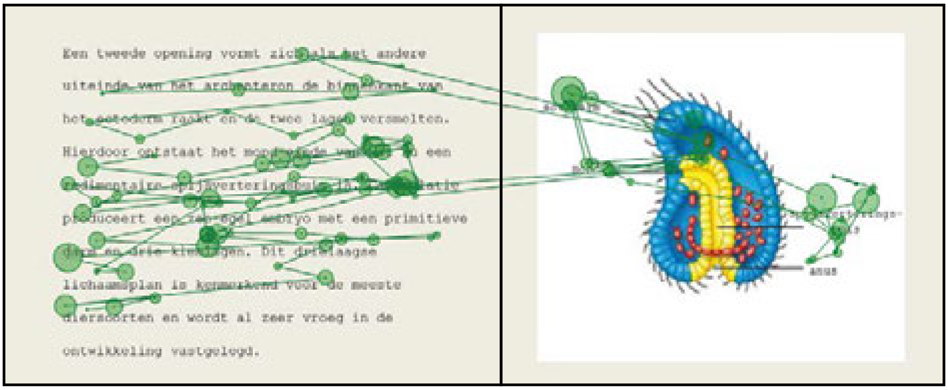
Materials

Multimedia Lessons

Participants were provided with two comparable biology multimedia lessons: pictures with i) written text, and ii) written text with added audio. The two lessons were presented to all the participants by means of slides on the computer (1920 × 1080 pixels). The lessons were based on the curriculum of the first study year of biology at university level (topics: gastrulation & small intestines). The text and images were taken from the book Campbell Biology (Reece et al., 2014) to ensure realistic content. The pictures are mainly interpretational illustrations, which are most effective for learning (Carney & Levin, 2002). Some pictures contained words: these words were one-on-one related to the written text on the same page.

Both lessons consisted of 15 slides, both with 900 words in total. Each slide contained an average of 60 words (SD = 13, Range 35–90 words). There was one image on each slide. The slides were split into two Areas of Interest: A Text-AOI on the left side (surface: 52%) and a Picture-AOI on the right side (surface: 48%) (see Figure 2.1). To ensure comparability between the conditions, all pages looked exactly the same with text on the left side and a picture on the right side. All pictures were exactly the same size (585 pixels × 385 pixels).

Figure 2.1
Areas of Interest (Left Text-AOI, Right Picture-AOI).



Participants could move though the lessons at their own pace and could move forward and backwards though the slides of the lessons. In the added audio condition, the written text was also read by a professional voice-over (female voice). The speed was approximately 130 words/minute, which is a commonly used reading speed for learning material. The voice-over started to read the text when a new slide appeared. Students were able to simply pause or replay the voice-over.

Before the lesson-slides, students were given an informational slide on the procedure. It stated (in Dutch) "You are now going to study a biology lesson (15 slides). After learning the material, you will be asked to answer knowledge and implementation questions. With the keys 'a' and 'l' you can go forward and backward through the slides at your own pace. Try to sit still/do not move in your chair, you are allowed to move your head.". In the added audio condition, it was also stated "With the 'p' you can pause and continue the audio. With the '?' you can replay the audio.". Next, a slide with the subject (Gastrulation/Small Intestines) appeared, then students could start the lesson by moving to the first lesson-slide.

Apparatus

The SMI RED500 was used to monitor and record eye movements of participants during learning. The eye tracker was controlled with the SMI IView program and for the data analyses SMI Experiment Center Be-Gaze 3.7 was used. Students were seated in front of the eye tracker at approximately 60 cm (eyes – eye tracker). A nine-point calibration was used for the calibration. The quality of the calibration was assessed by the researcher. Calibration continued until a value < 1.00 was reached or when the lowest possible value was achieved based on the calibration difficulties of that particular participant. On average, students needed two calibrations (first lesson: M = 2.11, SD = 1.74, second lesson: M = 1.93, SD = 1.28). Calibration values varied with means of 0.54 (SD = 0.25) and 0.64 (SD = 0.23).

Learning Process Measures

Students' learning process was defined by their study time, fixation duration of their eye movements, and their transitions in eye movements during studying. *Study time* was defined as the time students spent studying a multimedia lesson, as was extracted from the log data. *Fixation duration* was calculated (based on fixation times form Begaze) as the sum of all fixation times on one AOI (Text or Picture). The percentage fixation duration on the Picture-AOI was calculated by dividing the fixation duration of the Picture-AOI by the fixation duration of the total lesson (Text-AOI + Picture-AOI) and multiplying it by 100. The number of *transitions* between the two AOIs was computed: a transition was counted whenever a saccade started in one AOI and ended in the other.

Learning Outcome Measures

To examine students' learning outcome, retention and transfer knowledge was tested directly after the lessons. Retention knowledge was measured following Moreno and Mayer (2002) by asking the students to write down the content of the lesson (e.g., "describe the process of gastrulation"). From every lesson 63 words were identified that reflected the content. Students received one point per correctly named item (Mayer et al., 2014). Correct spelling of a word was not necessary to receive a point. The retention test was sufficiently reliable ($\alpha = 0.88$).

Transfer knowledge was also measured following Moreno and Mayer (2002) in asking four open-ended questions, e.g. "In an experiment the pancreas was removed from a dog. Explain how this affects the digestion of food". The questions were scored with 0, 1, or 2 points by the first Author according to a scoring-card. Students could thus receive max 8 points. The transfer questions were sufficiently reliable ($\alpha = 0.77$). To validate the scoring card, part of the data (N = 23) was double coded by two research assistants, inter-reliability was good (Spearman rho's: first Author vs. coder one $M_{rho} = 0.87$, SD = 0.11, first Author vs. coder two $M_{rho} = 0.85$, SD = 0.14).

In order to validate the transfer questions, a pilot was conducted in advance. Twenty-four university students were asked to test the newly made materials: 14 transfer questions were created per lesson and scored by two coders. Following the pilot, the most suitable questions per lesson were selected for the present study. This selection was made based on the *p*-value and the RIT-value. All the chosen questions had a p-value of between .4 and .6, and a RIT-value above 0.3. The final questionnaires were sufficient reliable (α's > 0.74) and had a strong inter-reliability (r_s's > 0.72).

Reading and Working Memory

To check for group differences between the students with and without dyslexia, (pseudo) word reading and (visual and verbal) working memory was examined. To measure word decoding and pseudo word decoding, the Een-Minute-Test (EMT) [One-Minute-Test] (Brus & Voeten, 1999) and the Klepel (Van den Bos et al., 1994) were used. In both tests, students have to read as many (pseudo) words as they can from a list of words on a card within one resp. two minutes. The score is the number of words that a participant reads correctly in 1 min.

To measure verbal working memory, the Digits-backwards (subtest WISC-III-

NL: Wechsler, 1992) was used. After hearing a list of digits, students were requested to repeat the sequence in reverse order. The number of digits in a list increased, and the test was aborted when two sequences of the same length were incorrect.

To measure visual working memory, an N-back working memory task with N = 2 (Gevins & Cutillo, 1993) was used. Students were presented with 225 single numbers (presented 600 ms with 645 ms in between) and a correct score was granted whenever students pressed a key when a number repeated after two intervening stimuli.

Procedure

Data collection was gathered by the first Author with support of two undergraduate students who were trained to use the Eye-tracker. Participants came to the lab three times (once per week, three weeks in a row). During the first two visits, they were provided with one multimedia lesson and the corresponding post-test per visit. Multimedia lessons, conditions and post-tests were randomized per participant. During the third visit, the additional reading and working memory tasks were performed. Data collection was performed according to the test protocol describing in detail the procedure, instructions, eye tracker set-up, calibration, and the tasks.

Data-analyses

To answer the first research question, data was analysed using GLM Repeated Measures with Condition (text/added audio) as within-subjects-factor, and Group (dyslexia/controls) as between-subjects-factors. This was done for learning outcomes (retention knowledge and transfer knowledge) and for learning processes (study time, fixation duration, and transitions) with a fixed significance threshold of $p < .05$. Interactions between Condition and Group were included. Due to skewed distributions some variables were transformed with a logistic transformation (retention knowledge, study time, and transitions), or with a cube root transformation (fixation duration on the text, fixations on the picture) (see Table 2.1).

To relate learning processes to outcomes and thus answer the second research question, first correlations between the measurements are presented, followed by exploratory regression analyses. In these analyses, learning processes, group, and the interaction between learning processes and group were entered (backward, to avoid suppressor effects, Field, 2013) as predictors with learning outcome as dependent variable. Separate analyses were performed for retention and transfer knowledge and the two conditions with a fixed significance threshold of $p < .05$.

Results

Descriptives

Students with dyslexia scored comparable on verbal (M = 8.00, SD = 2.10) and visual working memory (M = 13.31, SD = 4.16) to their typically developing peers (resp. M = 9.00, SD = 2.34), and (M = 14.79, SD = 4.20), verbal working memory, $t(77) = 1.98$, $p = .051$, $d = 0.44$, visual working memory, $t(77) = 1.57$, $p = .120$, $d = 0.35$. The means and standard deviations for learning outcomes and learning processes separately for students with and without dyslexia are provided in Table 2.2. To provide insight in the distribution of the measures, untransformed scores are presented in dot plots in Figure 2.2 and Figure 2.3.

Table 2.1
Transformations

		Raw Scores			Transformed Scores	
		Skewness	Kurtosis	Transformation	Skewness	Kurtosis
Learning Outcomes						
Retention	Text Condition	1.40	4.00	Log10	-.78	.55
	Added Audio Condition	1.32	2.01	Log10	-.22	-.17
Transfer	Text Condition	.03	-.63	n.a.	n.a.	n.a.
	Added Audio Condition	-.23	-.53	n.a.	n.a.	n.a.
Learning Processes						
Study Time	Text Condition	.91	1.08	Log10	.07	-.37
	Added Audio Condition	1.33	2.22	Log10	.38	-.42
Fixation Duration	Text Condition					
	AOI Text	.77	.73	Cube Root	.11	-.42
	AOI Picture	.67	.04	Cube Root	-.07	-.68
	%AOI Picture	.31	-.37	n.a.	n.a.	n.a.
	Added Audio Condition					
	AOI Text	1.97	7.84	Cube Root	.19	2.06
	AOI Picture	.89	.39	Cube Root	-.04	.03
	%AOI Picture	.75	.22	n.a.	n.a.	n.a.
Transitions	Text Condition	1.55	3.49	Log10	.08	-.19
	Added Audio Condition	2.47	10.10	Log10	.17	.64

2

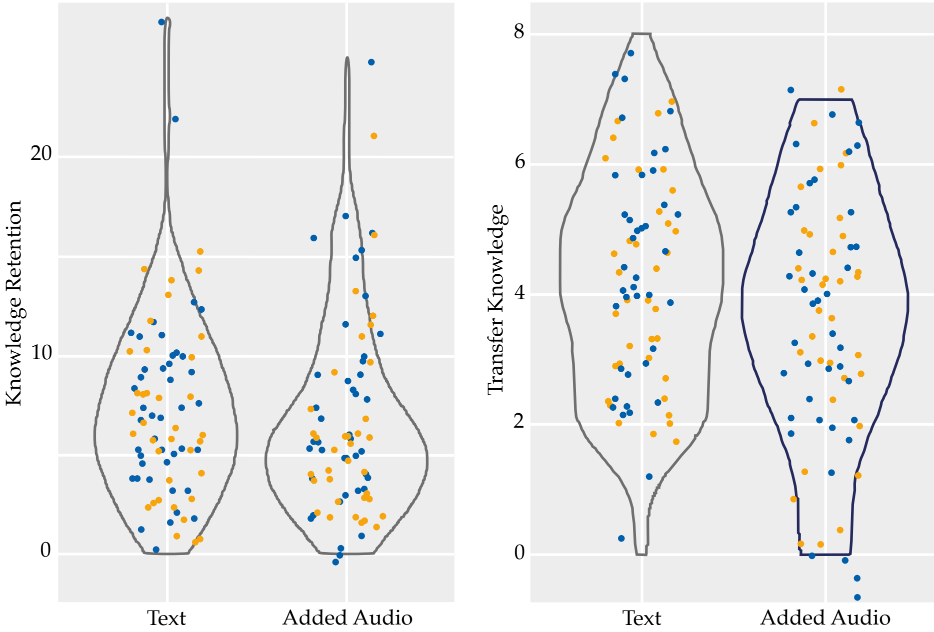
Table 2.2
Student Descriptives per Condition and Group

			Dyslexia			Typically Developing		
			N	M	SD	N	M	SD
Learning Outcomes	Retention	Text Condition	36	6.92	4.08	43	7.58	5.011
		Added Audio Condition	36	6.14	4.40	43	7.30	5.285
	Transfer	Text Condition	36	4.11	1.60	42	4.24	1.819
		Added Audio Condition	36	3.67	1.90	40	3.73	1.908
Learning Processes	Study Time	Text Condition	37	14.31	1.76	43	14.18	4.81
		Added Audio Condition	36	15.14	5.39	43	15.83	6.97
	Fixation Duration	Text Condition	37	9.78	3.95	43	8.88	3.26
		AOI Text	37	8.02	3.29	43	7.10	2.71
		AOI Picture	37	1.76	.97	43	1.78	.92
		%AOI Picture	37	17.86	7.06	43	19.84	6.54
		Added Audio Condition	36	9.35	4.25	43	9.37	4.33
		AOI Text	36	7.26	3.39	43	7.30	3.84
		AOI Picture	36	2.08	1.33	43	2.30	3.84
		%AOI Picture	36	21.83	8.84	43	22.97	8.31
	Transitions	Text Condition	37	101.54	53.94	43	129.16	53.60
		Added Audio Condition	36	144.97	70.30	43	171.98	92.30

Note. Study time and fixation duration are in minutes. Transitions are the sum (total number of transitions) of the 15 slides during a lesson.

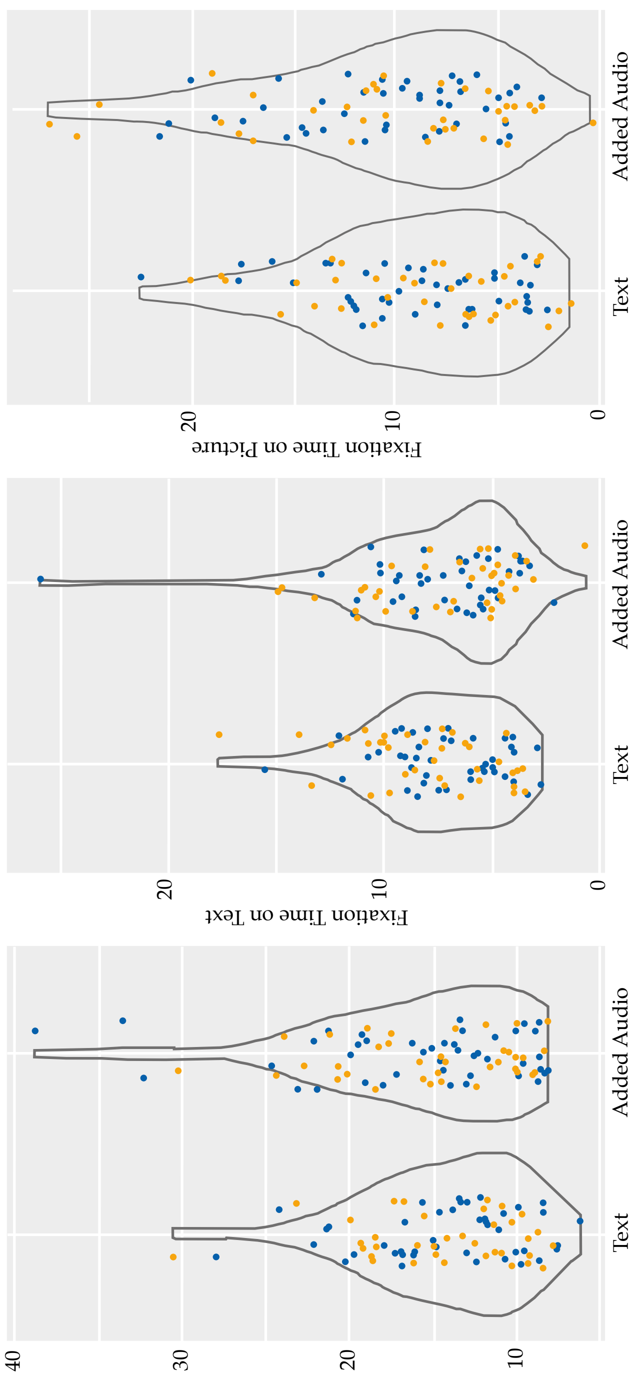
2

Figure 2.2
Overview of the Distribution of the Learning Outcomes



Note. Left panel shows retention knowledge, right panel shows transfer knowledge in students with dyslexia (orange) and typically developing students (blue).

Figure 2.3
Overview of the Distribution of the Learning Processes



Note. From left to right: panels show study time, fixation time on the text, and fixation time on the picture in students with dyslexia (orange) and typically developing students (blue).

2

Figure 2.3
(continued)

Note. (Continued) From left to right: panels show percentage fixation time on the picture and the number of transitions in students with dyslexia (orange) and typically developing students (blue).

Learning Outcomes

Regarding the *retention of knowledge*, there were no significant main effects of condition, $F(1, 72) = 0.53$, $p = .469$, $\eta^2_p = .007$, or group, $F(1, 72) = 3.93$, $p = .051$, $\eta^2_p = .052$. Also, there was no interaction between condition and group. The results show that the addition of audio did not impact learning of factual knowledge.

Analysis of the *transfer knowledge* showed a significant main effect of condition, $F(1, 72) = 6.05$, $p = .016$, $\eta^2_p = .077$. Students learned more in the text condition than in the condition where audio was added to the text. There was no main effect of group, $F(1, 72) = 0.16$, $p = .694$, $\eta^2_p = .002$, and no interaction effect between condition and group. The results thus show a redundancy effect for transfer knowledge; adding audio negatively impacted students' transfer of learning.

Learning Processes

With respect to the *amount of study time* students spent on learning the multimedia lessons, there was a significant main effect of condition, $F(1, 77) = 4.94$, $p = .029$, $\eta^2_p = .060$. When audio was added to the text, students studied longer compared to in the text condition. There was no main effect of group, $F(1, 77) = 0.01$, $p = .913$, $\eta^2_p < .001$, and no interaction between condition and group. The results thus show a redundancy effect for study time; adding audio slowed down students' learning process.

When examining students *absolute fixation duration* (the minutes they looked at the screen) there was no significant main effect of condition, $F(1, 77) = 0.383$, $p = .538$, $\eta^2_p = .005$, or group, $F(1, 77) = 0.01$, $p = .932$, $\eta^2_p < .001$. There was a significant main effect of AOI, $F(1, 77) = 1007.84$, $p < .001$, $\eta^2_p = .929$. In both conditions, students looked longer at the text than at the picture. There was an interaction between condition and AOI, $F(1, 77) = 9.26$, $p = .003$, $\eta^2_p = .107$. In the added audio condition, the difference in duration between examining the text and picture was smaller than in the text condition. There were no interactions with group. In a similar vein, when examining the *relative fixation duration* (the percentages students looked at the pictures versus the text) there was a significant main effect of condition, $F(1, 77) = 10.67$, $p = .002$, $\eta^2_p = .122$. In the added audio condition, students examined the picture relatively longer than in the text condition. There was no main effect of group, $F(1, 77) = 1.19$, $p = .278$, $\eta^2_p = .015$, and no interaction effect between condition and group. Results on fixation duration thus show that adding audio does change how students examine the material: adding audio drives students to spend relatively more time on the picture.

Analysis of the *number of transitions* between text and pictures, showed a significant main effect for condition, $F(1, 77) = 29.96$, $p < .001$, $\eta^2_p = .280$. Students made more transitions when audio was added compared to the text condition. There was no main effect of group, $F(1, 77) = 0.35$, $p = .554$, $\eta^2_p = .005$, and no interaction between condition and group. Results again show that adding audio changes the learning process: adding audio increases students' transitions between text and pictures.

Relation Learning Processes and Outcomes

To examine the extent to which learning outcomes and learning processes were related in students with and without dyslexia, first correlations are presented per group in Table 2.3, Table 2.4. In the text condition, in typically developing students, there was only one significant correlation between learning process and learning outcome: longer fixation time on the text related to lower transfer knowledge.

In contrast, in students with dyslexia in the text condition, longer study times, fixation duration on the text and fixation on the pictures, related to higher retention scores. In the added audio condition, in typically developing students and in students with dyslexia, there were no significant relations between process and outcomes measures in both groups.

Table 2.3
Learning Outcomes and Learning Processes for Typically Developing Students

Typically Developing	1.	2.	3.	4.	5.	6.	7.
1. Retention		.20	.10	-.06	.14	.10	-.01
2. Transfer	.32*		.17	.07	.20	.16	.07
3. Study Time	.08	-.24		.75**	.54**	-.10	.52**
4. Fix. Dur. AOI Text	.08	-.37*	.75**		.40**	-.41**	.06
5. Fix. Dur. AOI Picture	.05	-.03	.50**	.49**		.55**	.46**
6. Fix. Dur. %AOI Picture	-.03	.24	.00	-.16	.75**		.35*
7. Transitions	-.08	-.07	.41**	.24	.60***	.44**	

Note. Above the diagonal added audio condition, under diagonal text condition.
Note. *** $p < .001$, ** $p < .01$, * $p < .05$.

Table 2.4
Learning Outcomes and Learning Processes for Students with Dyslexia

Dyslexia	1.	2.	3.	4.	5.	6.	7.
1. Retention		.24	.01	-.20	-.10	.07	.09
2. Transfer	.47**		.33	.15	.15	.04	.30
3. Study Time	.47**	.27		.71**	.46**	-.02	.67***
4. Fix. Dur. AOI Text	.51**	.23	.90**		.54**	-.13	.18
5. Fix. Dur. AOI Picture	.29	.27	.68**	.60**		.72**	.41*
6. Fix. Dur. %AOI Picture	-.02	.20	.04	-.13	.66**		.27
7. Transitions	.22	.15	.64***	.53**	.71***	.31	

Note. Above the diagonal added audio condition, under diagonal text condition.
Note. ** $p < .01$, * $p < .05$.

These correlations thus show that the relation between learning outcomes and learning processes seem to differ for students with and without dyslexia and that these relations are found in students with dyslexia in the text condition. To follow-up on the above-described correlations between learning processes and outcomes, exploratory regression analyses were conducted. Below, only significant results are reported.

Regarding retention knowledge in the text condition, -although the model in which the interaction between group and fixation time predicted retention knowledge was significant-, none of the separate variables or interaction were, $F(3,77) = 4.47$, $p = .006$, $R^2 = 0.12$. In the added audio condition, retention knowledge was also not predicted by learning outcomes, $F(2,77) = 2.99$, $p = .088$, $R^2 = 0.04$.

Regarding transfer knowledge in the text condition, knowledge was predicted by fixation duration on the text ($\beta = -0.58$, $p = .001$), the fixation duration on the pictures ($\beta = 0.26$, $p = .047$), and the interaction between group and fixation duration on the text ($\beta = 0.44$, $p = .047$), $F(2,77) = 3.28$, $p = .016$, $R^2 = 0.15$. In both groups, examining the pictures led to higher learning outcomes, but whereas the time typically developing students used to examine the text predicted lower transfer knowledge ($R^2 = 0.05$), focusing on the text did not predict transfer knowledge in students with dyslexia. ($R^2 = 0.01$). In the added audio condition, transfer knowledge nor retention knowledge was predicted by learning processes.

Discussion

In educational contexts, students with dyslexia are often provided with audio-support to compensate their reading problems. The present study sought to answer the question whether this audio 'support' is or is not actually beneficial for learning in students with dyslexia. To do so, we examined to what extent adding audio to written text in multimedia environments impacted learning processes and outcomes in students with dyslexia as compared to their typically developing peers, and examined to what extent these processes explained learning outcomes. This fosters a new understanding of multimedia learning and helps to identify whether there are constraints to the redundancy effect as proposed in the Cognitive Theory of Multimedia Learning. Results regarding multimedia processes showed that students with and without dyslexia had longer study times, with more focus on pictures, and more transitions between text and pictures in the text-audio-picture condition than in the text-picture condition. With respect to learning outcomes, negative redundancy effects on transfer knowledge (deep learning), but not on (factual) retention knowledge were found across both groups: adding audio negatively impacted the quality of learning. When relating learning processes to learning outcomes, examining the pictures led to higher learning outcome for all students, whereas the time students examined the text predicted lower transfer knowledge in typically developing students only. Below we discuss the results in light of the current research and discuss its implications.

Learning Outcomes

Our first hypothesis was that there would be positive redundancy effects in students with dyslexia but no effects in students without dyslexia. Contrary to our expectation, there were no differences between students with and without dyslexia on learning outcomes. We did not observe any redundancy effect on retention knowledge. However, we did show effects on transfer knowledge: adding audio hampered the quality of learning.

The fact that there was a negative effect on transfer knowledge can be explained by the larger demand on the working memory as adding audio leads to faster overload of the information processing streams, which in turn hampers knowledge gain (Mayer, 2005). It is likely that the participants –who were after all university students– were such good readers that they could incorporate the factual knowledge. Nonetheless, they appeared hindered by the audio in processing and integrating the information into their knowledge base: audio may have distracted them more than it supported them. Narration with written text was found to be especially beneficial for students who have weak reading or language skills (Dunsworth & Atkinson, 2007). Indeed, better readers have less preference for adding audio to written text than poor readers, which has to do with the pacing of the audio (Gerbier et al., 2018). Gerbier and colleagues (2018) argued that this pacing has to be aligned with students' reading speed to optimize learning. In the present study, students often indicated that the pacing was either too slow or too fast, which would support the audio distraction claim. The discrepancy between students' reading pace and the narration pace increases external cognitive load (Van Merriënboer & Sweller, 2010). This is endorsed by the results of a hypermedia study on arithmetic problems in which verbal redundancy effects were shown: written-text-with-audio was found to be less efficient than written-text-only (Gerjets et al., 2009). In this study, students had much longer study times in the added audio condition, indicating that their reading pace also did not align with the narration pace. One could argue that if the audio speed had been customized to the learner, it would have been less distracting and therefore less problematic for learning, although the reading speed of a person with dyslexia might be distractingly low. Also, the mere fact of adding audio is an increase on the demands on the information processing system, which impacts learning.

Expected differences between the groups were thought to be explained by the reading problems in students with dyslexia and compensatory possibilities of adding audio. Certainly, the university students in this study showed much lower word reading skills than their typically developing peers. However, even though they scored lower on word decoding, their overall reading level remains high compared to non-university students as they have to be able to compensate for their reading problems to attain the university standard for students. The students with dyslexia in the present study may have learned to compensate their reading problems by means of effective learning approaches (Heiman & Precel, 2003) and they were used to long and difficult texts, which endorses that their reading skills did not drive multimedia differences.

Learning Processes

Our second hypothesis was that there would be differences in processing multimodal information when audio was added to a text and picture condition. In particular, we expected more focus on pictures and more transitions with added audio, and larger differences in students with dyslexia. We found that adding audio indeed changed the learning process in all students. As expected, when audio was added to the written text students examined the lesson -especially the pictures- longer and made more transitions between the written text and the pictures. These results replicate Schmidt-Weigand and colleagues (2010) showing that the distribution of visual attention in multimedia learning is largely guided by written text. Listening to information in addition to reading it, allows students to pay more attention to the pictures (Schmidt-Weigand et al., 2010; Wiebe & Annetta, 2008). These behavioural changes in eye-movements support the claim that adding audio to written text changes how students learn in multimedia environments.

In contrast to our expectations but similar to the results on learning outcome, we did not observe differences between students with and without dyslexia on learning processes. Students with dyslexia examined the written text as much as their typically developing peers, focussed as much on the pictures and made an equal number of transitions between the text and the pictures. This implies that in this high functioning group of students with dyslexia, there are no differences in learning regarding multimedia aspects of the lessons (a.k.a., examining text versus picture area of interest, transitions etc.). The two groups perform similarly on working memory and even though the students with dyslexia had lower word reading abilities (as discussed above), they are still high-functioning adults used to reading complex texts. Studies indicating that people with dyslexia are slower in learning in multimedia environments were either performed in primary school children (Knoop-van Campen et al., 2018), or concern graphs instead of textbooks (Kim et al., 2014). The former focus on much poorer readers, the latter provided less written text and a less realistic study behaviour as the graphs were singled out of the learning environment. As research indicates that eye tracking data can be used to separate students with dyslexia from their typically developing peers by means of machine learning (Rello & Ballesteros, 2015; Rello et al., 2018) differences in eye-movements of students with and without dyslexia clearly exist. The extent to which these differences apply to multimedia learning, however, might be less obvious.

Combining the results on learning processes and outcomes, we can discuss learning *efficiency*. Redundancy effects in primary school children with and without dyslexia showed that adding audio made learning more efficient: similar, yet faster learning outcomes, especially in children with dyslexia (Knoop-van Campen et al., 2018, 2019). This is in contrast with the current findings, in which added audio had a negative effect on efficiency (longer study time and less transfer knowledge). Primary school children are young and have less developed reading skills whereas university students are highly functioning adults. Audio can aid the former in speeding up and in comprehension, while in the latter group, audio could potentially distract and negatively impact learning. The question then arises: where is the tipping point when audio is no longer beneficial for efficient learning? This in turn provides information on possible boundary conditions: we foresee that when the reader can out-read the audio -reading pace is faster than the audio-audio will distract rather than support. The tipping point is, therefore, expected to be dependent on the reading pace of the learner and the difficulty level of the material.

Relation Learning Processes and Outcomes

The second research question was tackled using an exploratory approach to examine to what extent processing multimodal material explained learning outcomes. We showed that in the text condition, examining the pictures longer fostered transfer knowledge in all students whereas increased study times on the written text had a negative effect on transfer knowledge in typically developing students. To gain transfer knowledge and to achieve deep information processing, it is of no use to simply keep looking at the text. This longer viewing can be interpreted as an indication of incomprehension or as purely learning factual knowledge, instead of integrating information to achieve comprehension (Frieman & Gillings, 2007). This is illustrated by consumer research on internet-behaviour with eye-tracking, which showed that even if consumers can see specific clues they are also often not able to incorporate the meaning well and draw correct conclusions from these clues (Grazioli & Wang, 2001).

When students have audio-support, these relations between learning processes and learning outcomes disappear. As audio is volatile, students who study a bit longer could have used the opportunity to re-listen to the audio instead of staring incomprehensibly to the written text. This may support their learning outcome as they can use their listening comprehension skills (Perfetti et al., 2005). This way, even though they can read the text themselves, listening can add to their understanding and situation model building (Schnotz, 2005).

The relationship between fixations on text and transfer knowledge was also only found in typical readers and not in students with dyslexia. This could be explained by the fact that students with dyslexia use more meta-strategies, such as time management strategies (Kirby et al., 2008). By adapting their behaviour, they might have learned to cope with their reading problems in order to make sufficient progress and they might be less likely to linger at difficult parts of the written text.

No relation was found between the amount of time (absolute or relative) students spent examining the pictures and their retention knowledge, even though it does fosters transfer knowledge. So, pictures do foster learning (multimedia principle; Mayer, 2005; Ginns, 2005) but as retention knowledge involves the factual words used in the text, for this type of knowledge the written text may be more important than the pictures. Indeed, students focussed mostly on the written text (approximately 80% of the time in the present study) instead of on the pictures. This replicated the text-orientation of students in multimedia learning in previous research (Liu et al., 2011; Schmidt-Weigand et al., 2010).

Also, no relation was found between the number of transitions and the knowledge students gained. Even though transitions are commonly seen as a measure of integrating multimedia information (Alemdag & Cagiltay, 2018), our findings are in line with Krebs and colleagues (2019) who showed that transitions were not related to knowledge. They propose that in certain situations, more transitions may not be related to increased comprehension but indicate comprehension problems or even cognitive overload (Krebs et al., 2019). In the present study, audio seemed to facilitate transitions (see hypothesis 2), although not to such an extent that it changed learning outcomes.

Limitations and Future Research

Some limitations can be put forward. Firstly, as the present study examined the eye-movements over the whole lesson of 15 slides of information, smaller differences on the word processing level in the written text might have been missed (e.g., first pass reading and re-reading time: Schattka et al., 2010). This paper focussed on the relation between learning processes and learning outcome, which provides a baseline for deeper analyses in which the changes in learning processes *during* multimedia lessons can be examined. These moment-by-moment differences are, however, less likely to relate to more general learning outcomes: in order to reach those, a different (research analysis) approach might be more appropriated, which is not eligible to include in the present paper.

Secondly, the present results may not be generalizable to the population at large as participants were high functioning adults (but this goes for both the students with and without dyslexia). Over time and with experience, university students with dyslexia might have learned to (partly) compensate their decoding problems (Kirby et al., 2008). It should be noted, however, that they scored significantly below their peers on word reading measures, with large effect sizes. To gain a broader and more developmental perspective on the eye-movements during multimedia learning, this study should be replicated with younger and also lower educated (dyslexic) participants. These groups may show more variation in working memory or have more severe reading problems, which may elicit larger redundancy effects on both process as well as outcome measures.

Practical Implications

In education, one strives to teach students to learn for life, which makes the transfer of knowledge highly important. The present findings clearly indicate that providing audio as reading support to university students with dyslexia is not the perfect solution. For these students, it is far from efficient: they learn less and are slower. Research indicated that audio is efficient in primary school children with dyslexia (Knoop-van Campen et al., 2018, 2019). In university students, however, it seems to be counter-productive. Practitioners should make their students aware that audio may support their reading, but can also negatively impact their deep learning and study effectiveness. With this knowledge, students can make an informed decision about whether or not to use audio-support during learning. Students need training that is not merely focused on how they can (technically) use educational reading-software, but especially on how audio can affect their learning behaviour and, as a consequence, their learning outcomes. Such warnings about the possible impact of audio-support on learning may also be incorporated in educational computer systems. One of the simple solutions could be to place warning-signals on audio-play buttons or a disclaimer in audio-supported lessons. In addition, the default setting of audio-support systems could be set to 'audio-off' in order for students to make conscious choices during learning as to whether they will actually use audio-support for specific blocks of written text.

Conclusions

We aimed to understand how adding audio to written text affects learning processes and outcomes in students with dyslexia as compared to their typically developing peers and to shed light on the relation between learning processes and outcomes in multimedia environments. For university students, one can state that for students with and without dyslexia audio-support hinders deep processing of knowledge and makes students slower. This 'support' may compensate reading difficulties, but hampers learning.

This study shows two important aspects of multimedia learning. Firstly, the present study proves that the redundancy effect is robust against reading problems and in turn indicates that audio-support can be provided to students with low and high decoding skills alike. Secondly, it shows that the learning process impacts learning outcomes less than anticipated. The present study can only be seen as a first step in multimedia outcomes in light of their processes. To yield understanding of this relation, we urge researchers to relate these measures to each other instead of merely comparing groups and to report their results even though they might be different than foreseen.

It can be concluded that adding audio has a negative effect on students' quality of knowledge and leads to less efficient learning across the two groups. Reading ability does not impact the universality of the redundancy effect, but students with dyslexia should only use audio-support when aiming to learn factual knowledge and should be aware that it increases study time.

References

Adesope, O. O., & Nesbit, J. C. (2012). Verbal redundancy in multimedia learning environments: A meta-analysis. Journal of Educational Psychology, 104(1), 250. https://doi.org/10.1037/a0026147

Alemdag, E., & Cagiltay, K. (2018). A systematic review of eye tracking research on multimedia learning. Computers & Education, 125, 413–428. https://doi.org/10.1016/j.compedu.2018.06.023

Ari, F., Flores, R., Inan, F. A., Cheon, J., Crooks, S. M., Paniukov, D., & Kurucay, M. (2014). The effects of verbally redundant information on student learning: An instance of reverse redundancy. Computers & Education, 76, 199–204. https://doi.org/10.1016/j.compedu.2014.04.002

Beccue, B., Whitley, L. K., & Vila, J. (2001). The effects of adding audio instructions to a multimedia computer based training environment. Journal of Educational Multimedia and Hypermedia, 10(1), 47-47.

Beneventi, H., Tønnessen, F. E., Ersland, L., & Hugdahl, K. (2010). Working memory deficit in dyslexia: Behavioral and FMRI evidence. International Journal of Neuroscience, 120(1), 51–59. https://doi.org/10.3109/00207450903275129

Blomert, L. (2005). Dyslexie in Nederland. Uitgeverij Nieuwezijds.

Brus, B. T., & Voeten, M. J. M. (1999). Een-minuut-test: vorm A en B: Verantwoording en handleiding: Schoolvorderingentest voor de technische leesvaardigheid, bestemd voor groep 4 tot en met 8 van het basisonderwijs. Swets & Zeitlinger.

Carney, R. N., & Levin, J. R. (2002). Pictorial illustrations still improve students' learning from text. Educational psychology review, 14(1), 5–26. https://doi.org/10.1023/A:1013176309260

Casalis, S., Leuwers, C., & Hilton, H. (2013). Syntactic comprehension in reading and listening: A study with French children with dyslexia. Journal of Learning Disabilities, 46(3), 210–219. https://doi.org/10.1177/0022219412449423

De Jong, P. F., & Van der Leij, A. (2003). Developmental changes in the manifestation of a phonological deficit in dyslexic children learning to read a regular orthography. Journal of Educational Psychology, 95(1), 22. https://doi.org/10.1037/0022-0663.95.1.22

Draffan, E. A. (2002). Dyslexia and technology. In L. Phillipa, A. Sutherland, & J. Seale (Eds.), Access all areas: disability, technology and learning (pp. 24-48). JISC TechDis.

Dunsworth, Q., & Atkinson, R. K. (2007). Fostering multimedia learning of science: Exploring the role of an animated agent's image. Computers & Education, 49(3), 677–690. https://doi.org/10.1016/j.compedu.2005.11.010

Fidler, R., & Everatt, J. (2012). Reading comprehension in adult students with dyslexia. In N. Brunswick (Ed.), Supporting dyslexic adults in higher education and the workplace (pp. 91–100). John Wiley & Sons. https://doi.org/10.1002/9781119945000.ch10

Field, A. (2013). Discovering statistics using IBM SPSS statistics (4th ed.). SAGE Publications.

Frieman, C., & Gillings, M. (2007). Seeing is perceiving? World Archaeology, 39(1), 4–16. https://doi.org/10.1080/00438240601133816

Gerbier, E., Bailly, G., & Bosse, M. L. (2018). Audio–visual synchronization in reading while listening to texts: Effects on visual behavior and verbal learning. Computer Speech & Language, 47, 74–92. https://doi.org/10.1016/j.csl.2017.07.003

Gerjets, P., Scheiter, K., Opfermann, M., Hesse, F. W., & Eysink, T. H. (2009). Learning with hypermedia: The influence of representational formats and different levels of learner control on performance and learning behavior. Computers in Human Behavior, 25(2), 360–370. https://doi.org/10.1016/j.chb.2008.12.015

Gevins, A., & Cutillo, B. (1993). Spatiotemporal dynamics of component processes in human working memory. Electroencephalography and Clinical Neurophysiology, 87 (3), 128–143. https://doi.org/10.1016/0013-4694(93)90119-G

Ghesquière, P., Boets, B., Gadeyne, E., & Vandewalle, E. (2011). Dyslexie: Een beknopt wetenschappelijk overzicht. A. Geudens, D. Baeyens, K. Schraeyen, K. Maetens, J. De Brauwer, & M. Loncke (Eds.), Jongvolwassenen met dyslexie: diagnostiek en begeleiding in wetenschap en praktijk (pp. 41-58). Acco Uitgeverij.

Ginns, P. (2005). Meta-analysis of the modality effect. Learning and instruction, 15(4), 313–331. https://doi.org/10.1016/j.learninstruc.2005.07.001

Grazioli, S., & Wang, A. (2001). Looking without seeing: Understanding unsophisticated consumers' success and failure to detect internet deception. ICIS 2001 Proceedings (pp. 193- 204).

Gregg, N., & Banerjee, M. (2009). Reading comprehension solutions for college students with dyslexia in an era of technology. In G. Reid (Ed.), Dyslexia: A handbook for Research and Practice, (pp. 265–285). Routledge/Taylor & Francis Group.

Harrar, V., Tammam, J., Perez-Bellido, A., Pitt, A., Stein, J., & Spence, C. (2014). Multisensory integration and attention in developmental dyslexia. Current Biology, 24(5), 531–535. https://doi.org/10.1016/j.cub.2014.01.029

Heiman, T., & Precel, K. (2003). Students with learning disabilities in higher education: Academic strategies profile. Journal of Learning Disabilities, 36(3), 248–258. https://doi.org/10.1177/002221940303600304

Hyona, J. (2010). The use of eye movements in the study of multimedia learning. Learning and Instruction, 20(2), 172–176. https://doi.org/10.1016/j.learninstruc.2009.02.013

Jackson, N. E., & Doellinger, H. L. (2002). Resilient readers? University students who are poor recorders but sometimes good text comprehenders. Journal of Educational Psychology, 94(1), 64–78. https://doi.org/10.1037/0022-0663.94.1.64

Jamet, E., & Le Bohec, O. (2007). The effect of redundant text in multimedia instruction. Contemporary Educational Psychology, 32(4), 588–598. https://doi.org/10.1016/j.cedpsych.2006.07.001

Kalyuga, S., Chandler, P., & Sweller, J. (1999). Managing split-attention and redundancy in multimedia instruction. Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition, 13(4), 351–371. https://doi.org/10.1002/(SICI)1099-0720(199908)13:4<351::AID-ACP589>3.0.CO;2-6

Kim, S., Lombardino, L. J., Cowles, W., & Altmann, L. J. (2014). Investigating graph comprehension in students with dyslexia: An eye tracking study. Research in Developmental Disabilities, 35(7), 1609–1622. https://doi.org/10.1016/j.ridd.2014.03.043

Kirby, J. R., Silvestri, R., Allingham, B. H., Parrila, R., & La Fave, C. B. (2008). Learning strategies and study approaches of postsecondary students with dyslexia. Journal of Learning Disabilities, 41(1), 85–96. https://doi.org/10.1177/0022219407311040

Knoop-van Campen, C. A. N., Segers, E., & Verhoeven, L. (2018). The modality and redundancy effects in multimedia learning in children with dyslexia. Dyslexia, 24, 140–155. https://doi.org/10.1002/dys.1585

Knoop-van Campen, C. A. N., Segers, E., & Verhoeven, L. (2019). Modality and redundancy effects, and their relation to executive functioning in children with dyslexia. Research in Developmental Disabilities, 90, 41–50. https://doi.org/10.1016/j.ridd.2019.04.007

Koc-Januchta, M., Hoffler, T., Thoma, G. B., Prechtl, H., & Leutner, D. (2017). Visualizers versus verbalizers: Effects of cognitive style on learning with texts and pictures– An eye-tracking study. Computers in Human Behavior, 68, 170–179. https://doi.org/10.1016/j.chb.2016.11.028

Koning, B. B. de, Hooijdonk, C. M. van, & Lagerwerf, L. (2017). Verbal redundancy in a procedural animation: On-screen labels improve retention but not behavioral performance. Computers & Education, 107, 45–53. https://doi.org/10.1016/j.compedu.2016.12.013

Krebs, M. C., Schüler, A., & Scheiter, K. (2019). Just follow my eyes: The influence of model-observer similarity on eye movement modeling examples. Learning and Instruction, 61, 126–137. https://doi.org/10.1016/j.learninstruc.2018.10.005

Krejtz, I., Szarkowska, A., Krejtz, K., Walczak, A., & Duchowski, A. (2012). Audio description as an aural guide of children's visual attention: Evidence from an eye-tracking study. Proceedings of the Symposium on Eye Tracking Research and Applications, 99–106. https://doi.org/10.1145/2168556.2168572

Lallier, M., Donnadieu, S., & Valdois, S. (2013). Developmental dyslexia: Exploring how much phonological and visual attention span disorders are linked to simultaneous auditory processing deficits. Annals of Dyslexia, 63(2), 97–116. https://doi.org/10.1007/s11881-012-0074-4

Liu, H. C., Lai, M. L., & Chuang, H. H. (2011). Using eye-tracking technology to investigate the redundant effect of multimedia web pages on viewers' cognitive processes. Computers in Human Behavior, 27(6), 2410–2417. https://doi.org/10.1016/j.chb.2011.06.012

Lyon, G. R., Shaywitz, S. E., & Shaywitz, B. A. (2003). A definition of dyslexia. Annals of Dyslexia, 53(1), 1–14. https://doi.org/10.1007/s11881-003-0001-9

Mason, L., Pluchino, P., & Tornatora, M. C. (2016). Using eye-tracking technology as an indirect instruction tool to improve text and picture processing and learning. British Journal of Educational Technology, 47(6), 1083–1095. https://doi.org/10.1111/bjet.12271

Mayer, R. E. (2005). The Cambridge Handbook of Multimedia Learning. Cambridge University Press. https://doi.org/10.1017/CBO9780511816819

Mayer, R. E., & Fiorella, L. (2014). 12 principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles. In R. E. Mayer (Ed.), The Cambridge handbook of multimedia learning (Vol. 279, pp. 279-315). Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.015

Mayer, R. E., Lee, H., & Peebles, A. (2014). Multimedia learning in a second language: A cognitive load perspective. Applied Cognitive Psychology, 28(5), 653–660. https://doi.org/10.1002/acp.3050

Moreno, R., & Mayer, R. E. (2002). Learning science in virtual reality multimedia environments: Role of methods and media. Journal of Educational Psychology, 94(3), 598–610. https://doi.org/10.1037/0022-0663.94.3.598

Perfetti, C. A., Landi, N., & Oakhill, J. (2005). The acquisition of reading comprehension skill. In M. J. Snowling & C. Hulme (Eds.), The Science of Reading: A Handbook (pp. 227–247). https://doi.org/10.1002/9780470757642.ch13

Ponce, H. R., Mayer, R. E., Loyola, M. S., Lopez, M. J., & Mendez, E. E. (2018). When two computer-supported learning strategies are better than one: An eye-tracking study. Computers & Education, 125, 376–388. https://doi.org/10.1016/j.compedu.2018.06.024

Reece, J. B., Urry, L. A., Cain, M. L., Wasserman, S. A., Minorsky, P. V., & Jackson, R. B. (2014). Campbell biology (p. 135). Boston: Pearson.

Rello, L., & Ballesteros, M. (2015, May). Detecting readers with dyslexia using machine learning with eye tracking measures. Proceedings of the 12th Web for All Conference, Article 16. https://doi.org/10.1145/2745555.2746644

Rello, L., Romero, E., Rauschenberger, M., Ali, A., Williams, K., Bigham, J. P., White, N. C. (2018). Screening dyslexia for English using HCI measures and machine learning. Proceedings of the 2018 International Conference on Digital Health, 80–84. https://doi.org/10.1145/3194658.3194675

Roscoe, R. D., Jacovina, M. E., Harry, D., Russell, D. G., & McNamara, D. S. (2015). Partial verbal redundancy in multimedia presentations for writing strategy instruction. Applied Cognitive Psychology, 29(5), 669–679. https://doi.org/10.1002/acp.3149

Schattka, K. I., Radach, R., & Huber, W. (2010). Eye movement correlates of acquired central dyslexia. Neuropsychologia, 48(10), 2959–2973. https://doi.org/10.1016/j.neuropsychologia.2010.06.005

Schmidt-Weigand, F., Kohnert, A., & Glowalla, U. (2010). A closer look at split visual attention in system-and self-paced instruction in multimedia learning. Learning and Instruction, 20(2), 100–110. https://doi.org/10.1016/j.learninstruc.2009.02.011

Schnotz, W. (2005). An integrated model of text and picture comprehension. In R. Mayer (Ed.), The Cambridge handbook of multimedia learning (pp. 49-69). Cambridge University Press. https://doi.org/10.1017/CBO9780511816819.005

She, H. C., & Chen, Y. Z. (2009). The impact of multimedia effect on science learning: Evidence from eye movements. Computers & Education, 53(4), 1297–1307. https://doi.org/10.1016/j.compedu.2009.06.012

Sweller, J., Ayres, P., & Kalyuga, S. (2011). Cognitive load theory. Springer. https://doi.org/10.1007/978-1-4419-8126-4

Sweller, J., Van Merrienboer, J. J. G., & Paas, F. G. W. C. (1998). Cognitive architecture and instructional design. Educational Psychology Review, 10(3), 251–296. https://doi.org/10.1023/A:1022193728205

Tsai, M. J., Huang, L. J., Hou, H. T., Hsu, C. Y., & Chiou, G. L. (2016). Visual behavior, flow and achievement in game-based learning. Computers & Education, 98, 115–129. https://doi.org/10.1016/j.compedu.2016.03.011

Van Merrienboer, J. J., & Sweller, J. (2010). Cognitive load theory in health professional education: Design principles and strategies. Medical Education, 44(1), 85–93. https://doi.org/10.1111/j.1365-2923.2009.03498.x

Van Wermeskerken, M., Grimmius, B., & Van Gog, T. (2018). Attention to the model's face when learning from video modeling examples in adolescents with and without autism spectrum disorder. Journal of Computer Assisted Learning, 34(1), 32–41. https://doi.org/10.1111/jcal.12211

Van den Bos, K. P., Spelberg, H., Scheepsma, A., & De Vries, J. (1994). De Klepel. Vorm A en B. Een test voor de leesvaardigheid van pseudowoorden. Verantwoording, handleiding, diagnostiek en behandeling. Berkhout.

Veronikas, S., & Maushak, N. (2005). Effectiveness of audio on screen captures in software application instruction. Journal of Educational Multimedia and Hypermedia, 14(2), 199–205.

Wechsler, D. (1992). Wechsler intelligence scale for children (3rd ed.). The Psychological Corporation.

Wiebe, E., & Annetta, L. (2008). Influences on visual attentional distribution in multimedia instruction. Journal of Educational Multimedia and Hypermedia, 17(2), 259–277.

2

CHAPTER 3

IMPACT OF AUDIO ON NAVIGATION STRATEGIES IN CHILDREN AND ADULTS WITH DYSLEXIA

Abstract

Children and adults with dyslexia are often provided with audio-support, which reads the written text for the learner. The present study examined to what extent audio-support as a form of external regulation impacts navigation patterns in children and adults with and without dyslexia. We compared navigation patterns in multimedia lessons of learners with (36 children, 41 adults), and without dyslexia (46 children, 44 adults) in a text-condition vs. text-audio-condition. Log files were recorded to identify navigation patterns. Four patterns could be distinguished: linear reading (linear), linear reading with rereading (big peak), reading with going back to previous pages (small peaks), and a combination of strategies (combined peaks). Children generally used linear navigation strategies in both conditions, whereas adults mostly used combined-peaks strategies in the text-condition, but linear strategies in the text-audio-condition. No differences were found between learners with and without dyslexia. Audio-support seems to impact navigation strategies in adult learners, towards the use of more linear navigation patterns, reflecting less self-regulation. This implicates that when the goal is to learn the material, audio-support may be less desirable.

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Introduction

Children and adults with dyslexia are often provided with *audio-support* via which the written text is read to the learner (Ghesquière et al., 2010; Gregg, & Banerjee, 2009). Such audio-support results in multimodal information (spoken and written text) that must be integrated and combined to form a coherent mental model, requiring the learners to self-regulate their learning process (Caccamise et al, 2015; Juvina & Van Oostendorp, 2008). This self-regulation can be rendered by a visualization of the navigation pattern, in which it is shown how each learner moves through such multimedia learning environments (Barab et al., 1996; Jeske et al., 2014). Learners follow different navigation strategies to build a mental model, as seen in the level of linearity with which they go through the material (Paans et al., 2020). Audio-support can be regarded as a task feature that increases external regulation, since learners are guided in a linear way through the material. It would require additional self-regulation of the learner to ignore this guidance and follow their preferred navigation pattern. Especially for children, who have lower self-regulation skills (De Jong & van Joolingen, 1998), this may be a difficult task. Indeed, lower reading skills were found to be related to poorer navigation skills as well (Salmerón & García, 2011), but also that learners with dyslexia approach learning materials differently than their typically developing peers (e.g., Bråten et al., 2010; Polychroni et al., 2006). Adding narration to written text may thus impact the self-regulation and navigation strategies of learners with dyslexia differently than those of typically developing peers. We therefore examined to what extent adding audio-support to multimedia environments affected navigation strategies in children and adults with dyslexia compared to typically developing peers.

Self-regulation in Multimedia Learning Environments

Learning in multimedia environments is different from learning from plain text, while in education such environments are increasingly common. The Cognitive Theory of Multimedia Learning (CTML: Mayer, 2005) is based on three assumptions: the dual channel assumption – there are two separate channels for processing visual and verbal material (Paivio, 1986); the limited capacity assumption - only a limited amount of information can be processed in a channel at any one time (Baddeley, 1999); and the active processing assumption - meaningful learning occurs when relevant material is selected, organized and integrated (Wittrock, 1989; Mayer, 2002). As such the CTML states that redundant information (simultaneously presenting identical information visually and orally in a multimedia learning environment) hampers the learning process (Mayer & Fiorella, 2014), as it overloads the working memory channels and increases the cognitive load. Indeed, such multimedia environments create higher cognitive load (Paas et al., 2003), and have been shown to have a negative impact on learning outcomes (Adesope & Nesbit, 2012; Klepsch & Seufert, 2020). Since learners are provided with multiple sources of information, which all must be integrated and combined to form a coherent mental model (Graesser, 2007), regulating one's own learning process becomes more crucial (Azevedo & Cromley, 2004).

An important question is how self-regulation may support multimedia learning. Self-regulation in an educational context can be described as "an active, constructive process whereby learners set goals for their learning and then attempt to monitor, regulate, and control their cognition, motivation, and behavior, guided and constrained by their goals and the contextual features in the environment" (Pintrich, 2000, p. 453). It is assumed that self-regulated learning contains metacognitive, motivational, and behavioral aspects focussing on how learners achieve certain learning goals

(Zimmerman & Schunk, 2001). As such, metacognitive activities that monitor and control the learning progress and keep up the motivation to be engaged in the learning materials are important for self-regulation (Winne & Hadwin, 1998; Winne & Nesbit, 2010). On the other hand, a cyclical feedback loop is considered essential to self-regulated learning. Learners continuously monitor and adapt their learning tactics during the task to optimize their learning process and outcomes (Azevedo, 2009; Eilam & Aharon, 2003). This cycle of task definition, goal setting and planning, enacting study tactics and strategies, and metacognitively adaptive studying describes how learners process information (Winne & Hadwin, 1998).

Learners engage in different levels of self-regulation. As the ability to self-regulate during formal learning develops throughout childhood, young children are thought to be mostly incapable of regulating their learning compared to adults (De Jong & van Joolingen, 1998). Importantly, learners with more developed self-regulation skills might not *use* these skills to their fullest potential when they believe it is not necessary or beneficial (Zimmerman & Schunk, 2001). So even though self-regulating may increase learning outcomes (Eilam & Aharon, 2003; Van der Stel & Veenman, 2008), not all learners will show self-regulation during learning.

When examining learners' self-regulation, it is important to take the learning environment and its features into account (Boekaerts, 1999; Greene & Azevedo, 2010), as task features may affect the metacognitive activities during learning and learners' motivation (Winne & Hadwin, 1998). Whereas external regulation is incorporated in the design of the multimedia learning environment, self-regulation entails the purposeful deviation of this predefined pattern.

Audio-support in the form of narration added to learning environments, can be considered a task feature that increases external regulation within the task. As the audio voice may 'pull' learners in a linear way through the learning environment, this may go at the expense of learners' self-regulation. Self-regulation activities such as making decisions about which parts of the lessons learners want to (re)visit and the motivation to be actively engaged would then decrease. A recent hypermedia study indeed found that learners more often used a linear reading pattern in higher structured learning environments with more external regulation (Paans et al., 2020). Another study showed that learners' approach of a task can be affected by task conditions (Pieschl et al., 2012). Navigation patterns thus not only differ between learners, but also differ within learners when task conditions change. This fits with the statement that self-regulated learning is a "dynamic and developing process" (Boekaerts & Corno, 2005, *p*. 208). Thus, a learner may show less self-regulation (less reader-initiated decisions) when audio-support increases external regulation.

Reader-initiated decisions as described above have been demonstrated to contribute to reading comprehension (Van den Broek & Helder, 2017). Indeed, self-regulation has proven to be a strong predictor of better learning outcomes (Azevedo & Jacobson, 2008; Graesser et al., 2005; Song et al., 2016). Self-regulating contributes to effectively understanding and remembering the information and building a sound mental model (Caccamise et al., 2015; Juvina & Van Oostendorp, 2008). In particular, it has been found that learners who use planning strategies focusing on the specific materials they want to study, have higher comprehension scores (Amadieu et al., 2009; Madrid et al., 2009; Salmerón et al., 2006). The possible effect of audio on learners' self-regulation activities may thus have a negative impact on comprehension.

Measuring Self-regulation in Multimedia Learning Environments

A common way to measure self-regulation is to provide learners with questionnaires. Such measures rely heavily on learners' memory and/or reflective capacities (Paans et al., 2020) and may therefore be less reliable. Another way is using think-aloud protocols; however, they disrupt the learning process and rely on learners' capacity to verbalize their learning process (Veenman, 2011; Winne et al., 2010). A more objective and non-intrusive way to measure learners' self-regulating in multimedia environments, is by recording log files of learners' navigation activities (log files: time stamps to indicate when a learner goes from one page to another). An example of a study using such log data to examine learners' navigation activities in a (hyper)media setting showed that various navigation patterns could be distinguished, e.g., linear reading, selective reading, and unpredictable reading (Paans et al., 2020).

As Greene and Azevedo (2010) put forward in the introduction of their special issue on the measurement of self-regulation in computer-assisted learning environments, measuring self-regulation as a series of events by means of trace data (e.g., log files), can provide insight into learners' ability to self-regulate (Greene & Azevedo, 2010). Learners' movement through multimedia environments can be visualized by translating log files into navigational patterns (Barab et al., 1996; Jeske et al., 2014; Lawless & Kulikowich, 1996). Such sequential and temporal patterns as shown in navigation patterns may give insights into learners' self-regulation behavior (Saint et al., 2020). Navigation patterns can thus be interpreted as a proxy for (the amount of) self-regulation (Saint et al., 2020).

Audio-support in Dyslexia

Visualizing navigation patterns provides opportunities to examine self-regulation activities in multimedia learning environments. This is especially interesting for a specific group that often uses audio-support: learners with dyslexia (Ghesquière et al., 2010; Gregg, & Banerjee, 2009). Dyslexia is a learning disability characterized by severe and persistent reading problems that are not due to external factors such as poor education or cognitive problems (Lyon et al., 2003). On the one hand, audio-support has the potential to reduce learners' cognitive load due to compensating for reading difficulties. On the other hand, audio-support may increase external regulation with the risk of reducing reader-initiated decisions and hampering reading comprehension.

It has also been found that learners with dyslexia show more variation in academic learning strategies than their typically developing peers. For example, adults with dyslexia reported *larger* amount of monitoring and time management, (Bråten et al., 2010; Heiman & Precel, 2003; Kirby et al., 2008). In contrast, research in children with dyslexia indicated *lower* engagement (more passive learning) as compared to typically developing children (Polychroni et al., 2006) and Bender and Wall (1994) even pose that children with dyslexia may have lower self-regulation and less motivation on task performance in general. Salmerón and García (2011) showed that higher reading skills predicted a higher ability to strategically adapt learners' navigation route through the material to increase comprehension. In other words, navigation strategies were positively related to reading proficiency (Salmerón & García, 2011; Wu, 2014). Navigation patterns of adults and children with dyslexia may thus very well differ from each other and from the navigation patterns of their typically developing peers.

How audio-support impacts the navigation patterns of learners with dyslexia is far from clear. With regard to gaze behavior, some studies found that audio-support affects how learners with dyslexia look at written text as they focus less on the written information and make less transitions with audio, compared to their typically developing peers (Kim & Wiseheart, 2017). Integrating information from different modalities (visual and oral) also turned out to be challenging for them (Kim et al., 2018; MacCullagh et al., 2017). Learners with dyslexia seem to process multimedia information differently, but it is still unclear how audio-support affects their self-regulation in such environments, and consequentially their navigation patterns.

The Present Study

Even though in education audio-support by means of narration is frequently provided to learners, especially learners with dyslexia, the possible impact on learners navigating patterns is unclear. As self-regulation skills develop over time and differences in self-regulation between children and adults with dyslexia have been found, audio-support may impact children's and adults' navigation patterns differently. Overall, providing audio-support to learners with and without dyslexia seems to have the risk of impacting their navigation strategies.

Therefore, in the present study we examined how adding audio affects navigation strategies in children and adults with dyslexia and, in turn, aimed to provide developmental insight into its effect on navigation strategies. In two experimental studies, we compared the navigation strategies of primary school children (Experiment 1) and university students (Experiment 2) with dyslexia to those of their typically developing peers in multimedia learning environments with and without audio-support[1]. Navigation strategies were based on the log files of the learning environment. Research questions were:

RQ 1 Which navigation patterns can be distinguished in children and adults when learning in a multimedia environment?
RQ 2 To what extent does adding audio to multimedia learning environments affect navigation patterns?
RQ 3 Does the impact of audio on navigation patterns differ between learners with and without dyslexia?

First, we expected variation in self-regulation presented as different navigation patterns ranging from linear - in which learners linearly go from beginning till end through a lesson- to less linear -in which learners move back and forward between the multimedia slides in various ways. We expected less self-regulation in children than in adults, indicated by a higher number of linear patterns in children.

Secondly, we expected that adding audio-support would increase external regulation (and therefore decrease self-regulation), which would present as more linear patterns, but especially in adults as children would already show more linear patterns.

Finally, learners with dyslexia were expected to show less self-regulation and more linear navigation patterns than their typically developing peers, especially in adults.

1 Log file data (a.k.a. time stamps of the lesson slides) were taken from three experimental studies on multimedia learning and dyslexia (Knoop-van Campen et al., 2018, 2019, 2020). This log file data was not previously used for analysis or publication elsewhere and the data is unique for this study.

Experiment One

Method

Participants

A total of 82 grade-5 primary school children were included in the present study, of which 46 typically developing children (70% boys) aged 10.87 years (SD = .36), and 36 children with dyslexia (64% boys) aged 11.10 years (SD = .53). All children with dyslexia were diagnosed according to the clinical assessment of the Protocol Dyslexia Diagnosis and Treatment (Blomert, 2005), which assesses children's reading and a broad range of phonological abilities, inhibition and memory, and includes environmental factors. Only monolingual children were allowed to participate. Participants were from studies described in Knoop-van Campen and colleagues (2018, 2019). Some of the children could not be included due to missing log file data as a result of computer malfunction (Knoop-van Campen et al., 2018: 20 children, 50% dyslexia, Knoop-van Campen et al., 2019: 2 children, 0% dyslexia).

Even though all children were in grade 5, the children with dyslexia (M= 11.11, SD = .53) were on average two months older than the typical developing children (M= 10.87, SD = .36), $t(59.43) = 2.372$, $p = .021$, Cohen's $d = .53$. In line with their diagnosis, children with dyslexia scored significantly lower on word reading (M = 49.39, SD = 10.39) and pseudo word reading (M = 21.92, SD = 6.84) than their typically developing peers (resp. M = 71.09, SD = 11.04 / M = 38.20, SD = 9.30), resp. $t(80) = 9.06$, $p < .001$, Cohen's $d = 2.02$ for word reading, $t(80) = 8.80$, $p < .001$, Cohen's $d = 1.99$ for pseudo word reading.

Procedure

Testing was done in an individual setting in the schools. All children were provided with two comparable multimedia lessons: pictures with i) written text, and ii) written text with audio, offered in a randomized-block design (one lesson a week). Before the lesson, children were instructed (according to the test protocol) to learn the material as they would get a knowledge test afterwards. It was explained that they could move through the lessons by clicking marked keys on the keyboard. Before the lesson with audio-support, it was explained that they could pause and replay the audio (also with marked keys). In addition, some language tests were performed.

Materials

Multimedia Lessons. The lessons involved biology topics and were chosen from the schoolbooks one year above the children's school year (Van Hoof et al., 2009) to ensure that they had sufficient prior knowledge to understand the material, but at the same time did not receive the information before. The lessons were comparable in set-up and complexity. One lesson consisted of a title page and 11 content slides (approximately 530 words in total), with every slide showing written text with a picture (also from the school books). The original paragraphs of the school book text were each placed on a different slide, thus mimicking the schoolbook with its various text parts on different pages, which contributed to a realistic learning environment. Children studied the lessons at their own pace and were able to move back-and-forth through the pages.

Audio-support. In one of the two lessons, the material also included audio-support in the form of a voice-over. The voice-over (female voice) read out loud the exact (written) text on a page. The audio started automatically when children clicked to the next slide. Children were able to pause and replay the audio with the keyboard.

Log Files. Log files of children's navigation paths through the lessons were recorded by means of timestamps when they moved to a next/previous slide. To identify navigation strategies, all paths were plotted with time (in minutes) on the x-axis and slide number (1-11) on the y-axis (as similar to Jáñez & Rosales, 2016, and Paans et al., 2020).

Decoding. The Een-Minuut-Test (EMT) [One-Minute-Test] (Brus & Voeten, 1999) and the Klepel (Van den Bos, Spelberg, Scheepsma, & De Vries, 1994) were used to measure (pseudo) word decoding. In both tests, learners had to read as many (pseudo) words as possible within one minute. Total score is the number of words read correctly.

Data-analyses

In order to examine the first research question, regarding which navigation patterns could be distinguished, a qualitative analysis of children's navigation was performed (comparable to Paans et al., 2020). The type of pattern was based on the line graph with time on the x-axis and slide number on the y-axis for each lesson. The graphs were grouped together based on similarities and differences in their appearance. After all patterns were classified, the classification was re-evaluated to see if groups overlapped and could be merged, or if any additional patterns could be derived. This resulted in a final set of navigation patterns, on which coding criteria were formulated (see Figure 3.1 and Table 3.1). Finally, to check for grouping errors, all graphs were recoded based on this final encoding criteria. To ensure reliability, a second rater rated all the graphs. Inter-rater reliability was good (κ = .953 (95% CI, .91 to 1.00), $p < .001$).

Figure 3.1
The Four Navigation Patterns

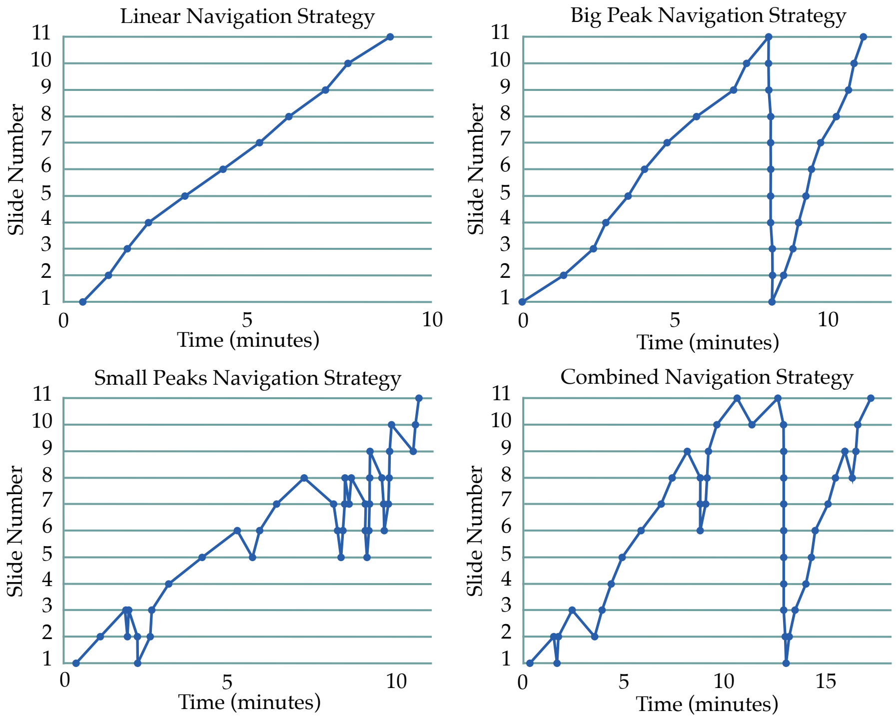

Table 3.1
Navigation Strategies

Navigation Strategy	Explanation	Coding
Linear	Participants go through the lesson from the first till the last slide. There is minimal revisiting of previous slides	Showing one straight line in the graph.
Big Peak	Participants go through the lesson linear, however, at the last slide, they go back to the beginning and run through the material a second time revisiting all the pages	Showing one big peak in the graph.
Small Peaks	When going through the lesson, participants often move back a few slides revisiting part of the slides during learning	Showing multiple small peaks in the graph.
Combined Peaks	Participants revisiting parts of the slides during learning, but also revisiting all the slides at the end of the lesson	Showing both small peaks and a big peak in the graph.

Note. All graphs could be coded in one of the four categories.

In order to investigate the second research question, the extent to which adding audio affected the navigation patterns, first, a 4x4 Chi-square analysis was performed to examine the strength and direction of association between the frequencies of the navigation strategies in the text-condition and the text-audio-condition. Then Wilcoxon tests were used to assess per strategy whether there was a significant difference between the two conditions.

To answer research question three, on whether the impact of audio on navigation patterns differed between children with and without dyslexia, first, Mann-Whitney tests were used per strategy to determine whether there was a significant difference between the two groups (both conditions combined). Then, to assess whether audio impacted the groups differently, difference scores were calculated (0 if the same strategy was used in both condition, 1 if different strategies were used) for the conditions and compared between the two groups with Mann-Whitney tests.

Due to the small sample sizes non-parametric analyses were performed. The significance threshold was set to alpha $< .05$, but due to the multiple tests for each strategy, the inflation of alpha error was controlled using the Holm's Step-Down Procedure (Holm, 1979).

Results

Based on the grounded approach, four different navigation strategies emerged (see Figure 3.1 and Table 3.1). Some participants go through the lesson from the first till the last slide (linear). Others do the same but at the last slide, they go back to the beginning and revisit the slides a second time (big peak). Yet others move back and forwards between fewer slides and thus revisit slides during learning (small peaks), and the last group combines navigation between small sets and an extra run through the material (combined peaks). Based on the increase in the number of self-initiated decisions, self-regulation is considered lowest in the linear strategy (children just follow the order of the material) and highest in the combined peaks (children follow their own path regardless of the material).

In primary school children (164 lessons; see Table 3.2), almost two-thirds of the navigation paths were coded as linear, the rest was coded as big, small and combined peaks. A Chi-square indicated that there was a statistically significant association between the navigation strategy children used in the text condition and the strategy they used in the text-audio condition, $\tau_b = .31$, $p = .003$. The contribution to the chi-square statistic is the largest ($N_{diff} = 6.80$) for the linear navigation strategy in both conditions.

Table 3.2
Navigation Strategies per Condition and Group

	Text		Text & Audio		Total	
	N	%	N	%	N	%
Dyslexia						
Linear	28	78%	25	69%	53	74%
Big Peaks	1	3%	5	14%	6	8%
Small Peaks	4	11%	4	11%	8	11%
Combined Peaks	3	8%	2	6%	5	7%
Controls						
Linear	28	61%	28	61%	56	61%
Big Peaks	8	17%	6	13%	14	15%
Small Peaks	8	17%	11	24%	19	21%
Combined Peaks	2	4%	1	2%	3	3%
Total						
Linear	56	68%	53	65%	109	66%
Big Peaks	9	11%	11	13%	20	12%
Small Peaks	12	15%	15	18%	27	16%
Combined Peaks	5	6%	3	4%	8	5%

To examine the impact of audio on the navigation patterns, analyses per strategy were performed (see Table 3.3). There were no significant differences between the text-condition and the text-audio-condition. From Table 3.3 it can also be concluded that children with and without dyslexia did not differ in the type of navigation strategies and that audio did not impact them differently. Children mostly used linear navigation strategies in both conditions and groups.

Table 3.3
Main and Interactions Effects for Condition and Group, per Navigation Strategy

	Main Effects						Interaction		
	Condition			Group			Condition*Group		
Navigation Strategy	Z	*p*	*r*	U	*p*	*r*	U	*p*	*r*
Linear	-.63	.532	.07	699.00	.355	.15	768.00	.477	.08
Big Peak	-.54	.593	.06	759.00	.360	.10	711.00	.095	.18
Small Peaks	-.73	.467	.08	740.00	.288	.12	780.00	.526	.07
Combined Peaks	-.82	.414	.09	788.50	.446	.08	823.00	.918	.01

Note. Condition: text vs. text and audio. Group: dyslexia vs. typically developing.

Conclusions

Four navigation strategies could be observed. In linear patterns, children just follow the order of the material, and thus show little self-regulation. In the other strategies, children increasingly show moments of learners' self-initiated decisions and increasingly follow their own path regardless of the material.

Primary school children mostly navigate through multimedia environments linearly; adding audio-support to the written text did not change that. As audio-support provides an external prompt and children were already showing a strategy in which they would follow the material, it naturally follows that audio did not impact their navigation strategy. There were no differences between the use of the four strategies across children with and without dyslexia. Both groups used mostly linear strategies, showing the same amount of self-regulation in their navigation pattern. Audio-support therefore does not impact navigation strategies of primary school children with and without dyslexia.

Experiment Two

Method

Participants

were 85 university and applied-university students. In total, 44 typically developing students (18% men) aged 21.64 years (SD = 2.10), and 41 students with dyslexia (15% men) aged 21.78 years (SD = 2.42) were included. As in experiment one, students with dyslexia were officially diagnosed with dyslexia. Only monolingual raised students were included. Participants were from the study described in Knoop-van Campen and colleagues (2020). One participant with dyslexia from that study could not be included due to missing log file data.

The university students with and without dyslexia did not differ in age, $t(83) = .29$, $p = .770$, Cohen's $d = .06$. In line with their diagnosis and despite their educational level, students with dyslexia scored significantly lower on word reading (M = 79.76, SD

= 11.38) and pseudo word reading (M = 71.39, SD = 18.64) than typically developing students (resp. M = 95.77, SD = 14.63 / M = 96.63, SD = 13.26), resp. $t(83) = 5.61$, $p < .001$, Cohen's $d = 1.22$ for word reading, $t(83) = 7.32$, $p < .001$, Cohen's $d = 1.56$ for pseudo word reading.

Procedure

Similar as in experiment one, testing was done in an individual setting and all students were provided with two comparable multimedia lessons: pictures with i) written text, and ii) written text with audio, offered in a randomized-block design (one lesson a week). Students received similar instructions before the lesson as in experiment one regarding the purpose of the lesson (to learn for a knowledge test) and the audio-support. Also, similar language tests were performed.

Materials

Multimedia Lessons. As in experiment one, the lessons involved biology topics but then based on the curriculum of the first study year of biology at university level (Campbell Biology: Reece et al., 2014). One lesson consisted of a title page and 15 content slides (900 words in total), with every slide showing written text with a picture. Students studied the lessons at their own pace and were able to move back-and-forth through the pages.

Audio-support. Audio-support was similar to experiment one. The voice-over (female voice) read out loud the exact (written) text on a page. The audio started automatically and could be paused and replayed.

Log Files. Log file recording and coding was similar to experiment one. Like in experiment one, inter-reliability was good ($\kappa = .953$ (95% CI, .84 to .95), $p < .001$).

Decoding. The same (pseudo) word decoding test were used. Total score is the number of words read correctly in 1 minute (EMT) and 2 minutes (Klepel).

Data-analyses. Analyses were similar to experiment one.

Results

The same four navigation strategies as in experiment one were observed: linear, big peaks, small peaks, and combined peaks (see Figure 3.1 and Table 3.1).

In university students (170 lessons; see Table 3.4), most navigation paths were coded as combined peaks, then linear and small peaks, and least as big peaks. A Chi-square indicated that there was a statistically significant association between the navigation strategy students used in the text condition and the strategy they used in the text-audio condition, $\tau_b = .49$, $p < .001$. The contribution to the chi-square statistic is the largest ($N_{diff} = 9.70$) for the combined navigation strategy, and the second largest ($N_{diff} = 7.60$) in the linear navigation strategy.

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Table 3.4
Navigation Strategies per Group and Condition

	Text		Text and Audio		Total	
	N	%	N	%	N	%
Dyslexia						
Linear	7	17%	12	29%	19	23%
Big Peaks	4	10%	9	22%	13	16%
Small Peaks	13	32%	7	17%	20	24%
Combined Peaks	17	41%	13	32%	30	37%
Controls						
Linear	8	18%	13	30%	21	24%
Big Peaks	7	16%	6	14%	13	15%
Small Peaks	9	20%	12	27%	20	24%
Combined Peaks	20	45%	13	30%	34	38%
Total						
Linear	15	18%	25	29%	40	24%
Big Peaks	11	13%	15	18%	26	15%
Small Peaks	22	26%	19	22%	40	24%
Combined Peaks	37	44%	26	31%	64	37%

To examine the impact of audio on the navigation patterns, analyses per strategy were performed (see Table 3.5). There were significant differences between the text-condition and the text-audio-condition for linear and combined strategies: more linear and less combined strategies were used in the text-audio-condition than in the text-condition.

From Table 3.5 it can also be concluded that students with and without dyslexia did not differ in the type of navigation strategies and that audio did not impact them differently.

Table 3.5
Main and Interactions Effects for Condition and Group, per Navigation Strategy

	Main Effects						Interaction		
	Condition			Group			Condition*Group		
Navigation Strategy	Z	*p*	*r*	U	*p*	*r*	U	*p*	*r*
Linear	-2.50	.012	.27	886.50	.870	.02	897.00	.948	.01
Big Peak	-1.00	.317	.11	871.50	.722	.04	782.50	.123	.17
Small Peaks	-.63	.532	.07	886.00	.870	.02	734.00	.058	.21
Combined Peaks	-2.40	.016	.26	891.00	.916	.01	853.00	.567	.06

Note. Condition: text vs. text and audio. Group: dyslexia vs. typically developing.

Conclusions

Like in experiment one, four navigation strategies could be distinguished, which increase in the number of learners' self-initiated decisions and whether they follow their own path regardless of the material. Audio-support changes navigation strategies in adults towards a strategy reflecting less self-regulation and does so similarly for adults with and without dyslexia.

Discussion

In the present study, we examined how children and adults with and without dyslexia navigate through multimedia learning environments and aimed to provide insight into the developmental perspective of navigation strategies. In two experiments, it was examined to what extent adding audio-support to written text impacted the navigation strategies in multimedia lessons of primary school children and university students with dyslexia as compared to those of their typically developing peers. Log files were recorded to identify the strategies. Children showed mostly linear navigation strategies in both conditions. Adults used mostly combined peaks strategies in the text-condition, but with audio-support, adults used more linear and less combined strategies. In neither group, differences were found between learners with dyslexia and the controls.

Navigation Strategies in Multimedia Learning

In line with the first hypothesis, we found several navigation strategies including one clear linear navigation strategy. In this linear navigation strategy, learners did not revisit previous pages during the lessons or at the end of the lesson. The other three strategies - linear reading of the whole chapter after which the chapter is reread once (big peak), reading with often going back to previous pages during the lesson (small peaks), and a combination of at least one big and multiple small peaks strategies (combined peaks) – show increased moments of learners' self-initiated decisions during learning in the multimedia environment. The navigation paths show an increase in deliberate actions through the material in a way that suggest that learners are actively involved in their learning process, which is expected to foster their comprehension and learning outcomes (Zimmermann, 2000; Van den Broek & Helder, 2017). Children were found to show mainly linear navigation strategies, as could be expected based on their less developed self-regulation skills (De Jong & van Joolingen, 1998). Adults with more developed regulation skills (Zimmerman, 2000) and more experience in navigating through multimedia environments (Mead et al., 1997) showed, as expected, more self-initiated decisions (reflecting self-regulation) by means of revisiting previous pages.

Mostly in line with the second hypothesis, audio-support impacted navigation strategies but only in adults and not in primary school children. Children in this study navigated through the multimedia environments linearly and generally did not revisit previous pages; the additional audio did not change that. As audio-support provided an external prompt and children were already showing a strategy in which they followed the material, it is no surprise that the audio did not impact their navigation strategies. As the adults used navigation strategies that reflected more self-regulation, they showed more revisiting of previous pages. In turn, the audio affected their navigation strategies towards a strategy reflecting less self-regulation, as with audio they showed less combined peak strategies and more linear strategies. With audio-support, they were less likely to revisit previous information. Pintrich and Zusho (2002) explained that regulation skills develop not only as a function of age but also of experience with the specific task (in this case, learning in multimedia environments). Our results show that audio-support can indeed be considered a valuable external prompt as it changes learning behavior in highly educated and experienced learners.

Navigation Strategies and Dyslexia

Differences were also expected between learners with and without dyslexia (hypothesis 3), however, none where found. This may be explaind by the fact that despite their decoding problems, learners with dyslexia officially do not have specific comprehension problems (Lyon et al., 2003). The referred to studies that show relations between reading skills and navigation strategies, used measures focused on reading comprehension, rather than on technical reading skills (Salmerón & García, 2011; Wu, 2014). Next to this, students with dyslexia - in contrast to poor comprehenders - use context to compensate for their reading problems (Nation & Snowling, 1998), which implies the use of certain reading strategies. In addition, learners with dyslexia generally read slower, but as our navigation strategies were coded based on the visual display of the navigation strategies, reading time was not considered. This allowed us to purely examine their navigation pattern and shows that even though there are differences between learners' with and without dyslexia on micro-level (e.g., reading skills, and see also Kim & Wiseheart, 2017), their navigation strategies to tackle a learning task are comparable. Another explanation could also be that as audio-support may both foster and hamper learners with dyslexia, as it has the potential to facilitate text representation but also to hinder learners' active involvement, it might be the case that these two aspects co-occur, and thus cancel each other out on the navigation paths. This way, no differences would arise even though the mechanism behind navigation could be different for learners with and without dyslexia.

Limitations and Future Research

Some limitations can be put forward. First of all, the fact that audio-support affects navigation strategies in adults, directly raises questions about its impact on students' learning outcome. Unfortunately, the measures in these studies are not suitable for analyzing this relation due to the randomized-block design, which complicates the interpretation of learning outcome results in combination with low numbers of some of the navigation strategies. In addition, the knowledge questions used in the two primary school studies (Knoop-van Campen et al., 2018, 2019), were not the same. Future research may investigate the link between navigation strategies and learning outcomes by adapting the set-up to suit this aim. As differences in learners' navigational behaviour was found to be related to their cognitive learning styles (Graf & Liu, 2010) future research could also investigate how the effect of navigation strategies on learning outcomes may depend on learning styles.

Second, it would be interesting to measure learners' self-regulation skills, to be able to validate the interpretation of the plotted graphs. However, as the results are clearly focused on the two most distant navigation strategies (linear and combined peaks), this validation is not likely to change the interpretation of the explained studies.

Third, while the first and fourth navigation strategies (linear and combined peaks) can be clearly defined in terms of regulation activities, one could debate which of the other two patterns (big peak / small peaks) reflects more self-regulation. We chose to order big peaks as 'less regulation', as learners with small peaks show more regulation decisions (instead of only once at the end of the lesson).

Finally, it is demonstrated that the exact navigation strategies are highly dependent on system characteristics. In a linear multimedia scenario, which was used in the present study, participants are only able to go back and forth through the slides. In the absence of hyperlinks within the text, possibilities to actively navigate the system are limited compared to, for example, hypermedia and learning on the internet – a typical learning environment in which navigation is important. To generalize the results of the present study to other environments, future research on navigation paths could use a more hierarchical or network-based learning environment. It should be noted that the linear set-up of the multimedia lessons was also a positive feature, as the effect of narration could be investigated. As learners with dyslexia often use software that reads the written text out loud to them when they read their schoolbooks on their computer screens, our results close a tap between 'typical' learning from a paper school book and learning in a hypermedia setting.

Practical Implications

There is an urgent need to understand how audio-support affects navigation strategies in learners with dyslexia. As the development of navigation strategies in learners with dyslexia is unidentified, less adequate counselling can be given regarding the use of audio-support in education. Since navigation strategies are important for learning, understanding the impact of individual differences on these navigation strategies is important. Many educators and educational designers use audio to support readers with dyslexia and these practitioners need information on how implementation of multimedia affects students' learning behavior. This study adds to existing multimedia learning knowledge in such a way that it transcends purely learning outcomes, while focusing on what happens *during* learning and how this develops. This developmental perspective is an uncultivated research area within multimedia learning.

The present study shows that the compensational components in education -which is often audio-support in the form of narrating the written text (Ghesquière et al., 2010)- have a different impact on young children than on adults. It raises the question where the tipping point is for audio to start affecting learning behavior. This might already be at secondary education. Our results thus urge practitioners to be cautious with providing audio-support when reading to learn the material. Costs and benefits of audio-support should be carefully considered per learner, as it can affect navigation strategies. In line with Schraw's call (2007) to understand the impact of regulation process on learning in computer-based learning environments, we yield that raising awareness and providing instruction about navigation strategies with its possible impact of audio, could be a solution to overcome unintended and unwanted changes in navigation behavior, although this of course has to be examined in future research.

Conclusions

In the present paper, we showed that audio-support changes navigation strategies but only for adults, and that it does so similarly for adult learners with and without dyslexia. Whereas children tend to navigate linearly through multimedia learning environments, adult learners use diverse navigation strategies, which tend to reflect less self-regulation in the case of audio-support. This implicates that audio-support may be less desirable when the goal is to learn the material. It also emphasizes the need for further research on the effects of navigation strategies on learning outcomes.

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References

Adesope, O. O., & Nesbit, J. C. (2012). Verbal redundancy in multimedia learning environments: A meta-analysis. *Journal of Educational Psychology*, *104*(1), 250. https://doi.org/10.1037/a0026147

Amadieu, F., Tricot, A., & Mariné, C. (2009). Interaction between prior knowledge and concept-map structure on hypertext comprehension, coherence of reading orders and disorientation. *Interacting with Computers*, *22*(2), 88-97. https://doi.org/10.1016/j.intcom.2009.07.001

Azevedo, R. (2009). Theoretical, conceptual, methodological, and instructional issues in research on metacognition and self-regulated learning: a discussion. *Metacognition and Learning*, *4*(1), 87–95. https://doi.org/10.1007/s11409-009-9035-7

Azevedo, R., & Cromley, J. G. (2004). Does training on self-regulated learning facilitate students' learning with hypermedia? *Journal of Educational Psychology*, *96*(3), 523–535. https://doi.org/10.1037/0022-0663.96.3.523

Azevedo, R., & Jacobson, M. J. (2008). Advances in scaffolding learning with hypertext and hypermedia: A summary and critical analysis. *Educational Technology Research and Development*, *56*(1), 93-100. https://doi.org/10.1007/s11423-007-9064-3

Barab, S. A., Fajen, B. R., Kulikowich, J. M., & Young, M. F. (1996). Assessing hypermedia navigation through Pathfinder: Prospects and limitations. *Journal of Educational Computing Research*, *15*(3), 185-205. https://doi.org/10.2190/014E-WWP6-1R2V-3MRY

Bender, W. N., & Wall, M. E. (1994). Social-emotional development of students with learning disabilities. *Learning Disability Quarterly*, *17*(4), 323-341. https://doi.org/10.2307/1511128

Blomert, L. (2005). *Dyslexie in Nederland*. Uitgeverij Nieuwezijds.

Boekaerts, M. (1999). Self-regulated learing: where we are today. *International Journal of Educational Research*, *31*, 445–457. https://doi.org/10.1016/S0883-0355(99)00014-2

Boekaerts, M., & Corno, L. (2005). Self-regulation in the classroom: A perspective on assessment and intervention. *Applied Psychology*, *54*(2), 199-231. https://doi.org/10.1111/j.1464-0597.2005.00205.x

Bråten, I., Amundsen, A., & Samuelstuen, M. S. (2010). Poor readers-good learners: A study of dyslexic readers learning with and without text. *Reading & Writing Quarterly*, *26*(2), 166-187. https://doi.org/10.1080/10573560903123684

Brus, B. T., & Voeten, M. J. M. (1999). *Een-minuut-test: vorm A en B: Verantwoording en handleiding: Schoolvorderingentest voor de technische leesvaardigheid, bestemd voor groep 4 tot en met 8 van het basisonderwijs*. Swets & Zeitlinger.

Caccamise, D., Friend, A., Littrell-Baez, M. K., & Kintsch, E. (2015). Constructive theory as a framework for instruction and assessment of reading. In S. R. Parris & K. Headley (Eds.), *Comprehension instruction: Research-based best practices* (3rd ed., pp. 88-104). Guilford Press.

De Jong, T., & van Joolingen, W. R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research*, *68*(2), 179–201. https://doi.org/10.3102/00346543068002179

Eilam, B., & Aharon, I. (2003). Students' planning in the process of self-regulated learning. *Contemporary Educational Psychology*, *28*(3), 304–334. https://doi.org/10.1016/S0361-476X(02)00042-5

Ghesquière, P., Boets, B., Gadeyne, E., & Vandewalle, E. (2011). Dyslexie: een beknopt wetenschappelijk overzicht. In A. Geudens, D. Baeyens, K. Schraeyen, K. Maetens, J. De Brauwer, & M. Loncke (Eds.), *Jongvolwassenen met dyslexie: diagnostiek en begeleiding in wetenschap en praktijk* (pp. 41-58). Acco Uitgeverij.

Graesser, A. C. (2007). An introduction to strategic reading comprehension. In D. S. McNamara (Ed.), *Reading comprehension strategies: Theories, interventions, and technologies* (pp. 3-26). Lawrence Erlbaum Associates Publishers.

Graesser, A. C., McNamara, D. S., & VanLehn, K. (2005). Scaffolding deep comprehension strategies through Point&Query, AutoTutor, and iSTART. *Educational psychologist*, *40*(4), 225-234. https://doi.org/10.1207/s15326985ep4004_4

Graf, S., & Liu, T. C. (2010). Analysis of learners' navigational behaviour and their learning styles in an online course. *Journal of Computer Assisted Learning*, *26*(2), 116-131. https://doi.org/10.1111/j.1365-2729.2009.00336.x

Greene, J. A., & Azevedo, R. (2010). The measurement of learners' self-regulated cognitive and metacognitive processes while using computer-based learning environments. *Educational psychologist*, *45*(4), 203-209. https://doi.org/10.1080/00461520.2010.515935

Gregg, N., & Banerjee, M. (2009). Reading comprehension solutions for college students with dyslexia in an era of technology. In G. Reid (Ed.), *Dyslexia: A handbook for research and practice* (pp. 265–285). Routledge.

Heiman, T., & Precel, K. (2003). Students with learning disabilities in higher education: Academic strategies profile. *Journal of learning disabilities*, *36*(3), 248-258. https://doi.org/10.1177/002221940303600304
Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics*. *6*(2), 65-70.
Jáñez, Á., & Rosales, J. (2016). Novices' need for exploration: Effects of goal specificity on hypertext navigation and comprehension. *Computers in Human Behavior*, *60*, 121-130. https://doi.org/10.1016/j.chb.2016.02.058
Jeske, D., Backhaus, J., & Stamov Roßnagel, C. (2014). Self-regulation during e-learning: using behavioural evidence from navigation log files. *Journal of Computer Assisted Learning*, *30*(3), 272-284. https://doi.org/10.1111/jcal.12045
Juvina, I., & Van Oostendorp, H. (2008). Modeling semantic and structural knowledge in web navigation. *Discourse Processes*, *45*, 346–364. https://doi.org/10.1080/01638530802145205
Kim, S., & Wiseheart, R. (2017). Exploring text and icon graph interpretation in students with dyslexia: An eye-tracking study. *Dyslexia*, *23*(1), 24-41. https://doi.org/10.1002/dys.1551
Kim, S., Wiseheart, R., & Walden, P. R. (2018). Do multimedia instructional designs enhance comprehension in college students with dyslexia? *Journal of Postsecondary Education and Disability*, *31*(4), 351-365.
Kirby, J. R., Silvestri, R., Allingham, B. H., Parrila, R., & La Fave, C. B. (2008). Learning strategies and study approaches of postsecondary students with dyslexia. *Journal of Learning Disabilities*, *41*(1), 85-96. https://doi.org/10.1177/0022219407311040
Klepsch, M., & Seufert, T. (2020). Understanding instructional design effects by differentiated measurement of intrinsic, extraneous, and germane cognitive load. *Instructional Science*, *48* (1), 45-77. https://doi.org/10.1007/s11251-020-09502-9
Knoop-van Campen, C. A.N., Segers, E., & Verhoeven, L. (2018). The modality and redundancy effects in multimedia learning in children with dyslexia. *Dyslexia*, *24*(2), 140-155. https://doi.org/10.1002/dys.1585
Knoop-van Campen, C. A.N., Segers, E., & Verhoeven, L. (2019). Modality and redundancy effects, and their relation to executive functioning in children with dyslexia. *Research in developmental disabilities*, *90*, 41-50. https://doi.org/10.1016/j.ridd.2019.04.007
Knoop-van Campen, C. A. N., Segers, E., & Verhoeven, L. (2020). Effects of audio support on multimedia learning processes and outcomes in students with dyslexia. *Computers & Education*, *150*, 103858. https://doi.org/10.1016/j.compedu.2020.103858
Lawless, K. A., & Kulikowich, J. M. (1996). Understanding hypertext navigation through cluster analysis. *Journal of Educational Computing Research*, *14*(4), 385–399. https://doi.org/10.2190/DVAP-DE23-3XMV-9MXH
Lyon, G. R., Shaywitz, S. E., & Shaywitz, B. A. (2003). A definition of dyslexia. *Annals of dyslexia*, *53*(1), 1-14. https://doi.org/10.1007/s11881-003-0001-9
MacCullagh, L., Bosanquet, A., & Badcock, N. A. (2017). University students with dyslexia: A qualitative exploratory study of learning practices, challenges and strategies. *Dyslexia*, *23*(1), 3-23. https://doi.org/10.1002/dys.1544
Madrid, R. I., Van Oostendorp, H., & Melguizo, M. C. P. (2009). The effects of the number of links and navigation support on cognitive load and learning with hypertext: The mediating role of reading order. *Computers in Human Behavior*, *25*(1), 66-75. https://doi.org/10.1016/j.chb.2008.06.005
Mayer, R. E. (2005). *The Cambridge Handbook of Multimedia Learning*. Cambridge University Press. https://doi.org/10.1017/CBO9780511816819
Mayer, R. E., & Fiorella, L. (2014). 12 principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles. In R. E. Mayer (Ed.),*The Cambridge handbook of multimedia learning* (Vol. 279, pp. 279-315). Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.015
Mead, S. E., Spaulding, V. A., Sit, R. A., Meyer, B., & Walker, N. (1997). Effects of age and training on World Wide Web navigation strategies. *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 41, No. 1, pp. 152-156). SAGE Publications. https://doi.org/10.1177/107118139704100135
Nation, K., & Snowling, M. J. (1998). Individual differences in contextual facilitation: Evidence from dyslexia and poor reading comprehension. *Child Development*, *69*(4), 996-1011. https://doi.org/10.1111/j.1467-8624.1998.tb06157.x
Paans, C., Molenaar, I., Segers, E., & Verhoeven, L. (2020). Children's macro-level navigation patterns in hypermedia and their relation with task structure and learning outcomes. *Frontline Learning Research*, *8*(1), 76-95. https://doi.org/10.14786/flr.v8i1.473

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Paas, F., Renkl, A., & Sweller, J. (2003). Cognitive load theory and instructional design: recent developments. *Educational Psychologist, 38*, 1-4. https://doi.org/10.1207/S15326985EP3801_1

Pieschl, S., Stahl, E., Murray, T., & Bromme, R. (2012). Is adaptation to task complexity really beneficial for performance? *Learning and Instruction, 22*(4), 281–289. https://doi.org/10.1016/j.learninstruc.2011.08.005

Pintrich, P. (2000). The role of goal orientation in self-regulated learning. In M., Boekaerts, P., Pintrich, M., & Zeidner (Eds.), *Handbook of self-regulation* (pp. 451–502). San Diego, CA: Academic. https://doi.org/10.1016/B978-012109890-2/50043-3

Pintrich, P. R., & Zusho, A. (2002). The development of academic self-regulation: The role of cognitive and motivational factors. In A. Wigfield & J. S. Eccles (Eds.), *Development of achievement motivation* (pp. 249-284). Academic Press. https://doi.org/10.1016/B978-012750053-9/50012-7

Polychroni, F., Koukoura, K., & Anagnostou, I. (2006). Academic self-concept, reading attitudes and approaches to learning of children with dyslexia: Do they differ from their peers?. *European Journal of Special Needs Education, 21*(4), 415-430. https://doi.org/10.1080/08856250600956311

Reece, J. B., Urry, L. A., Cain, M. L., Wasserman, S. A., Minorsky, P. V., & Jackson, R. B. (2014). *Campbell biology* (p. 135). Pearson.

Saint, J., Gašević, D., Matcha, W., Uzir, N. A. A., & Pardo, A. (2020). Combining analytic methods to unlock sequential and temporal patterns of self-regulated learning. *Proceedings of the Tenth International Conference on Learning Analytics & Knowledge*, 402-411. https://doi.org/10.1145/3375462.3375487

Salmerón, L., & García, V. (2011). Reading skills and children's navigation strategies in hypertext. *Computers in Human Behavior, 27*(3), 1143-1151. https://doi.org/10.1016/j.chb.2010.12.008

Salmerón, L., Kintsch, W., & Cañas, J. (2006). Coherence or interest as basis for improving hypertext comprehension. *Information Design Journal, 14*(1), 45-55. https://doi.org/10.1075/idj.14.1.06sal

Schraw, G. (2007). The use of computer-based environments for understanding and improving self-regulation. *Metacognition and Learning, 2*(2-3), 169-176. https://doi.org/10.1007/s11409-007-9015-8

Song, H. S., Kalet, A. L., & Plass, J. L. (2016). Interplay of prior knowledge, self-regulation and motivation in complex multimedia learning environments. *Journal of Computer Assisted Learning, 32*(1), 31-50. https://doi.org/10.1111/jcal.12117

Van den Bos, K. P., Spelberg, H., Scheepsma, A., & De Vries, J. (1994). *De Klepel. Vorm A en B. Een test voor de leesvaardigheid van pseudowoorden. Verantwoording, handleiding, diagnostiek enbBehandeling.* Berkhout.

Van den Broek, P., & Helder, A. (2017). Cognitive processes in discourse comprehension: Passive processes, reader-initiated processes, and evolving mental representations. *Discourse Processes, 54*(5-6), 360-372. https://doi.org/10.1080/0163853X.2017.1306677

Van der Stel, M., & Veenman, M. V. J. (2008). Relation between intellectual ability and metacognitive skillfulness as predictors of learning performance of young students performing tasks in different domains. *Learning and Individual Differences, 18*(1), 128–134. https://doi.org/10.1016/j.lindif.2007.08.003

Van Hoof, K., Siemensma, F., Smit, J., & Vegh, G. (2009). *Wijzer door natuur & techniek.* Noordhoff Uitgevers.

Veenman, M. V. J. (2011). Learning to self-monitor and self-regulate. In R. Mayer & P. Alexander (Eds.), *Handbook of research on learning and instruction* (pp 197-218). Routledge.

Winne, P. H., & Hadwin, A. F. (1998). Studying as self-regulated learning. In D. J. Hacker, J. Dunlosky, & A. C. Graesser (Eds.), *Metacognition in educational theory and practice* (pp. 277–304). Lawrence Erlbaum.

Winne, P. H., Hadwin, A. F., & Gress, C. L. Z. (2010). The learning kit project: software tools for supporting and researching regulation of collaborative learning. *Computers in Human Behavior, 26*(5), 787–793. https://doi.org/10.1016/j.chb.2007.09.009

Winne, P. H., & Nesbit, J. C. (2010). The psychology of academic achievement. *Annual Review of Psychology, 61*, 653–678. https://doi.org/10.1146/annurev.psych.093008.100348

Wu, J. Y. (2014). Gender differences in online reading engagement, metacognitive strategies, navigation skills and reading literacy. *Journal of Computer Assisted Learning, 30*(3), 252-271. https://doi.org/10.1111/jcal.12054

Zimmerman, B. (2000). Attaining self-regulation: A social cognitive perspective. In M. Boekaerts, P. Pintrich, & M. Zeidner (Eds.), *Handbook of self–regulation* (pp. 13–39). Academic Press. https://doi.org/10.1016/B978-012109890-2/50031-7

Zimmerman, B. J., & Schunk, D. H. (Eds.). (2001). *Self-regulated learning and academic achievement: Theoretical perspectives.* Routledge.

CHAPTER 4

MULTIMEDIA LEARNING IN CHILDREN WITH DYSLEXIA

Abstract

The present study aimed to examine the modality and redundancy effects in multimedia learning in children with dyslexia in order to find out whether their learning benefits from written and/or spoken text with pictures. We compared study time and knowledge gain in 26 11-year-old children with dyslexia and 38 typically reading peers in a within-subjects design. All children were presented with a series of user-paced multimedia lessons in 3 conditions: pictorial information presented with (a) written text, (b) audio, or (c) combined text and audio. We also examined whether children's learning outcomes were related to their working memory. With respect to study time, we found modality and reversed redundancy effects. Children with dyslexia spent more time learning in the text condition, compared with the audio condition and the combined text-and-audio condition. Regarding knowledge gain, no modality or redundancy effects were found. Although the groups differed on working memory, it did not influence the modality or redundancy effect on study time or knowledge gain. In multimedia learning, it thus is more efficient to provide children with dyslexia with audio or with auditory support.

This chapter is based on Knoop-van Campen, C. A. N., Segers, E., & Verhoeven, L. (2018). The modality and redundancy effects in multimedia learning in children with dyslexia. Dyslexia, 24(2), 140-155.

Introduction

There is continuous debate on how children with dyslexia can be best supported in their learning. Due to a phonological deficit and accompanying working memory problems, children with dyslexia have problems with learning from text (e.g., Berninger et al., 2008; Swanson et al., 2009). Multimedia may support their learning by replacing written text with audio or by adding audio to the written text. According to principles put forward in the cognitive theory of multimedia learning (Mayer, 2005), various types of multimedia may impact children's learning. The modality effect entails a larger learning effect for spoken text with pictures than for written texts with pictures (Mayer, 2005). However, this effect tends to reverse over time (e.g., Savoji et al., 2011; Scheiter et al., 2014; Tabbers et al., 2004). Furthermore, many studies have failed to replicate such a modality effect, which can be attributed to boundary conditions, such as pacing of the learning material (Tabbers, 2002). Evidence for a so-called redundancy effect has also been found in that presenting identical information in different modalities simultaneously may hamper the learning process (i.e., Gerjets et al., 2009; Mayer, 2005; Mayer et al., 2001). It is by no means clear how the modality effect and the redundancy effect apply to children with dyslexia. Therefore, in the present research, we examined whether these effects would affect the efficiency and knowledge gain in multimedia learning in children with dyslexia to the same extent as their typically reading peers while taking into account children's working memory capacity.

Modality Effect in Multimedia Learning

Information in learning situations is increasingly provided in multimedia form: input of both words (written/spoken) and visualizations (pictures/animations; Mayer, 2005). The dual-channel theory describes how sensory information is processed through both an auditory channel and a visual channel in working memory, which are seen as parallel and equal (Baddeley, 1995). Together with the limited-capacity theory (Baddeley, 1995), assuming that working memory can only process a certain amount of information at a time, it forms the basis of the cognitive theory of multimedia learning (CTML, Mayer, 2005). According to the CTML, it can be assumed that both the auditory and visual channels have a maximum capacity and that more information processing is possible when the two channels are combined. It is claimed that spoken texts with pictures have a larger learning effect than written texts with pictures (i.e., the modality effect, Mayer, 2005) because of the fact that the combination effectively triggers both the auditory and visual channels with less risk of information overload as is the case with written-text-with-pictures. The CTML states that both recall of facts (retention) and applying learned information to a new situation (transfer) is better when the material is presented as spoken-text-with-pictures instead of written-text-with-pictures. Most research has been done in system-paced environments, in which the software, and not the user, is in control of the study time. A meta-analysis of Ginns (2005), including 43 studies on the modality effect representing the performance of 1,887 students, indeed showed that people learn more from spoken-text-with-pictures than from written-text-with-pictures, with a moderate to large effect size.

Although the modality effect thus has been found directly after learning, many studies have failed to replicate the modality effect. This may be due to the fact that in all of the above studies, multimedia was presented in a system-paced learning environment. Studies investigating the effect in a user-paced system or over time showed no or even reversed modality effects (Savoji et al., 2011; Scheiter et al., 2014; Schmidt-Weigand et al., 2010; Segers et al., 2008; Tabbers et al., 2004; Van den Broek, Segers, & Verhoeven, 2014; Witteman & Segers, 2010). In a user-paced learning environment, students control the speed of the lessons. In contrast to learning in a system-paced setting, Tabbers and colleagues (2001) found no modality effects on learning gain (retention or transfer knowledge) in a user-paced learning environment. They also found reversed modality effects on retention or transfer knowledge in such a learning environment (Tabbers et al., 2004). Regarding retention knowledge, Witteman and Segers (2010) also showed a reversed modality effect directly after the lessons. A theoretical explanation for this superior effect of reading could be that reading activates both orthography and phonology and thus creates a double-memory trace (see Nelson et al., 2005). Thus, in the user-paced learning environment where children can determine their own pace, they seem to learn as much or even more from written-text-with-pictures than from spoken-text-with-pictures.

It has also been shown that modality effects tend to disappear in a user-paced learning environment on the long term. For example, Segers and colleagues (2008) showed that in primary school children (11-year-olds), learning from written-text-with-pictures in the long term was more effective than learning from spoken-text-with-pictures. The modality effect directly after learning on retention questions disappeared after 1 week. Also, with regard to transfer questions, directly after the lessons, a modality effect was found, whereas a week later, a reversed modality effect could be observed. Witteman and Segers (2010) as well as She and Chen (2009) showed long-term reversed modality effects for transfer knowledge but no effect on retention. Both sixth graders (Witteman & Segers, 2010) and seventh graders (She & Chen, 2009) learned in the long term more from text with pictures than from audio with pictures. In adults, reversed modality effects were found even after one night, on both retention and transfer knowledge (Van den Broek et al., 2014). A direct comparison between both short- and long-term system- and user-paced learning environments was made by Ruf and colleagues (2014). They showed a reversed modality effect over time in both the system and user-paced settings: learning from text and pictures led to more learning gain in the long term.

The disappearance of the modality effect in a user-paced system may be explained by the same theories underlying the modality effect in a system-paced environment: after all, the limited-capacity theory (Baddeley, 1995) states that working memory can only process a certain-amount of information at a time. So, when given enough time, the reader can process both the text and pictures (dual theory: Baddeley, 1995). In reading, the reader can in fact create a better understanding as it is easier to go back and forth in the text (Van den Broek et al., 2014). The reversed modality effect thus can be explained by the fact that spoken text is transient, whereas written text remains on the screen and can be absorbed longer. Singh and colleagues (2012) indeed showed this transient information effect: written text led to a larger learning gain than the (identical) spoken text. They argue that this is due to the extra cognitive load longer spoken texts create because of their lack of permanency.

Redundancy Effect in Multimedia Learning

Presenting identical information in different multimedia forms simultaneously, for example providing a text on screen and reading that text out loud, is considered to provide the learner with redundant information. The CTML states that instead of enhancing learning, redundant information hampers the learning process because it requires extra working memory capacity, which is no longer available for learning (Mayer, 2005). Redundant information can be in the form of written text, when an audio condition is compared with a text–audio condition, or in the form of audio, when comparing a written text condition with a text–audio condition. The redundancy effect is very robust, and many studies have shown this effect, especially when the redundant information was in the form of written text (Mayer, 2005). For example, Kalyuga and colleagues (1999) showed that students learned more from a diagram with spoken text than from a diagram with spoken-and-written text. Providing students with identical (redundant) information hinders their learning. The redundancy effect was also shown in a study by Mayer and Moreno (2002) in which students examined an animation about lightning formation. Half of the participants were also presented with redundant on-screen text. Results showed that adding the same text to presented narration and animation led to decreased retention and transfer knowledge. Mayer and Johnson (2008) added to this finding that redundant information hindered learning when it consumes cognitive load that is essential for processing the material: when the narrative text is also presented on screen. Also, Jamet and Le Bohec (2007) demonstrated the redundancy effect on both retention and transfer knowledge. Students learned more from diagrams with spoken information, compared with adding the same information as written text to the materials.

Next to redundant information in the form of written text as described above, redundant information can also be in the form of spoken text. Only few studies have looked into this aspect of the redundancy effect. For example, Diao and Sweller (2007) showed redundancy effects on redundant aural information. They examined reading comprehension in second-language learners and compared reading comprehension between written text and written and spoken text containing the same information. Students could comprehend the information better when only presented with text, compared with simultaneous presenting of written and spoken text. Moreno and Mayer (2002) compared pictures accompanied by written text, spoken text, and written-and-spoken text in a virtual-reality environment. Contrary to Diao and Sweller (2007), they found a reversed redundancy effect on audio information: text alone led to less retention and transfer knowledge compared with the combination of written and spoken text. The findings were attributed to the virtual-reality environment: Moreno and Mayer (2002) argued that students were perhaps more inclined to look around and observe instead of reading the textual material. Likewise, in a hypermedia study, Gerjets and colleagues (2009) showed that students learned more from written text only than from spoken or combined written and spoken text.

So, in general, the redundancy effect is clear when the redundant information is in written form and added to aurally presented information with pictures. When the redundant information is in oral form, and added to a written text, there are contradicting results on whether written text combined with audio benefits the learning outcomes compared with text only. Moreover, all these studies focused on redundancy effects directly after learning. Studies on long-term effects of the redundant information are generally lacking.

Multimedia Learning in Children with Dyslexia

Dyslexia is an impairment in reading and spelling, given adequate intelligence and educational opportunities, which is in particular associated with a phonological core deficit (Lyon et al., 2003). Although children with dyslexia are often provided with (extra) audio to support their reading, little is known about the effects of multimedia on learning in these children. Only a small number of studies have been conducted on multimedia learning in people with dyslexia. As children with dyslexia often have lower working memory -an important aspect in multimedia learning- they may learn differently in a multimedia setting.

Many studies have shown children with dyslexia to be impaired on verbal working memory tasks (e.g., Beneventi et al.,2010; Berninger et al., 2008; Menghini et al., 2011; Swanson et al., 2009; Tijms, 2004). However, there is debate on whether this relies on their phonological core deficit or not. For example, Smith-Spark and Fisk (2007) found that when phonological differences are taken into account, children with dyslexia still show working memory deficits, whereas Schuchardt and colleagues (2008) found that differences between children with and without dyslexia disappear when controlling for phonological differences. Pickering (2012) argued that children with dyslexia have difficulties with the phonological aspects of working memory and the central executive function of working memory.

Visual working memory is less commonly measured in people with dyslexia, and there is no consensus whether it is impaired in children with dyslexia. Menghini and colleagues (2011) showed that working memory in children with dyslexia was impaired in the phonological loop, as well as in visual aspects of the working memory. In a similar vein, Reiter and colleagues (2005) showed differences between children with and without dyslexia on visual working memory, just like Smith-Spark and Fisk (2007) found adults with dyslexia to be impaired on visuospatial working memory. On the other hand, Jeffries and Everatt (2004) found no differences between children with and without dyslexia on visuospatial working memory tasks.

Based on the CTML (Mayer, 2005), children with working memory problems, such as children with dyslexia, would benefit more from spoken-text-with-pictures compared with written-text-with-pictures (larger modality effect), as they would be more susceptible to cognitive overload in the written text condition. In a similar vein, combining written and spoken text with pictures would also create extra cognitive overload for these children (larger redundancy effect). However, the existing studies examining multimedia learning in dyslexia are contradictive. Audio-support (in children with dyslexia) most often focuses on word recognition and phonological skills (e.g., Magnan & Ecalle, 2006; Underwood, 2000), in other words, on reading. Little is known on the effects of multimedia on knowledge learning in children with dyslexia. One of the few studies on multimedia learning in people with dyslexia is from Alty and colleagues (2006). They investigated learning from different media combinations in university students with and without dyslexia when studying statistics in an e-learning environment. Students with dyslexia performed better in a text-only condition, compared with text-and-diagrams and with audio-and-diagrams, whereas typically developing students scored higher in the audio-and-diagram condition. This is in contrast to the expectation that text only would hinder the students with dyslexia, and Alty and colleagues (2006) suggested that this has to do with compensating strategies in the students with dyslexia. It could also be explained by the finding of Harrar and colleagues (2014) that people with dyslexia have a larger cost when switching their attention from visual information to audio-presented information, leading to more or faster cognitive (over)load. Beacham and Alty (2006) also showed differences between students with and without dyslexia with respect to different multimedia learning environments; however, they did not find one specific media condition that is more beneficial for all students with dyslexia. With regard to the redundancy effect, Lallier and colleagues (2013) showed that children with dyslexia have more difficulties processing verbal- and audio-presented information simultaneously. This is in line with the CTML (Mayer, 2005) that children with working memory problems would learn less in a combined multimedia environment and thus would show larger redundancy effects.

Although working memory is theoretically related to the modality and redundancy effects, the relation of working memory to these effects has hardly been examined in typically developing children, let alone in children with dyslexia. Only

Witteman and Segers (2010) examined individual differences in working memory in a user-paced learning environment in typically developing children but found no relation of working memory with the modality effect.

As children with dyslexia experience reading difficulties and generally read slower than typically developing children (Shaywitz & Shaywitz, 2001), it is important to also take study time into account during their multimedia learning. These children are expected to need more study time when they have to read a text themselves, compared with a situation where information is presented to them aurally. Kim and colleagues (2014) examined college students with developmental dyslexia in an eye-tracking study on the comprehension of graphs. They found that students with dyslexia processed visually presented information (text and picture) differently compared with their typically developing peers. Students with dyslexia needed more time to process both linguistic (the text) and nonlinguistic (the graphs) stimuli. Study time is thus an important aspect when focusing on efficient learning.

The Present Study

To sum up, children with dyslexia read slower, which increases their study time, and they may have lower working memory capacities. In practice, they are often provided with multimedia (audio-only or audio-support added to a written text) to compensate their reading problems. Indeed, multimedia offer various possibilities for supporting learning in children with dyslexia; however, it can also hinder their learning due to cognitive overload. Given the discrepancy between what could be expected based on theory and the few contradicting studies on multimedia learning in people with dyslexia, it is by no means clear whether the optimal way of presenting information to typically developing children is also the optimal way of presenting information to children with dyslexia.

In the present study, we aimed to examine the impact of modality and redundancy effects on efficiency and knowledge gains in multimedia learning in children with dyslexia. The research questions were (a) to what extent do modality and redundancy effects have the same impact on the study time and knowledge gain in children with dyslexia as compared with typically reading peers and (b) to what extent are individual differences in children's working memory capacity related to these effects. Consideration was given to both retention and transfer knowledge, on both the short and long terms, in a realistic, user-paced learning environment.

In order to answer these research questions, children with dyslexia and a control group of typically developing children were presented with three different types of user-paced multimedia lessons in a within-subjects design: pictorial information presented with (a) written text, (b) audio, or (c) combined text and audio. Children were tested on retention and transfer questions directly after studying and after 1 week.

With regard to study time, it was hypothesized that in children with dyslexia, compared with their typically developing peers, larger modality and redundancy effects would be observed. Children with dyslexia were expected to spend more time in lessons with written text than in lessons with audio. With respect to knowledge gain, on the basis of the CTML, also stronger modality and redundancy effects in children with dyslexia were expected starting from the assumption that these children would be more susceptible to cognitive overload. In a similar vein, it was expected that poorer working memory would lead to larger modality and redundancy effects. However, in light of the literature reviewed above, one could also expect no or reversed modality effects on knowledge gain in typically developing children due to the user-paced learning environment. In children with dyslexia, differences could then be expected in favour of the text condition, which would lead to smaller modality effects, due to the transiency of audio.

Method

Participants

Out of an existing database of 550 school, 13 schools in the central region of the Netherlands signed up to participate. Informed active consent was obtained from the parents and the schools before children were allowed to participate. 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 provided by a certified child psychologist according to the clinical assessment of the Protocol Dyslexia Diagnosis and Treatment. The Protocol Dyslexia Diagnosis and Treatment is a guide to diagnosing, indicating, and treating clients with dyslexia with the aim of describing optimal care for clients with dyslexia based on current scientific, professional, and social insights (Blomert, 2006). The control group was selected from the same classrooms as the children with dyslexia to diminish group influence. In total, 38 typically developing children (22 boys) aged 10.92 years ($SD = 0.37$) and 26 children with dyslexia (13 boys) aged 11.22 years ($SD = 0.53$) participated in this research (64 in total). Only monolingual children with no developmental deficits (only dyslexia) were included in the research.

Procedure

Children were tested between January 2016 and April 2016 by five undergraduate students. Before data collection started, they received training twice (each 2.5 hr) on the lessons and tests. Testing was done in an individual setting at a quiet room in school. The children were tested for 45 min/week, 4 weeks in a row. All 64 children were provided with three multimedia lessons offered in a randomized-block design with lessons, modalities, and posttests randomized per child. So, all children studied every lesson once (one lesson a week). During studying, children's learning time was recorded. After the lessons, children immediately filled out the first posttest to measure the learning effect in the short term. They did not receive feedback on their answers. The second, alternative version of the posttest was administered a week later to measure long-term effects. In addition, some other tests were performed on working memory, non-verbal reasoning, and language. For five children, not all data were complete, due to absence during one of the measurements.

Measures

General Non-verbal Intelligence

Raven's (2006) Progressive Matrices General was used to measure non-verbal intelligence and administered according to its individual 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. Raw scores (number of correct answers) were used for analysis. In the present study, Cronbach's alpha was .84, indicating good reliability.

Word Decoding

The Een-Minuut-Test (One-Minute Test), was used to measure the children's word decoding (Verhoeven, 1995). The Een-Minuut-Test is a standardized test that consists of a reading card with different words in increasing difficulty level. Children have to correctly read out loud as many words as possible in 1 min. The number of correct read words in 1 min was used for analysis.

Pseudo-word Decoding

The Klepel was used to measure the children's pseudo-word decoding (Verhoeven, 1995). The Klepel is a standardized test that consists of a reading card with different pseudo-words (non-existing words) in increasing difficulty level. Children have to correctly read out loud as many pseudo-words as possible in 1 min. The number of correctly read words in 1 min was used for analysis.

Verbal Working Memory

The subtest digits backwards of the Dutch version Wechsler Intelligence Scale for Children III (Wechsler, 2005) was used to measure verbal working memory and administered according to its individual 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 by one, until two sequences of the same length were incorrect. There were no time limits. The score given was the number of correct recalled lists. Higher scores reflected better performance. Raw scores were converted into standardized values for analyses.

Visual Working Memory

An N-backwards working memory task with N = 2 (a variant of the 'n-back' procedure of Gevins & Cutillo, 1993) was used to measure visual working memory. This task is commonly used in literature as a working memory measure (Baddeley, 2003) and useful in experimental research (Jaeggi et al., 2010). On a laptop screen (1,366 × 768 pixels), 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 2–5–2 and had to press the key at the second 2. Stimuli were presented for 600 ms with 645 ms in between. Children were presented with 225 stimuli, of which 32 were an N = 2 item. The score given was the number of correct responses. Higher scores reflected better performance. Raw scores were converted into standardized values for analyses.

Multimedia Lessons

All children made three multimedia lessons, namely, balance in nature, motion, and global warmth in different types (modalities) of learner-paced multimedia lessons: pictorial information presented with (a) written text, (b) audio, or (c) combined text and audio. One lesson consisted of 12 slides, including a title page. The children were able to move back and forth through the pages at their own pace. The lessons were based on a text book of Grade 6 (1 year above children's school year; Van Hoof et al., 2009) to ensure that the children had not had these lessons and to enable the possibility of learning gain. Pictures were also from the same schoolbook or, when unavailable, from the Internet (open source). The schoolbook from which the lessons were taken provides a very similar build-up per lesson. The lessons were thus comparable, and they each involved approximately 530 words.

Pictures are expected to support learning (CTML: Mayer, 2005). There are five kinds of pictures, which decrease in added value for learning (Carney & Levin, 2002): transformational, interpretational, organizational, representational, and decorative. The first four categories are considered to be beneficial for learning, whereas decorative pictures are not. To determine the relevance of the pictures used in this study, 11 educational experts (PhD students in Educational Science) judged the pictures and labelled them in the five categories. Of all the pictures in this study, 6.57% was labelled as transformational, 10.35% as interpretational, 10.61% as organizational, 35.61% as representational, and 36.87% as decorative pictures. So, almost two thirds of the pictures can be considered to be beneficial for learning. The used pictures were a good reflection of pictures used in schoolbooks, thus adding to the realistic learning environment we aimed to replicate.

Knowledge Gain

Children studied every lesson once, with two posttests (directly after learning and 1 week later). The posttests consisted of both retention and transfer questions. Children were presented with eight retention and four transfer questions per test. The retention questions were multiple-choice questions, for example, "The vertebral column provides protection to the ...? A) heart and lungs B) brains C) spinal cord D) hips". Children received one point per correct answer and could thus receive 8 points per posttest on retention knowledge. The transfer questions were open-ended questions, for example, "What would happen if the bones of a bird were not hollow inside?" The questions were scored with 0, 1, or 2 points by the first author according to a scoring card. Children could thus receive 8 points per posttest on transfer knowledge.

To ensure the reliability of the posttests, a pilot study was performed before conducting the present research. All posttests were administered in approximately 40 children, divided over three schools (Grade 5). After the pilot, the questions were adapted based on their means and corrected item-total correlation. If the mean was not between 0.4 and 0.8 or if the corrected item–total correlation was lower than 0.3, it was adapted. Out of the 48 retention questions, 36 (75%) were improved, and out of the 24 transfer questions, nine (38%) were improved. The alpha of the posttests was .82, indicating good reliability.

Learning Time

Learning time was defined as the time (in minutes) children spent studying a multimedia lesson, as extracted from the log data of the multimedia lessons from the timestamp of the last slide.

Data-analyses

To answer the research questions, general linear model repeated-measures analyses of covariance were conducted. First, the modality effect was examined, with time (short term or long term) and condition (text or audio) as within-subject factors and with group (dyslexia or typically developing) as the between-subject factor. Verbal and visual working memory were added as covariates. Second, a similar analysis was conducted for the redundancy effect, but with the conditions text, audio, and text and audio. Simple contrasts were performed with the text-and-audio condition as a reference category, as we wanted to compare text versus text and audio and audio versus text and audio. Both the modality and redundancy analyses were performed separately for retention and transfer knowledge.

Then, similar analyses were performed to examine the time children spent in the various conditions (learning time). First, the analysis was performed for the modality effect, with learning time (text or audio) as the within-subject factor and group (dyslexia or typically developing) as the between-subject factor. Second, the analysis was performed for the redundancy effect, with learning time (text or audio or text and audio) as the within-subject factor and group (dyslexia or typically developing) as the between-subject factor. Similar to before, simple contrasts were performed with the text-and-audio condition as a reference category. These analyses on learning time also included verbal and visual working memory as covariates.

Due to illness, five children missed one of the six questionnaires (all long term): one child (dyslexia) in the audio condition and four (one child with dyslexia and three typically developing) in the text-and-audio condition. According to Elliott and Hawthorne (2005), performing a repeated analysis with a listwise deletion is an inefficient missing-data method. They argue that the best way to deal with missing data in repeated measures is to substitute a missing value with an average value. The five missing values were thus replaced by the group means (dyslexia or typically developing).

Results

Descriptive Statistics

As an extra check on the dyslexia statement, we compared the children with and without dyslexia on general non-verbal intelligence and reading ability with independent-samples *t*-tests. In line with their diagnosis, children with dyslexia did not differ on general non-verbal intelligence compared with the typically developing children in this study, also not after controlling for age differences, but as expected, they did score significantly lower on word reading and pseudo word reading (see Table 4.1).

In addition, children with dyslexia scored significantly lower on verbal working memory (large effect). With regard to visual working memory, there was no homogeneity of variance, Levene's statistics$(1, 62) = 7.70$, $p = .007$, so contrast tests were performed. Children with dyslexia scored marginally significantly lower on visual working memory (small effect).

Also, there was no homogeneity of variance for time spent in the time condition, Levene's statistics$(1, 44) = 9.85$, $p = .003$, so contrast tests were performed. Children with dyslexia spent significantly more time in the text condition (large effect). In the other two conditions, children with dyslexia did not differ in the amount of time they spent in the audio or combined text-and-audio condition, compared with typically developing children (see Table 4.1).

The means and standard deviations for the different conditions on the short and long terms for both retention and transfer knowledge, separately for children with dyslexia and typically developing children, are provided in Table 4.2. Both in all children together and in children with dyslexia and typically developing children separately, no significant correlations could be observed between the time children spent on learning the multimedia lessons and their retention and transfer knowledge of the lessons (p's $>$ .05).

Table 4.1
Descriptives for Childrens' General Nonverbal Intelligence, Word Decoding, Pseudo Word Decoding, Verbal and Visual Working Memory, and Learner Time per Condition per Group

	Dyslexia			Typically Developing				
	N	M	SD	N	M	SD	*t*	*d*
GNvI-R	26	40.23	6.00	38	42.03	6.77	1.09	.27
GNvI-P	26	52.31	26.99	35	58.71	28.03	.90	.23
Reading Ability								
Word Decoding	26	45.27	11.91	38	68.84	9.48	8.80***	2.49
Pseudo Word Decoding	26	19.73	5.33	38	36.21	7.67	9.49***	2.15
Working Memory								
Verbal Working Memory	26	3.62	1.13	38	5.13	1.30	4.82***	1.24
Visual Working Memory	26	8.38	2.74	38	10.18	5.01	1.85+	.45
Time Multimedia Lessons								
Time Text Condition	17	8.32	4.38	29	4.57	1.34	3.45***	1.16
Time Audio Condition	17	4.90	.33	29	4.95	.82	.21	.08
Time Text and Audio Condition	17	5.00	1.15	29	5.03	1.21	.07	.03

Note. + $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$.
Note. GNvI-R = General Nonverbal Intelligence Raw scores. GNvI-P = General Nonverbal Intelligence percentile score (controlled for age).
Note. Although we used standardized scores for the analysis of working memory, we report the sum scores here because the standardized scores by default have M = 0 and SD = 1.
Note. Birthdates of three children were unknown, hence the different N in the percentile score of general non-verbal intelligence.
Note. Due to computer failure, learning time was only recorded in part of the children.

Table 4.2
Means and Standard Deviations over Time, per Condition and Group

		Dyslexia				Typically Developing			
		Short Term		Long Term		Short Term		Long Term	
	Condition	M	SD	M	SD	M	SD	M	SD
Quantity of Learning	Text	5.65	1.65	4.96	1.82	5.79	1.42	5.03	1.55
	Audio	5.62	1.70	5.08	1.55	5.53	1.47	4.82	1.61
	Text and Audio	5.58	1.58	5.20	1.83	5.89	1.57	5.37	1.36
Quality of Learning	Text	4.27	2.01	3.62	2.12	4.37	1.68	3.74	1.66
	Audio	4.19	1.81	4.00	1.63	4.00	1.77	4.00	1.74
	Text and Audio	3.73	2.15	3.60	1.65	4.63	1.84	3.97	1.65

Note. N dyslexia = 26, N typically developing = 38.

4

Modality Effect

Retention

Analysis of the retention knowledge with verbal and visual working memory as covariates showed a significant decrease in scores over time, $F(1, 60) = 15.79$, $p < .001$, $\eta^2_p = .208$. Children could recall less information after a week compared with directly after the lessons. No significant main effects were found on condition, $F(1, 60) = .09$, $p = .765$, $\eta^2_p = .002$; group, $F(1, 60) = .001$, $p = .976$, $\eta^2_p < .001$; verbal working memory, $F(1, 60) = .07$, $p = .798$, $\eta^2_p = .001$; or visual working memory $F(1, 60) = .07$, $p = .794$, $\eta^2_p = .001$. No two- or three-way interactions were observed (p's > .10).

Transfer

Analysis of the transfer knowledge, with verbal and visual working memory as covariates, showed no significant main effects were found over time, $F(1, 60) = 2.62$, $p = .111$, $\eta^2_p = .042$, on condition; $F(1, 60) = .16$, $p = .693$, $\eta^2_p = .003$; on group, $F(1, 60) = 0.23$, $p = .634$, $\eta^2_p = .004$; on verbal working memory, $F(1, 60) = .72$, $p = .400$, $\eta^2_p = .012$; or on visual working memory $F(1, 60) = .10$, $p = .757$, $\eta^2_p = .002$. No two- or three-way interactions were observed (p's > .10).

Learning Time

4

Analysis of the amount of time children spent on learning the multimedia lessons, including verbal and visual working memory as covariates, showed a significant main effect of condition, $F(1, 42) = 13.15$, $p = .001$, $\eta^2_p = .238$. Children spent significantly more time on learning in the text condition than in the audio condition. Also, a significant main effect of group was observed, $F(1, 42) = 12.84$, $p = .001$, $\eta^2_p = .234$. Children with dyslexia spent more time learning than typically developing children did. No significant main effects were found on verbal working memory, $F(1, 42) = .54$, $p = .466$, $\eta^2_p = .013$, or visual working memory, $F(1, 42) = .09$, $p = .77$, $\eta^2_p = .002$.

A significant interaction effect between condition and group was found, $F(1, 42) = 13.68$, $p = .001$, $\eta^2_p = .246$. To interpret the interaction effect further, the analysis was performed separately for children with and without dyslexia. These analyses showed that children with dyslexia spent significantly more time in the text condition than in the audio condition, $F(1, 14) = 6.80$, $p = .021$, $\eta^2_p = .327$, pairwise comparisons $p = .006$, whereas typically developing children spent an equal amount of time in both conditions, $F(1, 26) = 1.65$, $p = .211$, $\eta^2_p = .060$, pairwise comparisons $p = .194$. No further two-way interactions were observed ($p > .05$).

Redundancy Effect

Retention

Analysis of the retention knowledge, with verbal and visual working memory as covariates, showed a significant decrease in scores over time, $F(1, 60) = 24.29$, $p < .001$, $\eta^2_p = .288$. Children could recall less information after a week compared with directly after the lessons. No significant main effects were found on the redundancy effect: text condition versus combined text-and-audio condition, $F(1, 60) = 1.13$, $p = .292$, $\eta^2_p = .019$, or audio condition versus combined text-and-audio condition, $F(1, 60) = 1.62$, $p = .208$, $\eta^2_p = .026$. Further, no significant main effects were found on group, $F(1, 60) = 0.04$, $p = .835$, $\eta^2_p = .001$; verbal working memory, $F(1, 60) = .01$, $p = .924$, $\eta^2_p < .001$; or visual working memory $F(1, 60) = .02$, $p = .889$, $\eta^2_p < .001$. No two- or three-way interactions were observed (p's > .10).

Transfer

Analysis of the transfer knowledge, with verbal and visual working memory as covariates, showed a significant decrease in scores over time, $F(1, 60) = 4.76$, $p = .033$, $\eta^2_p = .073$. Children could recall less information after a week compared with directly after the lessons. No significant main effects were found on the redundancy effect: text condition versus combined text-and-audio condition, $F(1, 60) = .03$, $p = .874$, $\eta^2_p < .001$, or audio condition versus combined text-and-audio condition, $F(1, 60) = .35$, $p = .556$, $\eta^2_p = .006$. Further, no significant main effects were found on group, $F(1, 60) = .11$, $p = .737$, $\eta^2_p = .002$; verbal working memory, $F(1, 60) = .18$, $p = .671$, $\eta^2_p = .003$; or visual working memory, $F(1, 60) = .01$, $p = .924$, $\eta^2_p < .001$.

With respect to the audio condition versus the combined text-and-audio condition, a significant interaction was found between condition and group, $F(1, 60) = 7.83$, $p = .007$, $\eta^2_p = .115$. To interpret this interaction effect further, the analysis was performed separately for children with and without dyslexia. These analyses showed that children with dyslexia performed similar in the audio and the combined text-and-audio condition, $F(1, 23) = 2.42$, $p = .133$, $\eta^2_p = .095$, while typically developing children differed in scores on the audio condition compared with the combined text-and-audio condition, $F(1, 35) = 4.24$, $p = .047$, η2 p = .108. However, pairwise comparisons of the latter group showed no significant difference between the audio condition and the combined text-and-audio condition ($p = .670$). To summarize, there seemed to be indications for differences between the audio condition and the combined text-and-audio condition in typically developing children, but deeper analysis did not show significant differences. Further, no two- or three-way interactions were observed (p's > .05).

4

Learning Time

Analysis of the amount of time children spent on learning in the multimedia lessons, including verbal and visual working memory as covariates, showed a significant main effect of condition for the text condition versus the combined text-and-audio condition, $F(1, 42) = 10.93$, $p = .002$, $\eta^2_p = .206$, but not for the audio condition versus combined text-and-audio condition, $F(1, 42) = .31$, $p = .582$, $\eta^2_p = .007$. Also, a significant main effect of group was observed, $F(1, 42) = 8.92$, $p = .005$, $\eta^2_p = .175$. No significant main effects were found on verbal working memory, $F(1, 42) = .22$, $p = .642$, $\eta^2_p = .005$, or visual working memory, $F(1, 42) = .10$, $p = .755$, $\eta^2_p = .002$.

With respect to the text condition versus the combined text-and-audio condition, a significant interaction effect between condition and group was found, $F(1, 42) = 14.15$, $p = .001$, $\eta^2_p = .252$. To interpret the interaction effect between condition and group further, the analysis was performed separately for children with and without dyslexia. These analyses showed that children with dyslexia spent significantly more time in the text condition than in the combined text-and-audio condition, $F(1, 14) = 7.40$, $p = .017$, $\eta^2_p = .346$, pairwise comparisons $p = .026$, whereas typically developing children spent significantly more time in the combined text-and-audio condition than in the text condition, $F(1, 26) = 3.14$, $p = .088$, $\eta^2_p = .108$. Pairwise comparisons of the latter group showed no significant difference between the text condition and the combined text-and-audio condition ($p = .258$). To sum, children with dyslexia spend more time in the text condition than in the combined text-and-audio condition, whereas in typically developing children, there is no difference between the conditions. Further, no two-way interactions were observed (p's > .10).

Discussion

In the present research, we aimed to find an optimal multimedia environment for children with dyslexia. Multimedia offers various opportunities to help children with dyslexia; however, it is not clear yet how it can be used in an optimal way to support both study time and knowledge gain, thus leading to efficient learning. Therefore, children with dyslexia and a control group were provided with several multimedia lessons in three conditions: pictorial information presented with (a) written text, (b) audio, or (c) combined text and audio. This way, it was examined to what extent the modality and redundancy effects had an impact on study time and knowledge gain in children with dyslexia and to what extent individual differences in children's working memory capacity were related to these effects.

Children with dyslexia showed weaker working memory capacities compared with typically developing children. With regard to study time, we found modality and reversed redundancy effects on the amount of time children with dyslexia spent in different conditions, whereas in typically developing children, study time was independent of the multimedia environment. Children with dyslexia spent more time in the text condition than in the other two conditions. Concerning knowledge gain, no modality or redundancy effects were found in children with or without dyslexia. In this user-paced learning environment, children learned as much from pictures with text, audio, or combined text and audio. Working memory did not influence the modality of redundancy effects on study time of knowledge gain.

4

With respect to study time, partly in line with our first hypothesis, we found modality and reversed redundancy effects on the amount of time children with dyslexia spent in different conditions, but not for typical readers. Children with dyslexia were expected to spend more time in lessons with written text than in lessons with audio, due to slower reading abilities. Our results showed that they spent more time in the written text condition than in the other two conditions: showing a modality effect (text takes longer than audio) and a reversed redundancy effect (text takes longer than text combined with audio). The fact that for children with dyslexia the material in which text was combined with audio did not lead to additional study time (whereas only text did) was not fully in line with our expectation. An obvious explanation could be that children with dyslexia do not really read in a learning environment with both text and audio. An eye-tracking study would be necessary to confirm this. Considering the fact that study time is relevant, it is important to note that in system-paced learning environments, study time is a stable factor because it is determined by the system and not the learner and that in research with user-paced learning environments, study time has often not been taken into account (e.g., Alty et al., 2006; Jamet & Le Bohec, 2007; Scheiter et al., 2014). In the meta-analysis of Ginns (2005), the only time condition that is indicated is the time spent on the transfer test, not study time itself. In a study by Gerjets and colleagues (2009), study time was connected to learner control and intuitive knowledge, not to the different multimedia conditions. In a study by Segers and colleagues (2008), study time was connected to media conditions with no differential effects. However, previous research concerned typically developing children, and not children with dyslexia who read slower. Our results show that study time is an important factor to consider when examining multimedia learning in children with dyslexia. The study time of these children can be reduced, by providing them with audio-support.

Concerning knowledge gain, in contrast to the expectations based on the CTML, no differences were found between children with and without dyslexia with respect to modality or redundancy effects. On the basis of CTML, stronger effects would be expected in children with dyslexia, and these differences were expected to be grounded in more difficulties in reading the text and differences in a poorer working memory. Indeed, the children with dyslexia showed weaker working memory capacities, on both the verbal and visual aspects of working memory. However, these differences did not lead to differences in modality or redundancy effects. These results are in line with our alternative hypothesis and research by Mann and colleagues, who did not replicate the modality effect in primary school children. They hypothesized that this was due to the not yet fully developed working memory system in children. Children of 11 years old indeed have a not yet fully developed working memory system, which continues to develop into young adulthood (Gathercole et al., 2004). However, if this argumentation would hold, then we still would have seen differences between children with and without dyslexia due to differences in working memory.

Our results follow the argumentation of Tabbers and colleagues (2001) that the modality effect does not lie in more efficient use of memory resources. They argued that in system-paced learning environments, people do not have enough time to relate text and pictorial information, whereas they can listen to a text and look at pictures at the same time. So, in a user-paced system, where one is in charge of one's own time management, a person can create enough time to switch between text and pictures to optimize his or her learning process. The explanation of the modality and redundancy effects would then be less likely to lie in a working memory overload, but more likely to be a result of a more efficient learning strategy: looking at a picture and listening at the same time to the complementary information (Tabbers et al., 2001). The scattered and scarce research on multimedia learning in children with dyslexia shows no consistent image of this specific group. In adults with dyslexia, Beacham and Alty (2006) showed that optimal conditions for typically developing students are not automatically also optimal conditions for students with dyslexia. However, we did not find differences between the two groups on the modality and redundancy effects on knowledge gain. An explanation could be a variation in learning strategies of children with dyslexia versus controls. Indeed, Kirby and colleagues (2008) showed that university students with dyslexia use more time management strategies and more often reported a deep approach to learning than students without dyslexia. These differences can be interpreted as a compensation strategy for the reading difficulties that the students with dyslexia experience, which in turn may drive the lack of differences in the modality and redundancy effects on knowledge gain.

The arguments with regard to working memory also apply to the final hypothesis, as in all children, it was expected that poorer working memory would lead to larger modality and redundancy effects. In contrast to our expectation, we did not find individual differences in working memory that would explain modality or redundancy effects in study time of knowledge gain. This is in line with Witteman and Segers (2010) who also did not find a relation between working memory and the size of the modality effect. Given the theoretical importance of the working memory, this null effect is quite remarkable. Children with poorer working memory were able to more optimally use their working memory in a user-paced learning environment. Indeed, Ginns (2005) and Tabbers and colleagues (2004) state that auditory and visual information processing had no impact on learning when children can determine their own pace, which may result in a better integration of audio and visual information. Our study adds to the discussion that individual differences in working memory capacity do not guide differences in multimedia learning in a user-paced learning environment. A study on the association between working memory and the size of the modality effect in a systempaced environment would shed more light on this matter.

Based on our results, we can state that study time is an important factor when considering multimedia learning in children with dyslexia. With similar knowledge gain but different study times in the text condition, children with dyslexia need more time to come to an equal amount of knowledge. Study time and knowledge gain were not related: Children with dyslexia simply needed more time to read the whole lesson. Providing them with more study time gave children with dyslexia the opportunity to record all the information. Because children learn as much in both conditions (no redundancy effect on knowledge gain), the combined condition allows children to actively learn in a text condition, without spending too much time purely on reading. Thus, to optimize learning, it is more efficient to provide children with dyslexia with extra audio.

Future research could add to understanding this difference in study time between the text and combined conditions, by using eye tracking to check whether children do read in the combined condition and, if so, whether this reading along is different from reading only in the text condition. In a similar vein, future research could also examine the role of working memory during learning. Beacham and Alty (2006) argued that the difference between children with and without dyslexia on multimedia learning might lie in the development of compensating strategies in children with dyslexia to compensate for their reading difficulties. Eye tracking would provide the opportunity to examine their possible differences in learning strategies during the lessons. It could also shed light on the cognitive load during multimedia learning, for example, by examining children's cognitive load by pupil dilation. Eye tracking would thus provide information about the learning process. Whereas working memory may explain differences in outcome measures between children in a system-paced environment, in user-paced environments, it could be expected that working memory explains differences in process measures, which can be taken into account in future research.

The need for evidence-based knowledge on multimedia learning in children with dyslexia is urgent. Practitioners need information on how to implement multimedia in an optimal way to support children. We can conclude that in a user-paced multimedia learning environment, it is more efficient to provide information in an auditory way or with auditory support to children with dyslexia, but not necessary for typical readers.

References

Alty, J. L., Al-Sharrah, A., & Beacham, N. (2006). When humans form media and media form humans: An experimental study examining the effects different digital media have on the learning outcomes of students who have different learning styles. *Interacting With Computers, 18*(5), 891–909. https://doi.org/10.1016/j.intcom.2006.04.002

Baddeley, A. (1995). *Working memory.* Oxford Psychology Series No. 11. Oxford: Clarendon Press.

Baddeley, A. (2003). Working memory and language: An overview. *Journal of Communication Disorders, 36*(3), 189–208. https://doi.org/10.1016/S0021-9924(03)00019-4

Beacham, N. A., & Alty, J. L. (2006). An investigation into the effects that digital media can have on the learning outcomes of individuals who have dyslexia. *Computers & Education, 47*(1), 74–93. https://doi.org/10.1016/j.compedu.2004.10.006

Beneventi, H., Tønnessen, F. E., Ersland, L., & Hugdahl, K. (2010). Executive working memory processes in dyslexia: Behavioral and fMRI evidence. *Scandinavian Journal of Psychology, 51*, 192–202. https://doi.org/10.1111/j.1467-9450.2010.00808.x

Berninger, V. W., Raskind, W., Richards, T., Abbott, R., & Stock, P. (2008). A multidisciplinary approach to understanding developmental dyslexia within workingmemory architecture: Genotypes, phenotypes, brain, and instruction. *Developmental Neuropsychology, 33*(6), 707–744. https://doi.org/10.1080/87565640802418662

Blomert, L. P. M. (2006). *Protocol voor Dyslexie Diagnostiek en Behandeling en Eindrapport: Onderzoek en Verantwoording.*

Carney, R. N., & Levin, J. R. (2002). Pictorial illustrations still improve students' learning from text. *Educational Psychology Review, 14*(1), 5–26. https://doi.org/10.1023/A:1013176309260

Diao, Y., & Sweller, J. (2007). Redundancy in foreign language reading comprehension instruction: Concurrent written and spoken presentations. *Learning and Instruction, 17*(1), 78–88. https://doi.org/10.1016/j.learninstruc.2006.11.007

Elliott, P., & Hawthorne, G. (2005). Imputing missing repeated measures data: how should we proceed?. *Australian and New Zealand Journal of Psychiatry, 39*(7), 575–582. https://doi.org/10.1080/j.1440-1614.2005.01629.x

Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. *Developmental Psychology, 40*(2), 177. https://doi.org/10.1037/0012-1649.40.2.177

Gerjets, P., Scheiter, K., Opfermann, M., Hesse, F. W., & Eysink, T. H. (2009). Learning with hypermedia: The influence of representational formats and different levels of learner control on performance and learning behavior. *Computers in Human Behavior, 25*(2), 360–370. https://doi.org/10.1016/j.chb.2008.12.015

Gevins, A., & Cutillo, B. (1993). Spatiotemporal dynamics of component processes in human working memory. *Electroencephalography and Clinical Neurophysiology, 87*(3), 128–143. https://doi.org/10.1016/0013-4694(93)90119-G

Ginns, P. (2005). Meta-analysis of the modality effect. *Learning and Instruction, 15*(4), 313–331. https://doi.org/10.1016/j.learninstruc.2005.07.001

Harrar, V., Tammam, J., Perez-Bellido, A., Pitt, A., Stein, J., & Spence, C. (2014). Multisensory integration and attention in developmental dyslexia. *Current Biology, 24*(5), 531–535. https://doi.org/10.1016/j.cub.2014.01.029

Jaeggi, S. M., Buschkuehl, M., Perrig, W. J., & Meier, B. (2010). The concurrent validity of the N-back task as a working memory measure. *Memory, 18*(4), 394–412. https://doi.org/10.1080/09658211003702171

Jamet, E., & Le Bohec, O. (2007). The effect of redundant text in multimedia instruction. *Contemporary Educational Psychology, 32*(4), 588–598. https://doi.org/10.1016/j.cedpsych.2006.07.001

Jeffries, S., & Everatt, J. (2004). Working memory: Its role in dyslexia and other specific learning difficulties. *Dyslexia, 10*(3), 196–214. https://doi.org/10.1002/dys.278

Kalyuga, S., Chandler, P., & Sweller, J. (1999). Managing split-attention and redundancy in multimedia instruction. *Applied Cognitive Psychology, 13*(4), 351–371. https://doi.org/10.1002/(SICI)1099-0720(199908)13:4<351::AID-ACP589>3.0.CO;2-6

Kim, S., Lombardino, L. J., Cowles, W., & Altmann, L. J. (2014). Investigating graph comprehension in students with dyslexia: An eye tracking study. *Research in Developmental Disabilities, 35*(7), 1609–1622. https://doi.org/10.1016/j.ridd.2014.03.043

Kirby, J. R., Silvestri, R., Allingham, B. H., Parrila, R., & La Fave, C. B. (2008). Learning strategies and study approaches of postsecondary students with dyslexia. *Journal of Learning Disabilities, 41*(1), 85–96. https://doi.org/10.1177/0022219407311040

Lallier, M., Donnadieu, S., & Valdois, S. (2013). Developmental dyslexia: Exploring how much phonological and visual attention span disorders are linked to simultaneous auditory processing deficits. *Annals of Dyslexia, 63*(2), 97–116. https://doi.org/10.1007/s11881-012-0074-4

Lyon, G. R., Shaywitz, S. E., & Shaywitz, B. A. (2003). A definition of dyslexia. *Annals of Dyslexia, 53*(1), 1–14. https://doi.org/10.1007/s11881-003-0001-9

Magnan, A., & Ecalle, J. (2006). Audio-visual training in children with reading disabilities. *Computers & Education, 46*(4), 407–425. https://doi.org/10.1016/j.compedu.2004.08.008

Mayer, R. E. (2005). *The Cambridge Handbook of Multimedia Learning*. Cambridge University Press. https://doi.org/10.1017/CBO9780511816819

Mayer, R. E., Heiser, J., & Lonn, S. (2001). Cognitive constraints on multimedia learning: When presenting more material results in less understanding. *Journal of Educational Psychology, 93*(1), 187. https://doi.org/10.1037/0022-0663.93.1.187

Mayer, R. E., & Johnson, C. I. (2008). Revising the redundancy principle in multimedia learning. *Journal of Educational Psychology, 100*(2), 380. https://doi.org/10.1037/0022-0663.100.2.380

Mayer, R. E., & Moreno, R. (2002). Aids to computer-based multimedia learning. *Learning and Instruction, 12*(1), 107–119. https://doi.org/10.1016/S0959-4752(01)00018-4

Menghini, D., Finzi, A., Carlesimo, G. A., & Vicari, S. (2011). Working memory impairment in children with developmental dyslexia: Is it just a phonological deficity? *Developmental Neuropsychology, 36*(2), 199–213. https://doi.org/10.1080/87565641.2010.549868

Moreno, R., & Mayer, R. E. (2002). Learning science in virtual reality multimedia environments: Role of methods and media. *Journal of Educational Psychology, 94*(3), 598–610. https://doi.org/10.1037/0022-0663.94.3.598

Nelson, J. R., Balass, M., & Perfetti, C. A. (2005). Differences between written and spoken input in learning new words. *Written Language & Literacy, 8*(2), 25–44. https://doi.org/10.1075/wll.8.2.04nel

Pickering, S. J. (2012). *Working memory in dyslexia.* In T. P. Alloway, & S. E. Gathercole (Eds.), Working memory and neurodevelopmental disorders (pp. 161–186). New York, NY: Psychology Press.

Reiter, A., Tucha, O., & Lange, K. W. (2005). Executive functions in children with dyslexia. *Dyslexia, 11*(2), 116–131. https://doi.org/10.1002/dys.289

Ruf, A. P., Seckler, M., & Opwis, K. (2014). Long-term modality effect in multimedia learning. *Proceedings of the 8th Nordic Conference on Human–Computer Interaction: Fun, Fast, Foundational*, 963-966. https://doi.org/10.1145/2639189.2670251

Savoji, A. P., Hassanabadi, H., & Fasihipour, Z. (2011). The modality effect in learner-paced multimedia learning. *Procedia-Social and Behavioral Sciences, 30*, 1488–1493. https://doi.org/10.1016/j.sbspro.2011.10.288

Scheiter, K., Schuler, A., Gerjets, P., Huk, T., & Hesse, F. W. (2014). Extending multimedia research: How do prerequisite knowledge and reading comprehension affect learning from text and pictures. *Computers in Human Behavior, 31*, 73–84. https://doi.org/10.1016/j.chb.2013.09.022

Schuchardt, K., Maehler, C., & Hasselhorn, M. (2008). Working memory deficits in children with specific learning disorders. *Journal of Learning Disabilities, 41*(6), 514–523. https://doi.org/10.1177/0022219408317856

Segers, E., Verhoeven, L., & Hulstijn-Hendrikse, N. (2008). Cognitive processes in children's multimedia text learning. *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition, 22*(3), 375–387. https://doi.org/10.1002/acp.1413

Shaywitz, S. E., & Shaywitz, B. A. (2001). The neurobiology of reading and dyslexia. *Focus on Basics, 5*, 11–15.

She, H. C., & Chen, Y. Z. (2009). The impact of multimedia effect on science learning: Evidence from eye movements. *Computers & Education, 53*(4), 1297–1307. https://doi.org/10.1016/j.compedu.2009.06.012

Singh, A. M., Marcus, N., & Ayres, P. (2012). The transient information effect: Investigating the impact of segmentation on spoken and written text. *Applied Cognitive Psychology, 26*(6), 848–853. https://doi.org/10.1002/acp.2885

Schmidt-Weigand, F., Kohnert, A., & Glowalla, U. (2010). A closer look at split visual attention in system-and self-paced instruction in multimedia learning. *Learning and Instruction, 20*(2), 100–110. https://doi.org/10.1016/j.learninstruc.2009.02.011

Smith-Spark, J. H., & Fisk, J. E. (2007). Working memory functioning in developmental dyslexia. *Memory, 15*, 34–56. https://doi.org/10.1080/09658210601043384

Swanson, H. L., Zheng, X., & Jerman, O. (2009). Working memory, short-term memory, and reading disabilities: A selective meta-analysis of the literature. *Journal of Learning Disabilities, 42*(3), 260–287. https://doi.org/10.1177/0022219409331958

Tabbers, H. K. (2002). *The modality of text in multimedia instructions: Refining the design guidelines* [Doctoral dissertation, Open Universiteit]. Open Universiteit.
Tabbers, H. K., Martens, R. L., & Van Merrienboer, J. J. G. (2004). Multimedia instructions and cognitive load theory: Effects of modality and cueing. *The British Journal of Educational Psychology*, *74*(1), 71–81. https://doi.org/10.1348/000709904322848824
Tabbers, H. K., Martens, R. L., & Van Merriënboer, J. J. G. (2001). The modality effect in multimedia instructions. In J. D. Moore, & K. Stenning (Eds.), *Proceedings of the twenty-third annual conference of the Cognitive Science Society* (pp. 1024–1029).
Mahwah, NJ: Erlbaum. Tijms, J. (2004). Verbal memory and phonological processing in dyslexia. *Journal of Research in Reading*, *27*, 300–310. https://doi.org/10.1111/j.1467-9817.2004.00233.x
Underwood, J. (2000). A comparison of two types of computer support for reading development. *Journal of Research in Reading*, *23*(2), 136–148. https://doi.org/10.1111/1467-9817.00110
Van den Broek, G. S. E., Segers, E., & Verhoeven, L. (2014). Effects of text modality in multimedia presentations on written and oral performance. *Journal of Computer Assisted Learning*, *30*, 438–440. https://doi.org/10.1111/jcal.12058
Van Hoof, K., Siemensma, F., Smit, J., & Vegh, G. (2009). Wijzer door Natuur & Techniek. Houten: Noordhoff Uitgevers.
Verhoeven, L. (1995). *Drie-Minuten-Toets*. Arnhem: Cito.
Wechsler, D. (1992). *Wechsler intelligence scale for children* (3rd edition). The Psychological Corporation.
Witteman, M. J., & Segers, E. (2010). The modality effect tested in children in a user-paced multimedia environment. *Journal of Computer Assisted Learning*, *26*(2), 132–142. https://doi.org/10.1111/j.1365-2729.2009.00335.x

CHAPTER 5

MULTIMEDIA LEARNING AND EXECUTIVE FUNCTIONS IN CHILDREN WITH DYSLEXIA

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 this 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, irrespective of children's executive functions, adding audio-support for all children, can potentially lead to more efficient learning.

This chapter is based on Knoop-van Campen, C. A.N., Segers, E., & Verhoeven, L. (2019). Modality and redundancy effects, and their relation to executive functioning in children with dyslexia. Research in Developmental Disabilities, 90, 41-50.

Introduction

Children with dyslexia have a phonological deficit and experience reading difficulties (Lyon et al., 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 et al., 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 et al., 2011) and may 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 et al., 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.

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 et al., 2011; Scheiter et al., 2014; Segers et al., 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 shown in two ways: 1) comparing audio to written-text-with-audio, or 2) comparing text 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 et al., 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 and colleagues (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.

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 et al., 2008). A study that compared university students with high and low working memory capacity on the redundancy effect (Seufert et al., 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 impact 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 et al., 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 and colleagues (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 and colleagues (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 increased 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.

Multimedia Learning in Children With Dyslexia

Children and students with dyslexia often use multimedia in the form of reading software (Ghesquière et al., 2010) and/or text-to-speech software (Draffan et al., 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 et al., 2008; Swanson et al., 2009) and also inhibition is generally assumed to be hampered (Reiter et al., 2005; Wang et al., 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 et al., 2015), while others did not find differences between children with and without dyslexia (Reiter et al., 2005; Van der Sluis et al., 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 et al., 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 and colleagues (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 et al., 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. We thus concluded to have found 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 (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 into 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.

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 influence 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).

Method

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 non-verbal 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 scores 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.

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 post-tests were offered in a randomized-block-design. Tests were performed on executive functioning.

Measures

General Non-verbal Intelligence

The Raven's Progressive Matrices General was used to measure non-verbal 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.

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.

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.

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 et al., 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.

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).

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.

Multimedia Lessons

All children made three multimedia lessons (balance in nature, motion, and global warmth) in different types of user-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.

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 alphas of the transfer knowledge were >.80, indicating good reliability.

Study Time

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

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.

Results

Descriptives

The means and standard deviations for executive functions and study time, separately for children with and without dyslexia, are provided in Table 5.1. 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 5.2.

Table 5.1
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 5.2
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 5.3
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

Note. * $p < .05$ ** $p < .01$
Note. Vis-wm = visual working memory, Ver-wm = verbal working memory, Inh = inhibition, Cogf = cognitive flexibility

5

Modality Effect

Retention

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

Transfer

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

Study Time

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

5

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.

Redundancy Effect

Retention

Analysis of the retention knowledge showed a significant main effect of time, $F(1, 38) = 159.70$, $p < .001$, $\eta^2_p = .808$. 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, $F(1, 38) = .42$, $p = .523$, $\eta^2_p = .011$, or audio vs. combined condition, $F(1, 38) = .02$, $p = .881$, $\eta^2_p = .001$. Further, there were no main effects on group, $F(1, 38) = .50$, $p = .484$, $\eta^2_p = .013$, and no interactions (p's > .10).

Transfer

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

There was a significant interaction between condition (audio vs. the combined condition) and group, $F(1, 38) = 5.54$, $p = .024$, $\eta^2_p = .127$. 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, $F(1, 38) = .93$, $p = .341$, $\eta^2_p = .024$, but did show a significant difference between the groups in the combined condition, $F(1, 38) = 4.52$, $p = .040$, $\eta^2_p = .106$. 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 $> .10$).

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, $F(1, 36) = 4.62$, $p = .038$, $\eta^2_p = .114$, but not for the audio condition vs. combined condition, $F(1, 36) = .02$, $p = .884$, $\eta^2_p = .001$. 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, $F(1, 36) = 1.45$, $p = .237$, $\eta^2_p = .0$, and no interactions (p's $> .10$).

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, $F(1, 32) = 4.10$, $p = .051$, $\eta^2_p = .113$, instead of significant. This is probably due to the smaller number of degrees of freedom: when adding the covariates separately, in pairs, or groups of three the effect remained significant.

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-audio than students with dyslexia did. With regard to study time, modality and reversed redundancy effects were found 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.

5

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 in line with previous studies in children (Savoji et al., 2011; Tabbers et al., 2004; She & Chen, 2009), and replicates the finding of Knoop-van Campen and colleagues (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 and colleagues (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-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 et al., 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.

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 taking a break.

Another explanation is that in primary school children, executive functions are still in a state of flux (Davidson et al., 2006). Diamond (2006) even argues that although the development of cognitive flexibility starts early, it continues for almost twenty years. While Seufert and colleagues (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 were 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.

Limitations and Future Research

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, but 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 et al., 2013), and including process measures could shed light on differences in children's' learning behavior.

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 weighed 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 and colleagues (2007) argued that a powerful learning environment is multi-modal. 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.

Conclusions

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 weighed 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.

References

Ainsworth, S. (1999). The functions of multiple representations. *Computers & education*, *33*(2-3), 131-152. https://doi.org/10.1016/S0360-1315(99)00029-9

Alty, J. L., Al-Sharrah, A., & Beacham, N. (2006). When humans form media and media form humans: An experimental study examining the effects different digital media have on the learning outcomes of students who have different learning styles. *Interacting With Computers*, *18*(5), 891–909. https://doi.org/10.1016/j.intcom.2006.04.002

Baddeley, A. (2003). Working memory and language: An overview. *Journal of Communication Disorders*, *36*(3), 189–208. https://doi.org/10.1016/S0021-9924(03)00019-4

Bellocchi, S., Muneaux, M., Bastien-Toniazzo, M., & Ducrot, S. (2013). I can read it in your eyes: What eye movements tell us about visuo-attentional processes in developmental dyslexia. *Research in Developmental Disabilities*, *34*(1), 452–460. https://doi.org/10.1016/j.ridd.2012.09.002

Berninger, V. W., Raskind, W., Richards, T., Abbott, R., & Stock, P. (2008). A multidisciplinary approach to understanding developmental dyslexia within workingmemory architecture: Genotypes, phenotypes, brain, and instruction. *Developmental Neuropsychology*, *33*(6), 707–744. https://doi.org/10.1080/87565640802418662

Best, J. R., Miller, P. H., & Naglieri, J. A. (2011). Relations between executive function and academic achievement from ages 5 to 17 in a large, representative national sample. *Learning and Individual Differences*, *21*(4), 327–336. https://doi.org/10.1016/j.lindif.2011.01.007

Blomert, L. (2005). *Dyslexie in Nederland*. Uitgeverij Nieuwezijds.

Booth, J. N., Boyle, J. M., & Kelly, S. W. (2010). Do tasks make a difference? Accounting for heterogeneity of performance of children with reading difficulties on tasks of executive function: Findings from a meta-analysis. *The British Journal of Developmental Psychology*, *28*(1), 133–176. https://doi.org/10.1348/026151009X485432

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia*, *44*(11), 2037–2078. https://doi.org/10.1016/j.neuropsychologia.2006.02.006

Diamond, A. (2006). The Early Development of Executive Functions. In E. Bialystok & F. I. M. Craik (Eds.), *Lifespan cognition: Mechanisms of change* (pp. 70–95). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195169539.003.0006

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Diao, Y., & Sweller, J. (2007). Redundancy in foreign language reading comprehension instruction: Concurrent written and spoken presentations. *Learning and Instruction*, *17*(1), 78–88. https://doi.org/10.1016/j.learninstruc.2006.11.007

Draffan, E. A. (2002). Dyslexia and technology. In L. Phillipa, A. Sutherland, & J. Seale (Eds.), *Access all areas: disability, technology and learning* (pp. 24-48). JISC TechDis.

Gerjets, P., Scheiter, K., Opfermann, M., Hesse, F. W., & Eysink, T. H. (2009). Learning with hypermedia: The influence of representational formats and different levels of learner control on performance and learning behavior. *Computers in Human Behavior*, *25*(2), 360–370. https://doi.org/10.1016/j.chb.2008.12.015

Gevins, A., & Cutillo, B. (1993). Spatiotemporal dynamics of component processes in human working memory. *Electroencephalography and Clinical Neurophysiology*, *87*(3), 128–143. https://doi.org/10.1016/0013-4694(93)90119-G

Ghesquière, P., Boets, B., Gadeyne, E., & Vandewalle, E. (2011). Dyslexie: een beknopt wetenschappelijk overzicht. In A. Geudens, D. Baeyens, K. Schraeyen, K. Maetens, J. De Brauwer, & M. Loncke (Eds.), *Jongvolwassenen met dyslexie: diagnostiek en begeleiding in wetenschap en praktijk* (pp. 41-58). Acco Uitgeverij.

Ginns, P. (2005). Meta-analysis of the modality effect. *Learning and Instruction*, *15*(4), 313–331. https://doi.org/10.1016/j.learninstruc.2005.07.001

Gyselinck, V., Jamet, E., & Dubois, V. (2008). The role of working memory components in multimedia comprehension. *Applied Cognitive Psychology*, *22*(3), 353–374. https://doi.org/10.1002/acp.1411

Harrar, V., Tammam, J., Perez-Bellido, A., Pitt, A., Stein, J., & Spence, C. (2014). Multisensory integration and attention in developmental dyslexia. *Current Biology*, *24*(5), 531–535. https://doi.org/10.1016/j.cub.2014.01.029

Helland, T., & Asbjornsen, A. (2000). Executive functions in dyslexia. *Child Neuropsychology*, *6*(1), 37–48. https://doi.org/10.1076/0929-7049(200003)6:1;1-B;FT037

5

Jaeggi, S. M., Buschkuehl, M., Perrig, W. J., & Meier, B. (2010). The concurrent validity of the N-back task as a working memory measure. *Memory, 18*(4), 394–412. https://doi.org/10.1080/09658211003702171

Jamet, E., & Le Bohec, O. (2007). The effect of redundant text in multimedia instruction. *Contemporary Educational Psychology, 32*(4), 588–598. https://doi.org/10.1016/j.cedpsych.2006.07.001

Kalyuga, S. (2000). When using sound with a text or picture is not beneficial for learning. *Australian Journal of Educational Technology, 16*(2), 161–172. https://doi.org/10.14742/ajet.1829

Kalyuga, S. (2007). Enhancing instructional efficiency of interactive e-learning environments: A cognitive load perspective. *Educational Psychology Review, 19*(3), 387–399. https://doi.org/10.1007/s10648-007-9051-6

Kalyuga, S., Chandler, P., & Sweller, J. (1999). Managing split-attention and redundancy in multimedia instruction. *Applied Cognitive Psychology, 13*(4), 351–371. https://doi.org/10.1002/(SICI)1099-0720(199908)13:4<351::AID-ACP589>3.0.CO;2-6

Kester, L., Kirschner, P., & Corbalan, G. (2007). Designing support to facilitate learning in powerful electronic learning environments. *Computers in Human Behavior, 23*(3), 1047–1054. https://doi.org/10.1016/j.chb.2006.10.001

Kieffer, M. J., Vukovic, R. K., & Berry, D. (2013). Roles of attention shifting and inhibitory control in fourth-grade reading comprehension. *Reading Research Quarterly, 48*(4), 333–348. https://doi.org/10.1002/rrq.54

Knoop-van Campen, C. A. N., Segers, E., & Verhoeven, L. (2018). The modality and redundancy effects in multimedia learning in children with dyslexia. *Dyslexia, 24*(2), 140–155. https://doi.org/10.1002/dys.1585

Koehler, M. J., & Mishra, P. (2005). Teachers learning technology by design. *Journal of Computing in Teacher Education, 21*(3), 94–102.

Lallier, M., Donnadieu, S., & Valdois, S. (2013). Developmental dyslexia: Exploring how much phonological and visual attention span disorders are linked to simultaneous auditory processing deficits. *Annals of Dyslexia, 63*(2), 97–116. https://doi.org/10.1007/s11881-012-0074-4

Liu, H. C., Lai, M. L., & Chuang, H. H. (2011). Using eye-tracking technology to investigate the redundant effect of multimedia web pages on viewers' cognitive processes. *Computers in Human Behavior, 27*(6), 2410–2417. https://doi.org/10.1016/j.chb.2011.06.012

Lyon, G. R., Shaywitz, S. E., & Shaywitz, B. A. (2003). A definition of dyslexia. *Annals of Dyslexia, 53*(1), 1–14. https://doi.org/10.1007/s11881-003-0001-9

Mayer, R. E. (2005). *The Cambridge Handbook of Multimedia Learning*. Cambridge University Press. https://doi.org/10.1017/CBO9780511816819

Mayer, R. E., & Fiorella, L. (2014). 12 principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles. In R. E. Mayer (Ed.),*The Cambridge handbook of multimedia learning* (Vol. 279, pp. 279-315). Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.015

Mayer, R. E., & Moreno, R. (2002). Aids to computer-based multimedia learning. *Learning and Instruction, 12*(1), 107–119. https://doi.org/10.1016/S0959-4752(01)00018-4

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Moreno, R., & Mayer, R. E. (2002). Learning science in virtual reality multimedia environments: Role of methods and media. *Journal of Educational Psychology, 94*(3), 598–610. https://doi.org/10.1037/0022-0663.94.3.598

Moura, O., Simoes, M. R., & Pereira, M. (2015). Executive functioning in children with developmental dyslexia. *The Clinical Neuropsychologist, 28*(s1), 20–41. https://doi.org/10.1080/13854046.2014.964326

Raven, J. C. (1998). *Raven's progressive matrices.* Oxford Psychologists Press.

Reitan, R. M., & Wolfson, D. (1985). *The Halstead–Reitan neuropsycholgical test battery: Therapy and clinical interpretation*. Neuropsychological Press.

Reiter, A., Tucha, O., & Lange, K. W. (2005). Executive functions in children with dyslexia. *Dyslexia, 11*(2), 116–131. https://doi.org/10.1002/dys.289

Riener, C., & Willingham, D. (2010). The myth of learning styles. *Change the Magazine of Higher Learning, 42*(5), 32–35. https://doi.org/10.1080/00091383.2010.503139

Savoji, A. P., Hassanabadi, H., & Fasihipour, Z. (2011). The modality effect in learner-paced multimedia learning. *Procedia-Social and Behavioral Sciences, 30*, 1488–1493. https://doi.org/10.1016/j.sbspro.2011.10.288

Segers, E., Verhoeven, L., & Hulstijn-Hendrikse, N. (2008). Cognitive processes in children's multimedia text learning. *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition*, *22*(3), 375–387. https://doi.org/10.1002/acp.1413

Scheiter, K., Schuler, A., Gerjets, P., Huk, T., & Hesse, F. W. (2014). Extending multimedia research: How do prerequisite knowledge and reading comprehension affect learning from text and pictures. *Computers in Human Behavior, 31*, 73–84. https://doi.org/10.1016/j.chb.2013.09.022

Schmidt-Weigand, F., Kohnert, A., & Glowalla, U. (2010). A closer look at split visual attention in system-and self-paced instruction in multimedia learning. *Learning and Instruction*, *20*(2), 100–110. https://doi.org/10.1016/j.learninstruc.2009.02.011

Seufert, T., Schutze, M., & Brunken, R. (2009). Memory characteristics and modality in multimedia learning: An aptitude–treatment–interaction study. *Learning and Instruction*, *19*(1), 28–42. https://doi.org/10.1016/j.learninstruc.2008.01.002

She, H. C., & Chen, Y. Z. (2009). The impact of multimedia effect on science learning: Evidence from eye movements. *Computers & Education*, *53*(4), 1297–1307. https://doi.org/10.1016/j.compedu.2009.06.012

Smith, S. M., & Woody, P. C. (2000). Interactive effect of multimedia instruction and learning styles. *Teaching of Psychology*, *27*(3), 220–223. https://doi.org/10.1207/S15328023TOP2703_10

St Clair-Thompson, H. L., & Gathercole, S. E. (2006). Executive functions and achievements in school: Shifting, updating, inhibition, and working memory. *The Quarterly Journal of Experimental Psychology*, *59*(4), 745–759. https://doi.org/10.1080/17470210500162854

Swanson, H. L., Zheng, X., & Jerman, O. (2009). Working memory, short-term memory, and reading disabilities: A selective meta-analysis of the literature. *Journal of Learning Disabilities*, *42*(3), 260–287. https://doi.org/10.1177/0022219409331958

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, *12*(2), 257–285. https://doi.org/10.1207/s15516709cog1202_4

Tabbers, H. K. (2002). *The modality of text in multimedia instructions: Refining the design guidelines* [Doctoral dissertation, Open Universiteit]. Open Universiteit.

Tabbers, H. K., Martens, R. L., & Van Merrienboer, J. J. G. (2004). Multimedia instructions and cognitive load theory: Effects of modality and cueing. *The British Journal of Educational Psychology*, *74*(1), 71–81. https://doi.org/10.1348/000709904322848824

Terras, M. M., & Ramsay, J. (2012). The five central psychological challenges facing effective mobile learning. *British Journal of Educational Technology*, *43*(5), 820–832. https://doi.org/10.1111/j.1467-8535.2012.01362.x

Unsworth, N., & Engle, R. W. (2007). The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory. *Psychological Review*, *114*(1), 104–132. https://doi.org/10.1037/0033-295X.114.1.104

Van der Sluis, S., De Jong, P. F., & Van der Leij, A. (2004). Inhibition and shifting in children with learning deficits in arithmetic and reading. *Journal of Experimental Child Psychology*, *87*(3), 239–266. https://doi.org/10.1016/j.jecp.2003.12.002

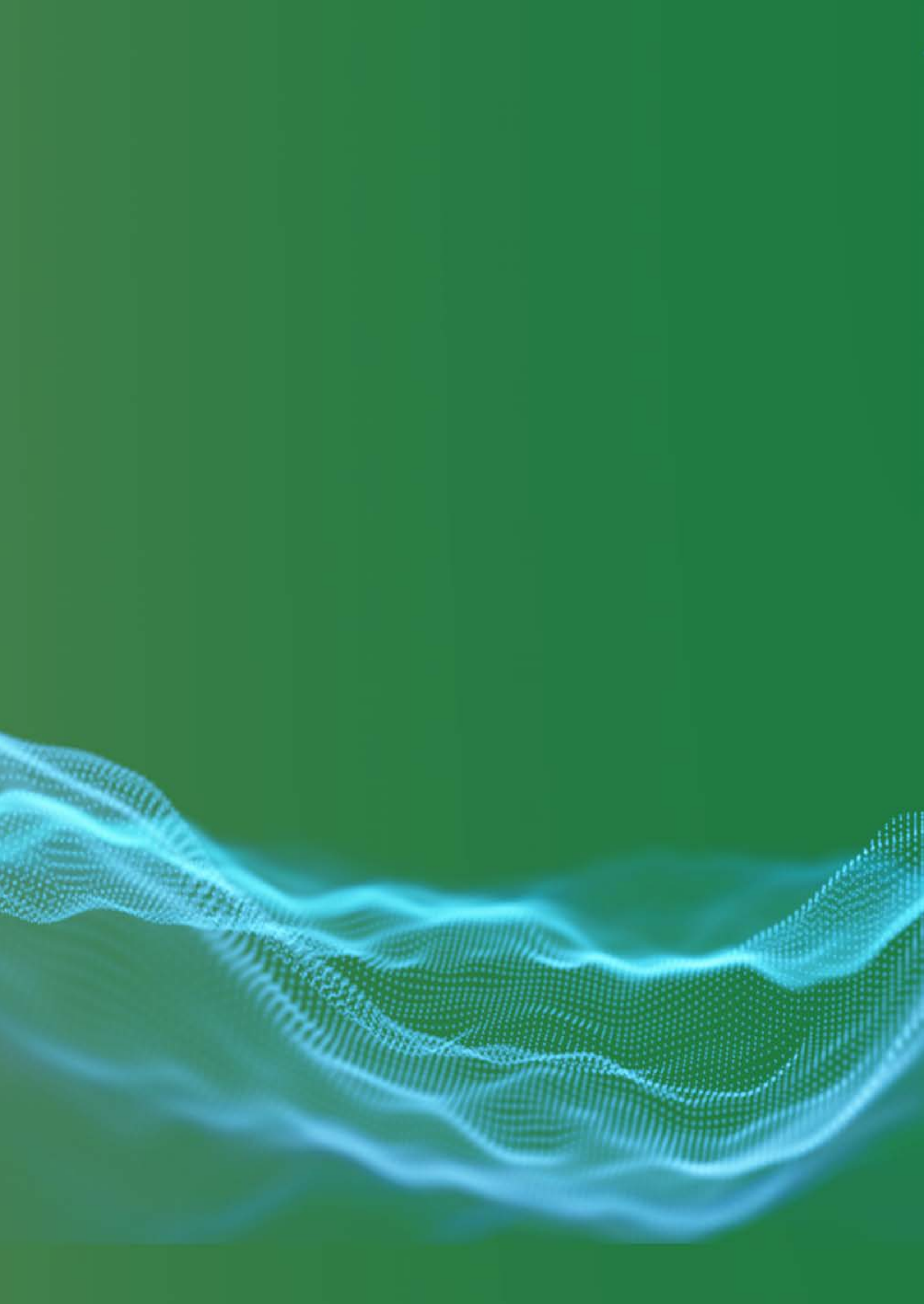
Verhoeven, L. (1995). *Een-Minuten-Toets*. Cito: Arnhem.

Wang, J., Dawson, K., Saunders, K., Ritzhaupt, A. D., Antonenko, P. P., Lombardino, L., ... Davis, R. O. (2018). Investigating the effects of modality and multimedia on the learning performance of college students with dyslexia. *Journal of Special Education Technology*, 1–12. https://doi.org/10.1177/0162643418754530

Wang, L. C., Tasi, H. J., & Yang, H. M. (2012). Cognitive inhibition in students with and without dyslexia and dyscalculia. *Research in Developmental Disabilities*, *33*(5), 1453–1461. https://doi.org/10.1016/j.ridd.2012.03.019

Wechsler, D. (1992). *Wechsler intelligence scale for children* (3rd edition). The Psychological Corporation.

Witteman, M. J., & Segers, E. (2010). The modality effect tested in children in a user-paced multimedia environment. *Journal of Computer Assisted Learning*, *26*(2), 132–142. https://doi.org/10.1111/j.1365-2729.2009.00335.x



CHAPTER 6

MODERATORS OF THE VERBAL REDUNDANCY EFFECT

Abstract

This study examined time of testing, pacing, and verbal and visual working memory as possible moderators of the verbal redundancy effect. This was done by examining self-reported cognitive load and retention and transfer knowledge directly after learning and one week later in different conditions. In a within-between-subject design, university students received two multimedia lessons with written text with and without audio either user-paced (N = 41) or system-paced (N = 56). Results on perceived cognitive load showed no verbal redundancy effects, but extraneous load was higher and germane load was lower in system-paced environments than in user-paced environments. Students with lower verbal working memory experienced higher cognitive load when audio-support was added. Regarding retention knowledge, there was a verbal redundancy effect on the long-term, while in transfer knowledge there was a verbal redundancy effect on the short-term. To conclude, overall, students profit most from a multimedia condition with pictures that does not include both audio and written text. However, especially time of testing seems to be a moderator of the verbal redundancy effect differing in retention and transfer knowledge.

This chapter is based on Knoop-van Campen, C. A. N., Segers, E, & Verhoeven, L. (submitted). Modarators of the verbal redundancy effect.

Introduction

In our ever more digitalized society, the instructional design of learning material is becoming increasingly multimodal. Written language is being enriched with pictures, and students can listen to a voice-over in addition to simply reading a text. For some specific groups, such as students with dyslexia, this form of audio-support is very common (Ghesquière et al., 2010). From a theoretical point of view, additional audio (i.e., audio-support; meaning a voice-over that reads the text out loud while the written text is presented onscreen) is thought to impact learning from such texts. Based on the Cognitive Theory of Multimedia Learning (CTML, Mayer, 2005), replacing written text with audio in a multimedia environment has been shown to be beneficial for learning (*modality principle;* Mayer, 2005), while adding written text to audio with pictures hampers learning (*redundancy principle*; Mayer & Fiorella, 2014), both due to respectively offloading and overloading working memory. However, as stated above, in the educational context, it is most often the case that audio is added to the existing written text with pictures (instead of the other way around). A possible negative effect of adding audio to written text with pictures is called a *verbal redundancy effect*. However, in a large-scale meta-analysis, Adesope and Nesbit (2012) showed that such effects have not been found in the few previous studies that have been done on this effect. This is not in line with theory, and the studies differed in time of testing (directly after learning or at a later point in time) and pacing of the material (user-paced vs. system-paced), which may have impacted the results. In addition, whereas working memory underlies the theoretical constructs of multimedia learning, the actual impact of individual differences of working memory on verbal redundancy effects, remain unclear. To further understand the verbal redundancy effect for the educational practice, it is crucial to understand how adding audio to written text in multimedia environments affects learning. Therefore, the aim of the present study was to identify boundary conditions of the verbal redundancy effect.

Theories in Multimedia Learning

The Cognitive Theory of Multimedia Learning (CTML, Mayer, 2005) provides a theoretical framework with various principles for creating efficient multimedia learning environments in which the information (or processing) that overloads the working memory capacity for learning is offloaded to enhance learning. The CTML is largely consistent with the Cognitive Load Theory (CLT: Paas et al., 2003), which explains how learners' cognitive load can be reduced so that learning is least hindered (Sweller, 1988).

The rationale behind the principles of the CTML is that one's working memory can only process so much information at the same time. Specifically, when identical information is presented simultaneously in two different modalities (e.g., written text and audio), working memory must unnecessarily process the information twice. The cognitive capacity necessary to process the identical information is no longer available in the working memory for learning and thus knowledge gain is hampered (Mayer & Fiorella, 2014). To facilitate learning, the instructional design should therefore contain as little duplicated information as possible (Paas et al., 2003).

The division in different types of cognitive load that is made in CLT, can be helpful to understand how cognitive load can be reduced. The three types are: intrinsic, extraneous, and germane cognitive load (Paas et al., 2003; Sweller, 1994; Sweller, & Chandler, 1994). Verbal redundancy effects are inherently linked to extraneous load as providing identical information simultaneously directly relates to the design of the task and the processing of extra information (Mayer, 2017). It also links to germane load as the effort learners put in the multimedia lessons could be different when confronted with additional audio-support.

Moderators of Verbal Redundancy

There is a lot of empirical evidence regarding Mayer's redundancy principle (meta-analysis, Adesope & Nesbit, 2012): students scored higher when learning from pictures with audio, than from pictures, audio and written text. These effects were quite robust (Kalyuga & Sweller, 2014; Mayer, 2017). However, regarding *verbal* redundancy, Adesope and Nesbit (2012) showed no overall statistical difference in their meta-analysis between learning from written-text or from written-text-with-audio (of which most studies also included pictures).

This contrast between theories on multimedia learning and actual observed effects, may, at least partly, be caused by possible moderators. Indeed, in multimedia research regarding the modality principle -comparing audio-with-pictures to written-text-with-pictures- Niekbeek (2018) found interaction effects between modality and pacing; differences between learning outcomes directly after learning and on the long term; and an impact of working memory on the learning effects over time. As such, three possible moderators emerge: time of testing, pacing, and working memory.

Time of Testing

Even though consolidation of learning is the ultimate goal of education, research on multimedia learning often does not include long-term learning effects (i.e., consolidation). The only studies specifically investigating the verbal redundancy effect by comparing written-text-with-pictures to written-text-with-pictures-and-audio that have taken consolidation into account, are two studies in primary school children (Knoop-van Campen et al., 2018; 2019). They found no short or long-term effects on learning outcomes when comparing written text with and without audio in primary school children.

Other studies did investigate consolidation regarding the modality effect (i.e., comparing audio-with-pictures to written-text-with-pictures). For example, Witteman and Segers (2010) found changes in modality effects when comparing learning gains directly after learning, one day, and a week later. The observed effect disappeared (retention knowledge) or reversed (transfer knowledge). When comparing various multimedia conditions, Segers and colleagues (2008) found an initial modality effect on transfer knowledge on the short-term but no effect on the long-term. In a similar vein, Van den Broek and colleagues (2014) and Ruf and colleagues (2014) showed no modality effects directly after learning, but did show reversed modality effects after one day and one week. Schweppe and Rummer (2012) found reversed modality effects on the long-term and argued that while multimedia principals may facilitate direct learning, they might be less effective on the long-term. The authors implored to include delayed tests in studies on multimedia learning (Schweppe et al., 2015; Schweppe & Rummer, 2016).

Pacing

A large meta-analysis of Adesope and Nesbit (2012) showed differences between learning from written-text-with-spoken-text as compared to spoken-only information. Spoken-written presentations outperformed learning from audio only in system-paced studies. However, in the user-paced studies such a difference was not found. Even though Adesope and Nesbit did not find similar pacing differences in studies comparing written-text-with-audio to written-only conditions, the overall mean effect size for included studies that compared written-text to written-text-with-audio was almost three times as large for system-paced studies as for user-paced studies (g = .07 vs. g = .21). This suggests possible differences between system-paced and user-paced environments. Similar differences in pacing were found in a meta-analysis on another multimedia principle (modality effect) that indicated that the pacing of the learning material constrained the observed effects (Wang et al., 2016).

More recent studies showed contradictory results. Studying adults, De Koning and collegues (2017) and Pastore and collegues (2018) found no verbal redundancy effect in user-paced learning environments, and neither did Kim and collegues (2018) in a system-paced learning environment. Schüler and colleagues (2013) found similar results: no verbal redundancy effects on retention and transfer. Manipulating the redundancy between the written text and the added audio in a user-paced learning environment did not affect students' learning outcomes (Roscoe et al., 2015). In addition, two comparable user-paced studies on the redundancy effects in primary school children did not find verbal redundancy effects in learning outcomes on retention (factual knowledge) and transfer knowledge (applying knowledge to a new situation) between written-text and written-text-with-audio (Knoop-van Campen et al., 2016; 2019).

However, Kim and Lombardino (2019) showed that -even after controlling for verbal ability and visual sequential memory- students scored lower on retention knowledge but not on transfer knowledge when audio was added to written text. It was not clear whether this study was system- or user-paced. Yet another study showed a reversed effect suggesting that redundant information is beneficial (Ari et al., 2014). The authors found a positive effect of adding spoken text to written text when learners have control over the pacing of the material.

Working Memory

Only few studies related working memory capacity to (the size of) the redundancy effect, all conducted in user-paced environments. Witteman and Segers (2010) indicated that in children multimedia effects were not affected by working memory. In comparable research in children, working memory also did not relate to the (absence of) verbal redundancy effects (Knoop-van Campen et al., 2018, 2019). Other research into multimedia learning showed different results. For example, Kozan and colleagues (2015) demonstrated that working memory moderates the modality effect: learners with higher working memory were able to retain more information over time when learning from written-text-with-audio as compared to audio-only. Gyselinc and colleagues (2008) argued that both verbal and visual working memory are important in multimedia learning, but that specific multimedia principles (in their case the modality effect) seem to depend more on individual differences than (only) on working memory capacity.

Cognitive load is related to working memory, but according to a recent systematic review of Mutlu-Bayraktar and colleagues (2019), only few cognitive load studies investigated verbal redundancy in multimedia learning with inconclusive results. The addition of a voice-over to both on-screen text as well as to video instruction, caused students to experience higher cognitive load than when there was no voice-over (Chen & Wu, 2015; Liu et al., 2011). In contrast, Pastore (2012) showed that students who were presented with written text and audio indicated similar levels of cognitive load as compared to students with audio-only. Other research did not find cognitive load differences (Ari et al., 2014) or even reduced cognitive load levels (Chang et al., 2011) when written text was added to audio.

Present Study

Research regarding verbal redundancy so far has come up with inconsistent results, and the role of possible moderators are unclear. Therefore, the aim of the present study was to investigate the role of time of testing, pacing, and working memory in moderating the effects of verbal redundancy in self-reported cognitive load and learning outcomes in multimedia learning environments, and, by doing so, identifying boundary conditions of verbal redundancy.

In this study, we examined university students in system- and user-paced learning environments who all were presented with two different types of multimedia lessons: pictorial information presented with (i) written text, and (ii) written text with audio. Directly after completing the learning task, students were asked about their perceived cognitive load and were tested on retention and transfer knowledge. One-week later, students received a second knowledge post-test. Students' verbal and visual working memory was also examined.

Our research question was: To what extent do time of testing (directly and a week later), pacing of the material (user-paced vs. system-paced) and verbal and visual working memory affect verbal redundancy effects on students' cognitive load and learning outcomes?

We expected stronger verbal redundancy effects directly after learning compared to one week later, stronger effects in system-paced versus user-paced environments, and stronger effects in learners with low working memory compared to learners with high working memory.

Method

Participants

In total, 104 students from Dutch (applied) universities participated in this study. They received a monetary reward (30 Euro) or course credit and gave active consent. The study was approved by the Ethics Committee of the Faculty of Social Sciences of our university. All students were raised monolingual. There was a large diversity of disciplines (humanities, natural sciences, and social sciences) among the students, however, given the nature of the multimedia lessons (i.e., biology lessons), biology and medicine students were not allowed to participate. Seven participants had to be excluded due to missing data on learning outcome measures.

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Of the 97 students who were included in the analysis (M_{age} = 21.48, *SD* = 1.88; 79% female), 41 received the user-paced, and 56 the system-paced materials. Students in the user-paced condition (M_{age} = 21.56, *SD* = 2.10; 83% female) and the system-paced condition (M_{age} = 21.43, *SD* = 1.72; 77% female) did not differ in age, $t(95) = .34$, $p = .733$, or gender, $X^2(1, 97) = .55$, $p = .460$. Students in the user-paced condition (M = 7.78, *SD* = 2.38) and in the system-paced condition (M = 9.77, *SD* = 2.44) did differ on prior knowledge, $t(95) = .78$, $p = .439$, $d = .83$, so this was included as a covariate in the analyses.

Research Design

The present study entails a within-between-subject design. All participants studied two biology multimedia lessons: written text, and written text with audio (audio-support). About half of the students received the lessons in a user-paced learning environment where they were in charge of the pacing of the materials (N = 41). The other part of the students (N = 56) received the lessons in a system-paced learning environment where the materials were automatically paced.

The data of the students in the user-paced condition[1]., was collected one year before the data of the system-paced condition, and as such, students were not randomly assigned to the between-subject factor. However, as both groups were tested in the same physical laboratory with the same equipment and the same procedure was followed, this reduces the risk to internal validity.

Every student was randomly assigned to a within-subject in which the two lessons, two modalities and two post-tests were offered in a randomized-block-design. As such, the student was randomly assigned a number from 1 to 8, in which for example '1' stands for first lesson is 'first week: topic 1, written condition, directly after learning posttest A, a week later posttest B, second week: topic 2, written-audio condition, directly after learning posttest B, a week later posttest A'.

Materials

Multimedia Lessons

Two 900-word text passages on first-year biology topics, one about gastrulation and the other about the small intestines, were used to create multimedia lessons (see Knoop-van Campen et al., 2020). Each lesson had a title page, an instruction page, and 900 words divided over 15 slides (see Figure 6.1 for an example slide). Two versions of each lesson were created. Both versions featured pictures with written text, but only one version provided redundant spoken text. In this text-audio condition, a professional female voice-over read the written text out load.

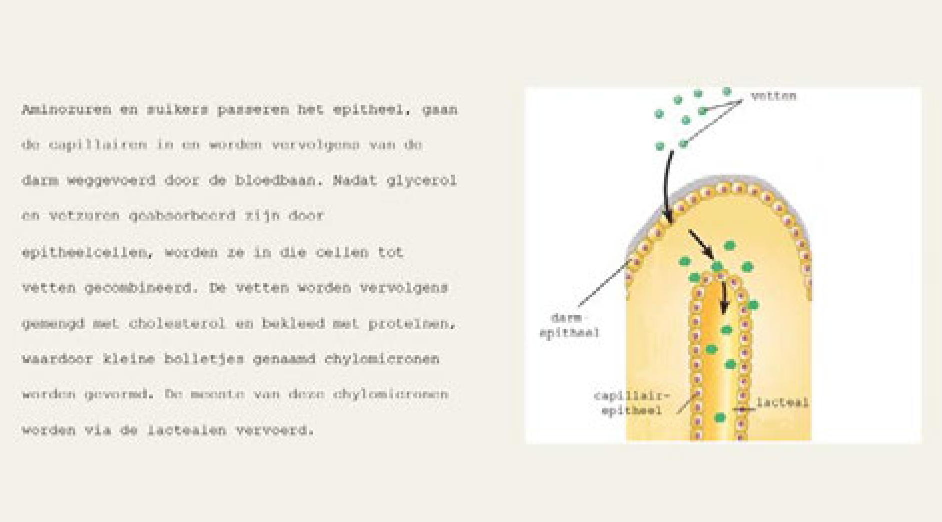
In the user-paced condition, participants were allowed to move though the lessons at their own pace and were able to move back and forwards though the slides. When audio was included in this condition, students were able to pause and replay it. In the system-paced condition, the slides were automatically paced, thus students could not navigate through the lesson and audio could not be stopped or replayed (lesson duration 7.05 minutes). When the voice-over was finished (or, in the written-only condition, when a similar amount of time had passed) the system would automatically move to the next slide.

Learning Outcomes

Directly after learning the multimedia lesson and a week later, students' retention and transfer knowledge was tested. First, students were given the assignment to recall as much as possible from the lesson (retention knowledge: 'Describe the process of gastrulation'). Then, four questions in which students had to apply their knowledge to a new situation (transfer knowledge: 'What would happen to the food digestion if the pancreas of a dog would be removed?') were provided.

1. Data regarding knowledge directly after learning of the participants in the user-paced condition was published before as control condition in a paper on dyslexia (Knoop-van Campen et al., 2020). In the present paper, all the data from the system-paced condition, as well as the long-term learning outcomes in the user-paced condition, as well as the cognitive load and working memory data of both conditions was new and not previously used for analysis or publication elsewhere. This means that approximately 12% of the data in the present study was published before, and 88% of the data is unique for this study.

Figure 6.1
Example Slide



For the retention score, 63 words were identified that reflected the content and students received one point per correctly named item (Mayer et al., 2014). Correct spelling of words was not necessary to receive points. The retention test was reliable (α = .90). According to a validated rubric (see Knoop-van Campen et al., 2020) students' answers on the transfer questions were scored by the first author. Students could receive 0-2 points per question, 8 points in total. The transfer questions were reliable (α = .79)

Cognitive Load

To assess students' cognitive load, the 'Subjective differentiated measurement of cognitive load' questionnaire (Klepsch & Seufert, 2012) was assessed directly after each lesson. Participants answered eight questions (two intrinsic cognitive load, three extraneous cognitive load, and three germane cognitive load) on a 10-point Likert-scale, in which low scores indicated low perceived cognitive load and high scores indicated high perceived cognitive load. Example questions of intrinsic load "This task was very complex", extraneous load "The design of this task was very inconvenient for learning", and germane load "My point while dealing with the task was to understand everything correctly". The average was calculated per type of cognitive load. Note that though high cognitive load is not desirable for intrinsic and extraneous load, high germane cognitive load is advantageous.

Working Memory

Verbal Working Memory. Verbal Working Memory was measured with a backward digit recall task (Digits-backwards, WISC-IV-NL: Wechsler, 2005), in which students had to recall increasing sequences of digits backwards. The test was discontinued after two incorrect sequences of the same length. Scores were the number of sequences correctly recalled. Scores were centered before entering analyzes.

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Visual Working Memory. Visual working memory was measured with an N-backwards working memory task with N = 2 (Gevins & Cutillo, 1993). The students were presented with a series of digits (one at a time: 225 stimuli of which 32 N=2 items, presented 600 milliseconds with 645 milliseconds in between), and were given the task to indicate for each stimulus when it matched the two items presented before. Scores were the number of correct responses to the N=2 items. Scores were centered before entering analyzes.

Prior Knowledge

Prior knowledge was measured by means of a paper-and-pen task as described in Zakaluk, and colleagues (1986). Participants were asked to write down as many words or phrases as possible related to the content of the lessons (small intestine or gastrulation) within one minute. One point was awarded for each unique word or phrase related to the topic. More points reflected higher prior knowledge. Scores were centered before entering analyzes.

Procedure

Testing was done in an individual setting in the lab by the first author with support of six undergraduate students. Students came to the lab once a week, three weeks in a row. The first week, they were provided with a multimedia lesson with a direct post-test to measure the learning effect on the short-term. During the second visit a week later, students first received a delayed test to measure long-term knowledge. They then were provided with a new lesson, again followed by a direct post-test. During the third visit, students received only the delayed test from the previous week, then the working memory tasks were conducted.

Data-analyses

Verbal redundancy effects in cognitive load were analyzed using GLM Repeated Measures with Types of Cognitive Load (intrinsic / extraneous / germane) as outcome measure and Modality (text / text-audio) as within-subjects-factor, Pacing (user-paced / system-paced) as between-subjects-factor, with Prior Knowledge added to the analysis as covariate, to control for existing group differences. To examine the influence of working memory on the verbal redundancy effect, in a follow-up analysis verbal and visual working memory were added as covariates, and it was checked whether there were any main effects of working memory, or interaction effects with working memory.

To examine verbal redundancy effects for retention knowledge and transfer knowledge, similar analyses were used with Time (short-term / long-term) as within-subjects-factor instead of cognitive load.

Due to skewed distributions of the retention knowledge, these four variables were transformed with a +1 logistic transformation prior to analysis (Field, 2012). For reporting, scores were transferred back to support understanding. A fixed significance threshold of $p < .05$ was used.

Results

Descriptives

Students in the user-paced and system-paced condition did not differ on verbal ($M_{user\text{-}paced}$ = 8.95, $SD_{user\text{-}paced}$ = 2.49) and visual working memory ($M_{system\text{-}paced}$ = 8.95, $SD_{system\text{-}paced}$ = 2.49), resp. $t(95) = .78$, $p = .439$, $d = .17$, and $t(95) = .83$, $p = .410$, $d = .16$. The system-paced condition took 7.05 minutes; students in the user-paced condition spent 14.28 minutes ($SD = 5.25$). The means and standard deviations for cognitive load and learning outcomes for the two conditions separately are provided in Table 6.1.

Table 6.1
Descriptives of Cognitive Load and Learning Outcomes per Condition

		User-paced				System-paced			
		Text		Text-audio		Text		Text-audio	
		M	SD	M	SD	M	SD	M	SD
Cognitive Load									
Intrinsic		4.90	1.37	4.82	1.32	4.96	1.35	5.19	1.26
Extraneous		3.50	1.02	3.95	1.44	4.04	1.18	4.14	1.11
Germane		5.67	.67	5.53	.84	5.13	.78	5.18	1.00
Learning Outcomes									
Retention	Short-term	7.51	5.13	7.61	5.21	5.21	4.04	5.34	4.10
	Long-term	4.39	3.01	4.68	4.03	4.02	3.35	3.98	2.94
Transfer	Short-term	4.17	1.92	3.54	1.90	3.41	1.83	2.89	2.02
	Long-term	3.34	1.82	3.59	1.87	2.52	1.66	2.68	1.57

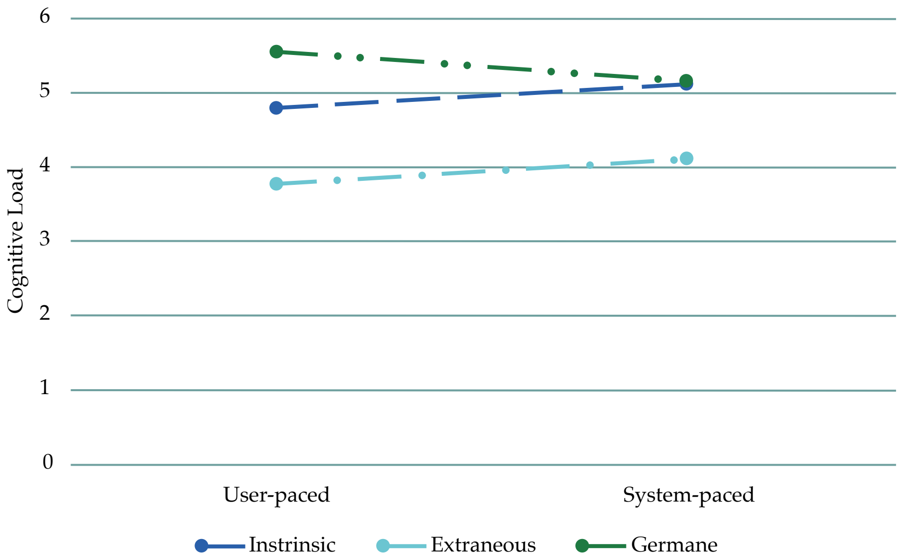
Perceived Cognitive Load

Analysis of the types of cognitive load showed a significant main effect of Cognitive Load, $F(1, 94) = 8.10$, $p = .005$, $\eta^2_p = .079$. Students indicated the most germane load, then intrinsic, and least extraneous load. There were no significant main effects on Modality, $F(1, 94) = 1.17$, $p = .283$, $\eta^2_p = .012$, or pacing $F(1, 94) = .41$, $p = .526$, $\eta^2_p = .004$.

There was an interaction between Cognitive Load and Pacing, $F(1, 94) = 4.91$, $p = .029$, $\eta^2_p = .050$. Differences in cognitive load were larger in user-paced learning environments than in system-paced environment. In a system-paced learning environment, students experienced less germane cognitive load but more intrinsic and extraneous cognitive load than in a user-paced environment (see Figure 6.2).

When adding Verbal and Visual Working Memory as covariates to the performed analysis, there were no main effects of verbal ($F(1, 92) = .06$, $p = .803$, $\eta^2_p = .001$) or Visual Working Memory ($F(1, 92) = 1.03$, $p = .314$, $\eta^2_p = .011$). An interaction between between Modality and Verbal Working Memory was found, $F(1, 92) = 4.58$, $p = .035$, $\eta^2_p = .047$. Students with lower verbal working memory seemed to experience higher cognitive load when audio-support was added to the lesson.

Figure 6.2
Cognitive Load per Condition



Knowledge Retention

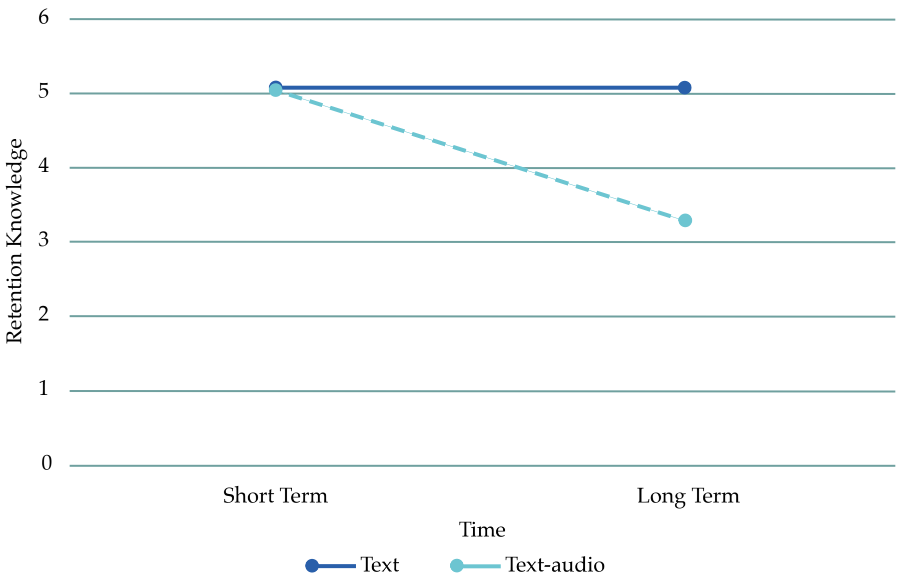
Analysis of the retention knowledge showed a significant main effect of Time, $F(1, 94) = 32.58$, $p < .001$, $\eta^2_p = .257$. Students recalled less information after a week compared to directly after the lessons. There was also a significant main effect on Modality, $F(1, 94) = 6.03$, $p = .016$, $\eta^2_p = .060$. Students recalled more information when they learned from written text, compared to learning from written text with audio. In addition, there was a significant main effect on Pacing, $F(1, 94) = 13.25$, $p < .001$, $\eta^2_p = .124$. Students recalled more information in the user-paced than in the system-paced condition.

There was an interaction between Modality and Time, $F(1, 94) = 32.58$, $p < .001$, $\eta^2_p = .257$. Whereas directly after learning, students recalled a similar amount of information in both conditions, after a week they recalled less in the text-audio condition (see Figure 6.3).

When adding Verbal and Visual Working Memory as covariates to the performed analysis, there were no main effects of Verbal ($F(1, 92) = 3.32$, $p = .072$, $\eta^2_p = .035$) or Visual working memory ($F(1, 92) = .08$, $p = .785$, $\eta^2_p = .001$). Also, no interactions with Verbal or Visual Working Memory were observed (p's > .05).

Figure 6.3

Retention Knowledge per Modality over Time.



Knowledge Transfer

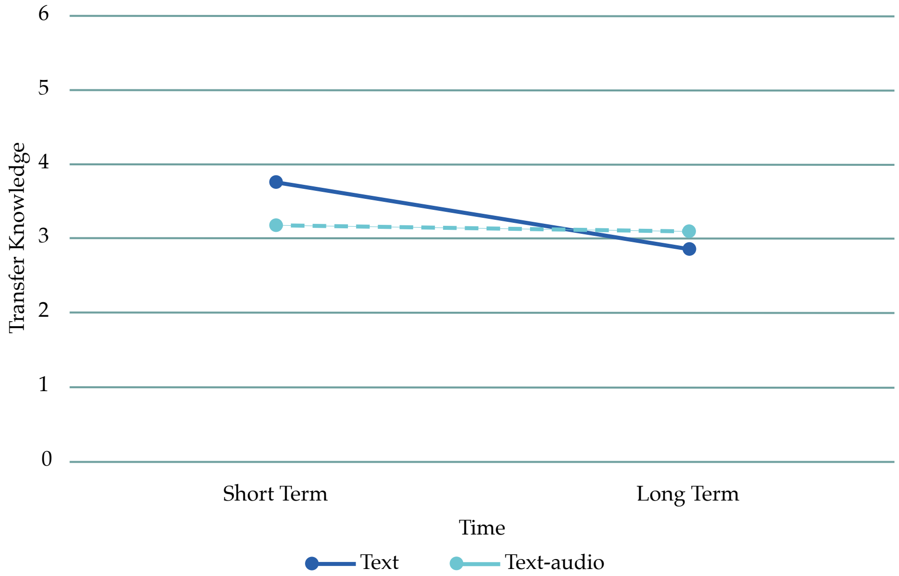
Analysis of the transfer knowledge showed a significant main effect of Time, $F(1, 94) = 13.18$, $p < .001$, $\eta^2_p = .123$. Students recalled less information after a week compared to directly after the lessons. There was also a significant main effect on Pacing, $F(1, 94) = 15.39$, $p < .001$, $\eta^2_p = .141$. Students scored higher on transfer knowledge in a user-paced environment than in a system-paced environment. There was no significant main effect on Modality, $F(1, 94) = 1.03$, $p = .313$, $\eta^2_p = .011$.

There was an interaction between Modality and Time, $F(1, 94) = 8.27$, $p = .005$, $\eta^2_p = .081$. Whereas directly after learning, students scored higher on transfer knowledge in the text-condition, after a week they scored equally well in both conditions (see Figure 6.4).

When adding Verbal and Visual Working Memory as covariates to the performed analysis, there was a main effect of Verbal Working Memory ($F(1, 92) = 3.97$, $p = .049$, $\eta^2_p = .041$), but no main effect of Visual Working Memory ($F(1, 92) = 3.72$, $p = .057$, $\eta^2_p = .039$). Students with higher verbal working memory scored higher on transfer knowlegde. No interactions with Verbal or Visual Working Memory were observed (p's $> .05$).

Figure 6.4

Transfer Knowledge per Modality over Time.



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Discussion

In this study, we examined the role of time of testing, pacing, and working memory in moderating the effects of verbal redundancy in self-reported cognitive load and learning outcomes in multimedia learning environments. University students received two multimedia lessons with written text, and written text with audio, either in a user-paced or system-paced multimedia learning environment. Results on perceived cognitive load showed no verbal redundancy effects, but extraneous load was higher and germane load was lower in system-paced environments than in user-paced environments. Students with lower verbal working memory experienced higher cognitive load when audio-support was added. Regarding retention knowledge, directly after learning, there was no verbal redundancy effect. However, after one week, students recalled less knowledge when they studied with audio-support than without audio-support, which can be interpreted as a verbal redundancy effect on the long-term. Regarding transfer knowledge, students scored lower when they studied with audio-support than without audio-support, but after a week, the difference had disappeared, which can be interpreted as a verbal redundancy effect on the short-term.

Time of Testing

Both for retention knowledge as well as for transfer knowledge, timing of testing, e.g., whether knowledge was assessed directly after learning or one week later, affected the verbal redundancy effect. Whereas for recall of facts (retention) a verbal redundancy effect on the long-term was found, for applying knowledge in a new situation (transfer), a verbal redundancy effect on the short-term was found. Like in studies on other long-term multimedia effects (e.g., Van den Broek et al., 2014; Ruf et al., 2014;), we found differences between learning outcomes directly after learning and later. The lack of direct learning effects in retention knowledge replicates previous research (e.g., De Koning et al., 2017; Knoop-van Campen et al., 2018, 2019; Pastore et al., 2018). Added audio seems to lead to less consolidation of factual knowledge, while in the long run, both lead to similar learning outcomes on transfer knowledge.

The differences between retention and transfer knowledge may partly be explained by the transience of spoken language. Transfer knowledge focuses on problems that are somewhat similar or even completely different to those presented in the lesson (Mayer, 2011) and as such rely more strongly on deep processing of information. As such, transfer knowledge connects pre-eminently to deep learning, and in order to build a contextual model of the information (instead of purely recalling the information) new inferences must be generated (Day & Goldstone, 2012). For retention knowledge, there is less need to create a mental model and place it into the long-term memory (Paas et al., 2003). Audio may distract students and therefore hamper connecting information to existing knowledge (similar to results of Gerjets et al., 2009).

In addition, our results show that, in the long run, students learn best without audio. In previous studies, added audio has been found to be mainly beneficial for students with weak reading skills (Dunsworth & Atkinson, 2007). The participants in our study - all university students - had high reading capacities. For them, the pacing of the audio is not on par with their own reading rate, and as such not supportive to their reading (Gerbier et al., 2018).

By combining the results on knowledge retention and knowledge transfer, we can state that the *time of testing* seems an important moderator for the verbal redundancy effect, and that the effects may also depend on how knowledge is applied and measured (type of assessment / knowledge).

Pacing

Stronger effects were expected in the system-paced learning environments then in the user-paced learning environments -due to possible relieving of one's own cognitive load- but no pacing effects were found. Both on retention as well as on transfer knowledge, the verbal redundancy effects found were similar in system-paced and user-paced environments. However, in a system-paced learning environment, students experienced less germane cognitive load but more intrinsic and extraneous cognitive load than in a user-paced environment. Students also scored lower in system-paced environments. Combined, these results support the superiority of user-paced learning environments over system-paced ones (Van Merriënboer & Kester, 2005; Stiller et al., 2011).

Even though the addition of audio to the written text was hypothesized to increase students' cognitive load especially in system-paced learning environments, such results were not found. This is similar to results from Pastore (2012) and Ari and colleagues (2014). However, relevant interactions with pacing were just short of the significance threshold (p's = .0504). So, the conclusion that adding audio has no effect at all might be too strong. When the written text was read out loud, learners might have estimated the duration of each slide better based on the observed reading speed, which could have contributed to a sense of (fictive) control. Being in control over a learning environment, can support students' interest and motivation (i.e., germane load; Scheiter & Gerjets, 2007), which in turn can lower extraneous load (Paas et al., 2003; Klepsch & Scheufert, 2020).

As expected, we did find that students in general experienced more extraneous load and less germane cognitive load in a system-paced learning environment than in a user-paced environment. These results are in line with Rop, and colleagues (2018) and Schüler and colleagues (2013). Just as in these studies, students in the present study spent more time in the user-paced environment than in the system-paced environment. This can be explained by the fact that in system-paced environments, students have to keep up with a predefined pacing, and cannot pause or decide to spend more time on specific parts of the lesson, and students may feel rushed in building a mental model of the text. The active engagement necessary to build a mental model (Caccamise et al., 2015; Juvina & Van Oostendorp, 2008) is put under (time) pressure, leading to higher cognitive load.

Our results indicate that *pacing* does not seem to be a prominent boundary condition for the verbal redundancy effect. However, pacing does impact the perceived cognitive load and as such, should be accounted for when one preforms research in multimedia environments.

Working Memory

In contrast to our hypothesis, working memory did not moderate the verbal redundancy effects. We did observe that students with lower verbal working memory experienced higher cognitive load when audio-support was added to the lesson. In addition, higher verbal working memory was associated with higher scores on transfer knowledge.

The absence of impact of working memory on the verbal redundancy effect is in line with most previous multimedia research (e.g., Gyselinck et al., 2008; Knoop-van Campen et al., 2018; 2019; Witteman & Segers, 2012). Even though students with lower verbal working memory experienced higher cognitive load, this did not result in stronger redundancy effects. Perhaps the fact that our participants were all high-performing university students may explain the lack of an effect of working memory. They might have compensated for their lower working memory (Titz & Karbach, 2014).

Ginns (2005) and Tabbers and colleagues (2004) stated that in user-paced learning environments, combining multiple modalities has no impact on learning due to the possibility of relieving the working memory. However, we show that even in a system-paced multimedia learning environment, the working memory capacity is not decisive for learning.

Despite the theoretical importance of *working memory* in theories of multimedia learning, our results point towards a modest role of working memory in multimedia learning.

Limitations and Future Research

Several limitations apply to the present study. First, as silent reading is faster in proficient readers than audio (Ashby et al., 2012), students in the system-paced environment without audio had more time than needed to read the text one time (like in the audio condition). However, we expect that when this amount of time would be reduced (for example based on individual reading pacing), the observed verbal redundancy effects would only be stronger and not weaker. Second, we measured cognitive load by asking students to indicate their perceived cognitive burden, which is a subjective way of measuring cognitive load. However, other more objective measures, like a dual-task paradigm, are intrusive by nature, increase cognitive load in itself (Klepsch et al., 2017), and lack the possibility to compare intrinsic and extraneous load against germane load (Klepsch, & Seufert, 2020). Finally, the first (immediate) test may have caused a retrieval practice effect (e.g., Roediger & Karpicke, 2006). However, as a randomized-block design was used to vary between the direct and delayed tests, and more importantly, this possible practice effect would apply to both conditions studied, this should not pose a risk to the results.

Practical Implications

The present research has some implications for education. Despite the initial positive effects directly after learning, learners should not be advised to use audio-support just for the sake of immediate results. As the long-term results in the present study show that adding audio hampered learning, we would not encourage university students with good reading capacities to use audio-support for learning purposes. Especially not since students with lower verbal working memory experienced higher cognitive load when audio-support was added to the lesson.

Conclusions

To conclude, overall, students profit most from a multimedia condition with pictures that does not include both audio and written text. Our results point toward certain boundary conditions for verbal redundancy effect - and possibly for multimedia learning in general with time of testing as the most important moderator. Pacing and working memory do not seem to be (important) boundary conditions, although pacing does impact learning. Research into multimedia learning should be attentive of the discrepancy between the foundations of the CTML and the practical boundary conditions of the verbal redundancy effect.

References

Adesope, O. O., & Nesbit, J. C. (2012). Verbal redundancy in multimedia learning environments: A meta-analysis. *Journal of Educational Psychology, 104*(1), 250. https://doi.org/10.1037/a0026147

Ari, F., Flores, R., Inan, F. A., Cheon, J., Crooks, S. M., Paniukov, D., & Kurucay, M. (2014). The effects of verbally redundant information on student learning: An instance of reverse redundancy. *Computers & Education*, *76*, 199-204. https://doi.org/10.1016/j.compedu.2014.04.002

Ashby, J., Yang, J., Evans, K. H., & Rayner, K. (2012). Eye movements and the perceptual span in silent and oral reading. *Attention, Perception, & Psychophysics*, *74*(4), 634-640. https://doi.org/10.3758/s13414-012-0277-0

Caccamise, D., Friend, A., Littrell-Baez, M. K., & Kintsch, E. (2015). Constructivist theory as a framework for instruction and assessment of reading comprehension. In S. R. Parris & K. Headley (Eds.), *Comprehension instruction: Research-based best practices* (3rd ed., pp. 88-102).

Chang, C.-C., Lei, H., & Tseng, J. -S. (2011). Media presentation mode, English listening comprehension, and cognitive load in ubiquitous learning environments: Modality effect or redundancy effect? *Australasian Journal of Educational Technology, 27*, 633–654. https://doi.org/10.14742/ajet.942

Chen, C. M., & Wu, C. H. (2015). Effects of different video lecture types on sustained attention, emotion, cognitive load, and learning performance. *Computers & Education*, *80*, 108-121. https://doi.org/10.1016/j.compedu.2014.08.015

Day, S. B., & Goldstone, R. L. (2012). The import of knowledge export: Connecting findings and theories of transfer of learning. *Educational Psychologist*, *47*(3), 153-176. https://doi.org/10.1080/00461520.2012.696438

De Koning, B. B., Van Hooijdonk, C. M., & Lagerwerf, L. (2017). Verbal redundancy in a procedural animation: On-screen labels improve retention but not behavioral performance. *Computers & Education*, *107*, 45-53. https://doi.org/10.1016/j.compedu.2016.12.013

Dunsworth, Q., & Atkinson, R. K. (2007). Fostering multimedia learning of science: Exploring the role of an animated agent's image. *Computers & Education*, *49*(3), 677-690. https://doi.org/10.1016/j.compedu.2005.11.010

Field, A. (2013). *Discovering statistics using IBM SPSS statistics* (4th ed.). SAGE Publications.

Gerbier, E., Bailly, G., & Bosse, M. L. (2018). Audio–visual synchronization in reading while listening to texts: Effects on visual behavior and verbal learning. *Computer Speech & Language*, *47*, 74-92. https://doi.org/10.1016/j.csl.2017.07.003

Gevins, A., & Cutillo, B. (1993). Spatiotemporal dynamics of component processes in human working memory. *Electroencephalography and clinical Neurophysiology*, *87*(3), 128-143. https://doi.org/10.1016/0013-4694(93)90119-G

Ghesquière, P., Boets, B., Gadeyne, E., & Vandewalle, E. (2011). Dyslexie: een beknopt wetenschappelijk overzicht. In A. Geudens, D. Baeyens, K. Schraeyen, K. Maetens, J. De Brauwer, & M. Loncke (Eds.), *Jongvolwassenen met dyslexie: diagnostiek en begeleiding in wetenschap en praktijk* (pp. 41-58). Acco Uitgeverij.

Gyselinck, V., Jamet, E., & Dubois, V. (2008). The role of working memory components in multimedia comprehension. *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition*, *22*(3), 353-374. https://doi.org/10.1002/acp.1411

Jäncke, L., & Shah, N. J. (2004). 'Hearing' syllables by 'seeing' visual stimuli. *European Journal of Neuroscience*, *19* (9), 2603-2608. https://doi.org/10.1111/j.0953-816X.2004.03350.x

Jarvis, H. L., & Gathercole, S. E. (2003). Verbal and non-verbal working memory and achievements on national curriculum tests at 11 and 14 years of age. *Educational and Child Psychology*, *20*(3), 123-140.

Juvina, I., & van Oostendorp, H. (2008). Modeling semantic and structural knowledge in web navigation. *Discourse Processes*, *45*(4-5), 346-364. https://doi.org/10.1080/01638530802145205

Kalyuga, S. (2011). Effects of information transiency in multimedia learning. *Procedia-Social and Behavioral Sciences*, *30*, 307-311. https://doi.org/10.1016/j.sbspro.2011.10.061

Kalyuga, S., & Sweller, J. (2014). 10 The redundancy principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 247-262). Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.013

Kim, S., & Lombardino, L. J. (2019). Multimedia learning: Contributions of learners' verbal abilities and presentation modalities. *International Journal of Learning, Teaching and Educational Research*, *18*(1), 76-91. https://doi.org/10.26803/ijlter.18.1.6

Kim, S., Wiseheart, R., & Walden, P. R. (2018). Do multimedia instructional designs enhance comprehension in college students with dyslexia? *Journal of Postsecondary Education and Disability*, *31*(4), 351-365.

6

Klepsch, M., Schmitz, F., & Seufert, T. (2017). Development and validation of two instruments measuring intrinsic, extraneous, and germane cognitive load. *Frontiers in Psychology*, *8*, Article 1997. https://doi.org/10.3389/fpsyg.2017.01997

Klepsch, M., & Seufert, T. (2012, April). *Subjective differentiated measurement of cognitive load* [Conference paper]. 5th International Cognitive Load Theory Conference, Tallahassee, USA.

Klepsch, M., & Seufert, T. (2020). Understanding instructional design effects by differentiated measurement of intrinsic, extraneous, and germane cognitive load. *Instructional Science*, *48* (1), 45-77. https://doi.org/10.1007/s11251-020-09502-9

Knoop-van Campen, C. A. N., Segers, E., & Verhoeven, L. (2018). The modality and redundancy effects in multimedia learning in children with dyslexia. *Dyslexia, 24*(2), 140-155. https://doi.org/10.1002/dys.1585

Knoop-van Campen, C. A.N., Segers, E., & Verhoeven, L. (2019). Modality and redundancy effects, and their relation to executive functioning in children with dyslexia. *Research in Developmental Disabilities*, *90*, 41-50. https://doi.org/10.1016/j.ridd.2019.04.007

Knoop-van Campen, C. A. N., Segers, E., & Verhoeven, L. (2020). Effects of audio support on multimedia learning processes and outcomes in students with dyslexia. *Computers & Education*, *150*, 103858. https://doi.org/10.1016/j.compedu.2020.103858

Kozan, K., Erçetin, G., & Richardson, J. C. (2015). Input modality and working memory: Effects on second language text comprehension in a multimedia learning environment. *System*, *55*, 63-73. https://doi.org/10.1016/j.system.2015.09.001

Li, J., Antonenko, P. D., & Wang, J. (2019). Trends and issues in multimedia learning research in 1996-2016: A bibliometric analysis. *Educational Research Review,28*, Article 100282. https://doi.org/10.1016/j.edurev.2019.100282

Liu, H. C., Lai, M. L., & Chuang, H. H. (2011). Using eye-tracking technology to investigate the redundant effect of multimedia web pages on viewers' cognitive processes. *Computers in Human Behavior*, *27* (6), 2410-2417. https://doi.org/10.1016/j.chb.2011.06.012

Mayer, R. E. (2005). *The Cambridge Handbook of Multimedia Learning*. Cambridge University Press. https://doi.org/10.1017/CBO9780511816819

Mayer, R. E. (2011). Applying the science of learning to multimedia instruction. *Psychology of learning and motivation*, *55*, 77-108. https://doi.org/10.1016/B978-0-12-387691-1.00003-X

Mayer, R. E. (2017). Using multimedia for e-learning. *Journal of Computer Assisted Learning*, *33*, 403-423. https://doi.org/10.1111/jcal.12197

Mayer, R. E., & Fiorella, L. (2014). 12 principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (Vol. 279, pp. 279-315). Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.015

Mayer, R. E., Lee, H., & Peebles, A. (2014). Multimedia learning in a second language: A cognitive load perspective. *Applied Cognitive Psychology, 28*(5), 653-660.

Mutlu-Bayraktar, D., Cosgun, V., & Altan, T. (2019). Cognitive load in multimedia learning environments: A systematic review. *Computers & Education*, *141*, Article 103618. https://doi.org/10.1002/acp.3050

Niebeek, M. G. A. (2018). *Short-term and long-term modality effects in a learner-paced vs. system-paced multimedia lesson for children* [Unpublished master's thesis]. University of Twente.

Nelson, J. R., Balass, M., & Perfetti, C. A. (2005). Differences between written and spoken input in learning new words. *Written Language & Literacy*, *8*(2), 25–44. https://doi.org/10.1075/wll.8.2.04nel

Paas, F., Renkl, A., & Sweller, J. (2003). Cognitive load theory and intructional design: recent developments. *Educational psychologist, 38,* 1-4. https://doi.org/10.1207/S15326985EP3801_1

Pastore, R. (2012). The effects of time-compressed instruction and redundancy on learning and learners' perceptions of cognitive load. *Computers & Education*, *58*(1), 641-651. https://doi.org/10.1016/j.compedu.2011.09.018

Pastore, R., Briskin, J., & Asino, T. (2018, March). The effects of the multimedia, modality, and redundancy principles in a computer based environment on adult learners. In E. Langran & J. Borup (Eds.), *Proceedings of Society for Information Technology & Teacher Education International Conference* (pp. 1663-1668). Association for the Advancement of Computing in Education (AACE).

Rias, R. M. & Zaman, H. B. (2013). Understanding the role of prior knowledge in a multimedia learning application. *Australasian Journal of Educational Technology, 29*(4), 537-548. https://doi.org/10.14742/ajet.419

Roediger III, H. L., & Karpicke, J. D. (2006). The power of testing memory: Basic research and implications for educational practice. *Perspectives on Psychological Science*, *1*(3), 181-210. https://doi.org/10.1111/j.1745-6916.2006.00012.x

Rop, G., Schüler, A., Verkoeijen, P. P. J. L., Scheiter, K., & Gog, T. V. (2018). The effect of layout and pacing on learning from diagrams with unnecessary text. *Applied Cognitive Psychology, 32*(5), 610–621. https://doi.org/10.1002/acp.3445

Roscoe, R. D., Jacovina, M. E., Harry, D., Russell, D. G., & McNamara, D. S. (2015). Partial verbal redundancy in multimedia presentations for writing strategy instruction. *Applied Cognitive Psychology, 29*(5), 669-679. https://doi.org/10.1002/acp.3149

Ruf, A. P., Seckler, M., & Opwis, K. (2014). Long-term modality effect in multimedia learning. *Proceedings of the 8th Nordic Conference on Human–Computer Interaction: Fun, Fast, Foundational*, 963-966. https://doi.org/10.1145/2639189.2670251

Scheiter, K., & Gerjets, P. (2007). Learner control in hypermedia environments. *Educational Psychology Review, 19* (3), 285-307. https://doi.org/10.1007/s10648-007-9046-3

Schüler, A., Scheiter, K., & Gerjets, P. (2013). Is spoken text always better? Investigating the modality and redundancy effect with longer text presentation. *Computers in Human Behavior, 29*(4), 1590-1601. https://doi.org/10.1016/j.chb.2013.01.047

Schweppe, J., Eitel, A., & Rummer, R. (2015). The multimedia effect and its stability over time. *Learning and Instruction, 38*, 24-33. https://doi.org/10.1016/j.learninstruc.2015.03.001

Schweppe, J., & Rummer, R. (2012). Long-term multimedia learning. In E. de Vries & K. Scheiter (Eds.), *EARLI Sig2 Meeting 2012: Staging Knowledge and Experience: How to Take Advantage of Representational Technologies in Education and Training* (pp. 196-198). Laboratoire des Sciences de l'Education.

Schweppe, J., & Rummer, R. (2016). Integrating written text and graphics as a desirable difficulty in long-term multimedia learning. *Computers in Human Behavior, 60*, 131-137. https://doi.org/10.1016/j.chb.2016.02.035

Segers, E., Verhoeven, L., & Hulstijn-Hendrikse, N. (2008). Cognitive processes in children's multimedia text learning. *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition, 22*(3), 375-387. https://doi.org/10.1002/acp.1413

Stiller, K. D., Petzold, K., & Zinnbauer, P. (2011). Presentation time concerning system-paced multimedia instructions and the superiority of learner pacing. *Australasian Journal of Educational Technology, 27*(4). https://doi.org/10.14742/ajet.945

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive science, 12*(2), 257-285. https://doi.org/10.1207/s15516709cog1202_4

Sweller, J. (1994). Cognitive load theory, learning difficulty, and instructional design. *Learning and Instruction, 4*(4), 295–312. https://doi.org/10.1016/0959-4752(94)90003-5

Sweller, J., & Chandler, P. (1994). Why some material is difficult to learn. *Cognition and Instruction, 12*(3), 185-233. https://doi.org/10.1207/s1532690xci1203_1

Sweller, J. (2016). Working memory, long-term memory, and instructional design. *Journal of Applied Research in Memory and Cognition, 5*(4), 360-367. https://doi.org/10.1016/j.jarmac.2015.12.002

Sweller, J., Van Merrienboer, J. J., & Paas, F. G. (1998). Cognitive architecture and instructional design. *Educational Psychology Review, 10*(3), 251-296. https://doi.org/10.1023/A:1022193728205

Titz, C., & Karbach, J. (2014). Working memory and executive functions: effects of training on academic achievement. *Psychological Research, 78*(6), 852-868. https://doi.org/10.1007/s00426-013-0537-1

Van den Broek, G. S., Segers, E., & Verhoeven, L. (2014). Effects of text modality in multimedia presentations on written and oral performance. *Journal of Computer Assisted Learning, 30*(5), 438-449. https://doi.org/10.1111/jcal.12058

Van Merriënboer, J. J., & Kester, L. (2014). The four-component instructional design model: Multimedia principles in environments for complex learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 71–93). Cambridge University Press. https://doi.org/10.1017/CBO9780511816819.006

Wang, F., Xie, H., & Li, H. (2016). Visual text or narration? Meta-analysis of the modality effect in multimedia learning. *Advances in Psychological Science, 24*(3), 335-350. https://doi.org/10.3724/SP.J.1042.2016.00335

Wechsler, D. (2005). *WISC-IV*: *Escala de inteligencia de Wechsler para niños* IV [Wechsler Intelligence Scale for Children – 4th Edition]. TEA Ediciones.

Witteman, M. J., & Segers, E. (2010). The modality effect tested in children in a user-paced multimedia environment. *Journal of Computer Assisted Learning, 26*(2), 132-142. https://doi.org/10.1111/j.1365-2729.2009.00335.x

Zakaluk B., Samuels S. J., Taylor B. M. (1986). A simple technique for estimating prior knowledge: Word association. *Journal of Reading, 30*, 56–60. https://www.jstor.org/stable/40011129

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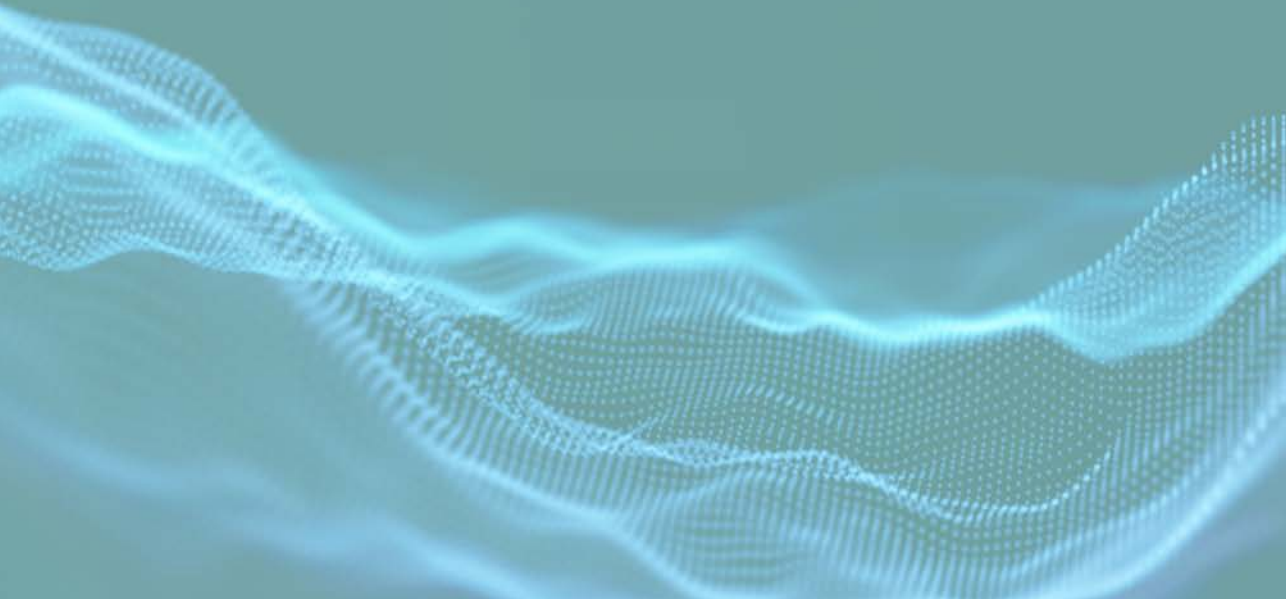


CHAPTER 7

GENERAL DISCUSSION

General Discussion

Multimedia learning environments in which written text can also be read to the reader are an integral part of present-day society. In educational settings, the possibility of narration or text-to-speech is used extensively, for example through recorded textbooks or reading software. Learners with dyslexia are particularly likely to use these digital possibilities to compensate for their reading difficulties (Ghesquière et al., 2010). However, from a theoretical point of view, combining different media may interfere with the learning process and affect learning outcomes (Mayer, 2005; Mayer & Fiorella, 2014). Although many children and adults with dyslexia use audio-support in their everyday lives, it is still unclear whether this has consequences for their multimedia learning outcomes.

The aim of this dissertation was to provide insight into the multimedia learning behavior and (long-term) learning outcomes of adults and children with dyslexia as compared to their typically developing peers. In a series of experimental studies, it was examined to what extent audio-support impacted **learning outcomes** and **learning processes** in these learners, and what the **boundary conditions** were for efficient multimedia learning. This final chapter combines the results described in this dissertation and provides a summary of the main findings, before discussing theoretical and practical implications and suggestions for future research.

Outcomes of Multimedia Learning

The first research question investigated the extent to which audio-support impact **what** learners with dyslexia learn compared to their typically developing peers. As such, it focused on short and long-term learning outcomes in multimedia environments and included both the recall of facts (retention) and application of the learned knowledge in a new situation (transfer knowledge).

Regarding adult learners, in Chapter 2, it was found that for students with and without dyslexia, audio-support did not impact retention knowledge, while in Chapter 6 long-term retention knowledge of typically developing learners was lower. Adding audio to a multimedia learning environment also led to lower transfer knowledge directly after learning in both groups, as presented in Chapter 2, and increased study times. We can thus conclude that, in line with the CTML (Mayer & Fiorella, 2014), the use of audio-support in multimedia environments is associated with lower learning outcomes in university students with and without dyslexia and that for consolidation purposes, it is more beneficial to learn from written text with pictures only.

This could be explained by the fact that reading is a more active process than listening as it activates both orthography and phonology (Nelson et al., 2005). Accordingly, reading may cause a deeper memory trace than listening, which only activaties phonology (Witteman & Segers, 2010). The adults were highly educated and had rather high reading skills: audio may have distracted them more than it supported them. As indicated in Chapter 2, audio-support is especially beneficial for students with low reading skills (Dunsworth & Atkinson, 2007), which may be due to mis-alignment between the pacing of the audio and the student's own reading pace. For good readers, the audio may be too slow and therefore distracting.

In primary school children there were hardly any differences in learning outcomes: none on retention knowledge in Chapter 4 and 5 and none on transfer knowledge in Chapter 4. In Chapter 5, the only difference found regarded transfer knowledge: children with dyslexia benefitted from learning from audio, while typically developing peers learned most from written text. In both chapters, audio-supported learning efficiency, especially in children with dyslexia, as a consequence of decreased study times. Compared to the adults at university, as presented in Chapters 2 and 6, these children form a heterogeneous group with much lower reading skills. The pace of the audio will therefore have been faster than their own reading speed, especially for the children with dyslexia (see Chapter 4), who are slow readers by definition (Lyon et al., 2003).

In Chapter 4 and 5 differences between transfer knowledge were observed – in Chapter 4 no multimedia effects where found, whereas in Chapter 5 a modality effect for children with dyslexia was observed. Notice that in Chapter 5 the children scored on average one point higher (on an 8-point scale) on transfer knowledge than they did in Chapter 4. This could be an indication that the children in this study had higher prior knowledge, which would have allowed them to better integrate the information in their memory (Cho et al., 2017), as that is necessary to make a good transfer. This would be especially beneficial for poor readers, who have more problems in processing written text. Hypermedia studies indeed showed that prior knowledge impacted knowledge gain differently in digital learning environments (Calisir et al., 2008; Calisir & Gurel, 2003). Having higher learning outcomes from reading than listening in typically developing children, is in line with Diao and Sweller (2007). This can be attributed to the transience of spoken language: it is not possible to gaze back to previous words or phrases. Typically developing children lean on the written word for remembering (Gerjets et al., 2009). Despite differences in transfer knowledge, in both chapters the same pattern regarding knowledge emerges: children with dyslexia learn most in the audio-only condition, while typically developing peers perform best in the combined text and audio condition. These results are in line with Beacham and Alty (2006) who also indicated that optimal conditions for typically developing learners are not automatically also optimal conditions for learners with dyslexia.

Combined, these studies show that audio-support leads to lower learning outcomes and efficiency in adults with and without dyslexia. They also show that in children with dyslexia audio-support does not have a negative effect on learning outcomes and may increase efficiency by reducing study time.

Process of Multimedia Learning

The second research question focused on how audio-support impacts **how** learners with and without dyslexia learn in multimedia environments. Both fine-grained (adults) and larger-grained (adults and children) learning processes were included.

In Chapter 2, it was found that audio-support impacted how students learned on a fine-grained level. University students with and without dyslexia looked longer and more often at the accompanying picture when they used audio-support compared to learning without audio-support. Also, on a larger-grained level, audio-support impacted learning processes, but only in adults and not in children (Chapter 3). Audio-support impacts navigation in adult learners towards the use of less internal regulation strategies. Both chapters did not found differences in learning processes between learners with and without dyslexia.

The results on how students' gaze changes when listening to information compared to reading-only (Chapter 2), are in line with existing literature on fine-grained learning processes (e.g., Krejtz et al., 2012; Schmidt-Weigand et al., 2010; Wiebe & Annetta, 2008). It shows that, even though students continue to be text-oriented, audio changes the way they examine the material. Even though more transitions can reflect better integration of multimodal information (Alemdag & Cagiltay, 2018), our findings are in line with Krebs and colleagues (2019) who showed that transitions were not related to knowledge (see paragraph 7.1). Audio-support facilitates more transitions, although no direct effect was found on learning outcomes.

Similar to the finding on fine-grained processes, we also found that in adults, audio-support impacted the larger-grained learning processes in multimedia learning (Chapter 3). Adults with more developed regulation skills (Zimmerman, 2000) and more experience in navigating through multimedia environments (Mead et al., 1997) showed more self-initiated decisions by means of revisiting previous pages. Audio-support, which is more linear in nature (from beginning to the end), impacted their navigation pattern towards use of more linear navigation patterns. As children already showed mostly linear navigation patterns, audio did not alter the way they navigated the material.

No differences were found between learners with and without dyslexia in both fine-grained (Chapter 2) as well as larger-grained learning processs (Chapter 3). That means that the way learners go through multimedia information, does not depend on reading ability per se. It is more likely that for learning in multimedia environments aspects like regulation abilities are much more important: the extent to which learners can foresee and model their desired learning path. In multimedia environments, self-regulation is indeed found to positively predict learning outcomes (Song et al., 2015), even though learners find it difficult to regulate their learning in such environments (Azevedo, 2014). Audio-support seems to hamper this regulation in adults, but not in children, probably since they already show less regulation.

Taken together, it can be stated that audio-support in multimedia environments affects learning processes similarly in learners with and without dyslexia. In adults, it affects fine-grained and larger-grained learning processes, even though the exact relation with learning outcomes is still unclear. In children, audio-support seems to have no impact on the way they navigate through multimedia environments.

Boundaries of Multimedia Learning

The third and last research question addressed the **boundary conditions** for efficient multimedia learning. Several possible boundary conditions (or so-called moderators) were taken into account: pacing of the material, timing of testing, and working memory capacities.

In Chapter 6, a long-term verbal redundancy effect on retention knowledge and one directly after learning in transfer knowledge was found in typically developing adults. Results in children in user-paced environments (Chapters 4 and 5) showed no impact of time of testing or working memory on multimedia learning. Hardly any differences between learners with and without dyslexia were found (Chapters 2, 4 and 5).

As expected, based on previous studies on the modality principle (e.g., Van den Broek et al., 2014; Ruf et al., 2014) *time of testing* (direct vs. later) and *type of knowledge assessed* (retention vs. transfer) seem to be important moderators of multimedia learning. However, the differences between children whose learning efficiency is improved by audio-support (Chapters 4 and 5) and adult learners whose learning is hindered by audio-support (Chapter 6) point toward a developmental constraint. This is in line with the findings in Reinwein's meta-analysis (2012) were he found similar differences regarding the modality effect comparing children, adolescents, and adults. Results from Chapter 3 seem to suggest that this developmental constraint could be (self-)*regulation capacities*. Self-regulation skills develop over time (De Jong & Van Joolingen, 1998; Zimmerman, 2000) and when learners must integrate and combine multiple forms of information (Graesser, 2007), regulating one's own learning process is essential (Azevedo

& Cromley, 2004; Caccamise et al., 2015). Audio may more strongly impact learners with more developed regulation capacities, as audio would interrupt the personalized regulation strategies, while younger learners may easily lean on "external steering" (like audio-support).

In contrast to the theoretical expectations, *working memory capacities* and *pacing* (which leans on the assumption of working memory overload by time pressure) seem less important boundary conditions regarding verbal redundancy (see Chapter 4, 5, & 6). Similar working memory did not constrain the modality effect (Chapters 4 and 5). The lack of impact of working memory on the examined multimedia effects is similar to that found in previous work (e.g., Gyselinck et al., 2008; Seufert et al., 2009; Witteman & Segers, 2010) and indicating that it is not a constraint in verbal redundancy. Chapter 6 shows that the abscence of impact of working memory capacity is not due to pacing differences.

To conclude, time of testing seems an important moderator for multimedia learning and research into multimedia principles should be aware that differences in learning outcomes may also depend on the way learning outcomes are assessed. Despite their theoretical importance, pacing and working memory do not seem to impact verbal redundancy and therefore may not be boundary conditions. In contrast, regulation capacities emerge as a new possible boundary condition.

Multimedia Learning and Dyslexia Revisited

The present dissertation aimed to shed more light on multimedia learning and dyslexia. Underlying the three research questions was the more general question how audio-support affects learning and thus highlighting the effect of verbal redundancy on learning outcomes in multimedia assignments. The results described above provide some guidance for refining the theory on multimedia learning.

The results in this dissertation do not necessarily contradict the CTML, but they do offer some nuance. Verbal redundancy can be considered as a combination of the two classical modality and redundancy principles of Mayer (2005). When comparing written-text-with-pictures and written-text-with-pictures-and-audio, the visual channel is maximally loaded in both cases: one must pay attention to both the picture and the text. When adding audio to this multimedia environment, according to the Cognitive Load Theory (CLT), the redundant auditory information requires unnecessary cognitive capacity, while according to the CTML, this only fills the 'empty' auditory processing channel and therefore does not overload auditory working memory. Present results are more in favor of the CLT in adults, and more in favor of the CTML in children.

The CTML is based on three assumptions: (1) the dual channel assumption – there are two separate channels for processing visual and verbal material (Paivio, 1986); (2) the limited capacity assumption - only a limited amount of information can be processed in a channel at any one time (Baddeley, 1995); and (3) the active processing assumption - meaningful learning occurs when relevant material is selected, organized and integrated (Wittrock, 1989; Mayer, 2005).

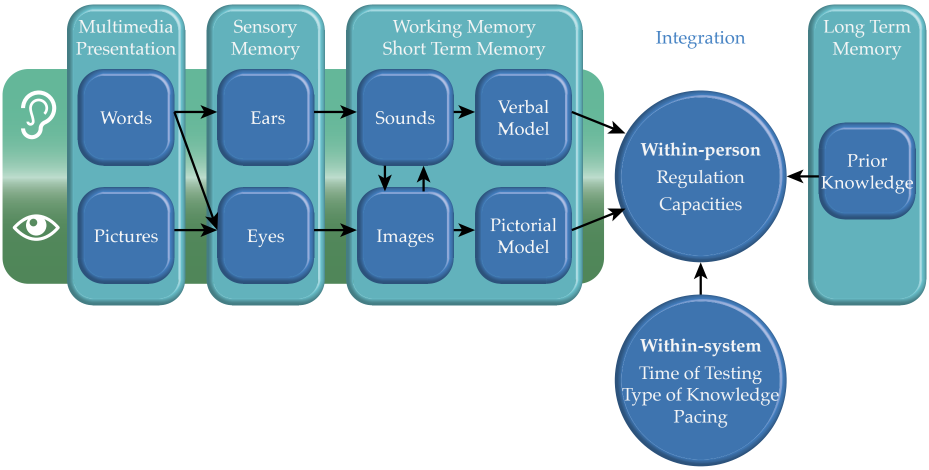
As posed before by Perfetti (1997), reading includes a verbal component as it leans on the combination of orthography and phonology. As such, the distinction the first assumption makes between the visual and verbal channel may be be too strict: there might be more overlap between these channels than is suggested by the CTML. That would support the explanation of the CLT that written and spoken words together are disadvantageous, as the auditory channel is 'double' loaded. In additon, results from this dissertation show that working memory capacity (the 'size' of the channels) is not the limiting factor for learning, as posited by assumption two. These results are consistent with previous research on the role of working memory in multimedia learning (e.g., Gyselinck et al., 2008; Witteman & Segers, 2010).

In this respect, the third assumption seems to be the crucial one. The way of processing information (assumption three) is the small circle in Mayer's traditional picture (see Figure 1.1 in General Introduction). The combined results on boundary conditions (Chapters 4 to 6) with the results in Chapter 3 endorse the fact that information processing must be active (and that audio makes it less active); this integration may very well depend on learners' regulatory capacities.

Therefore, an extended view on the multimedia learning process is proposed, in which the integration aspect is much more highlighted, as depicted in Figure 7.1. In line with results from present studies, the following changes are proposed to the original Figure 1.1, as presented in the General Introduction. Compared to the original figure, the two channels are presented as more interconnected, as depicted by the merging of the audio and the visal bar. The small circle, which represents integration, is enlarged to emphasize the importance of this particular phase. Integration takes place within a person, and individual differences in regulation capacities are proposed to be a limiting factor of efficient multimedia learning (within-*person* element in this enlarged integration circle). Next, the efficiency of information integration is, assumably, also dependent on within-*system* elements of efficient multimedia learning. Therefore, a second circle is added to the figure, with time of testing, type of knowledge and pacing. This includes material aspects, as learning outcomes may differ over time and across different types of knowledge. Even though pacing was not found to impact verbal redundancy, system-pacing does restrict the amount of knowledge acquired, and is therefore also included as within-system aspect. As such, this extended model of the CTML highlights the need for integration of information and acknowledges the fact that this depends on both person and system characteristics.

Figure 7.1

Cognitive Theory of Multimedia Learning Revisited



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Limitations and Directions for Future Research

Some limitations can be put forward. First, group sizes were relatively small, and, in adults, participants were high functioning (university students). By matching on school, class, and gender, and by using within-subject designs, we increased reliability of the studies. By choosing a more homogenous, high-functioning adult population, results would be more comparable to existing research. To gain a broader perspective on multimedia learning, future research should also include adolescents. As large differences in multimedia learning between children and adults were observed, research into this in-between-group has the potential to unmask the tipping point when audio-support stops being supportive for efficient multimedia learning.

Secondly, our studies would have benefitted from including an indepent measure of reading comprehension. That way we would have been able to detect possible differences between learners with and without dyslexia, or even individual differences in reading comprehension that could have influenced their learning (behavior) in the multimedia environments. The fact that we did not find differences in multimedia learning outcomes between learners with and without dyslexia is quite unexpected. Even though students with dyslexia are characterized by decoding problems and not comprehension difficulties, their decoding problems may lead to reduced reading comprehension (Snowling et al., 2020). It would be useful to know whether the lack of difference between learners with and without dyslexia in the present studies stems from aspects in the material (e.g., supporting pictures: multimedia principle, Mayer, 2005) or that the groups are indeed equal in reading comprehension. The latter would lead to the question on how these learners with dyslexia compensate for their decoding problems.

Third, a drawback in the studies is the fact that we do not know whether students read along with the audio or whether they are off-task. Chapter 2 partly tackles this problem, as we can see that students are text-oriented, however, we do not know whether students read the same words as the audio reads. It is likely that reading along with the audio (at the same pace) requires less cognitive load (Van Merriënboer & Sweller, 2010) than having to mentally 'block' the audio when it reads a different part of the text then you do yourself. Unfortunately, the stimuli used in Chapter 2 were not suitable for carrying out such an analysis, given the quantity of text on each page and the quality of the eye-tracking. For future research, however, it would be useful to find out, especially whether learners who read-along the audio learn more. In a similar vein, future research could investigate adapting the narration speed to match students' own reading speed. Such adaptation could have a positive influence on how cognitively demanding lessons are experienced and subsequently on learning outcomes (see also the work of Breznitz, e.g., Breznitz & Misra, 2003, on differences between modality asynchrony in learners with dyslexia).

Fourth, it is important to recognize the difference between fine-grained and larger-grained learning processes, and to recognize that there is a whole spectrum of learning processes that each in their own way provide information about the way learners create a mental model of a text. In this dissertation both ends of the spectrum are examined, but to give a more accurate impression of the actual process of learning, a larger part of the learning process should be captured. For example, fine-grained eye-tracking data can be merged into more meaningful constructs like reading strategies that are more easily connected to taught learning principles (e.g., examine the title and the picture, see Knoop-van Campen et al., 2021). In large multimedia environments with incorporated exercises, more specific log-file patterns can be distinguished that lend themselves to interpretating a self-regulation view (e.g., alternate between information pages and exercise pages, see Paans et al., 2020). As such, future research can develop an even broader view on learning processes in multimedia environments.

Finally, since the existing boundary conditions for multimedia learning may need to be expanded to regulation abilities (see 7.4), future research could incorporate (self-)regulation in multimedia learning. Learning within a multimedia environment, especially with all the current digital improvements, will only demand more of the learner. Research into self-regulation has the potential to reveal more about the learning process and could potentially be an indicator for distinguishing between efficient and inefficient learners.

Implications for Educational Practice

Generally speaking, audio-support has many advantages, as it can help to increase vocabulary and improve knowledge (MacArthur, 1996) and stimulate reading motivation (Byrom, 1998). Especially in students with dyslexia, audio-support may increase engagement and involvement in the material (Grusky et al., 2020; Rahman et al., 2010; Sidhu & Manzura, 2011), increase confidence (Caute et al., 2018), and support reading stamina and motivation (Larson, 2015). Results of the present dissertation acknowledge such advantages. However, some drawbacks of audio-support were also found, especially for adult learners. In that light, three implications for educational practice can be put forward.

First, publishers and creators should be motivated to include the possibility of audio-support in their materials for children, as it decreases their study time, especially in children with dyslexia.

Second, learners, especially adult learners, who use audio-support should receive instruction and explanation that informs them that although audio may support their reading, it can also negatively impact their deep learning and study effectiveness. When providing learners with audio-support, they have to learn how to use this support effectively by raising students' awareness of using audio-support and supporting them in its use. With this knowledge, students can make an informed decision about when they use audio-support during learning.

Finally, despite their crucial role in implementing educational technologies, teachers often have little knowledge on how audio can effectively be implemented (Koehler & Mishra, 2005). However, teachers can play an important role in supporting their students (children / adults) with regard to actively using the available audio-support. It is therefore argued to incorporate educational technologies with its possibilities and drawbacks in teacher education.

General Conclusions

The fact that audio-support is so often used as a compensatory aid for reading problems despite the lack of knowledge we have about its possible impact on learning (Greer et al. 2013), underlines the necessity of this dissertation. The findings in this dissertation show that theoretical models can certainly not be applied on a one-to-one basis to realistic learning environments. It happens often enough that scientific results are oversimplified for practical purposes, thereby losing nuance and quality. In addition, differential practices to distinct target groups tend to be overlooked (highly educated in the case of CTML, adult readers in Mayer's studies) and results are often automatically applied to completely different target groups, e.g., multimedia learning in children and user-paced environments.

Next to that, this dissertation highlights the importance of a developmental perspective when constructing theoretical models and provides a kick-start to research that combines learning processes and learning outcomes within such a developmental perspective. Specifically, future research should focus on learning processes in children and adolescents since they are still developing. The question raised in Chapter 4 remains: where is the tipping point when learning in multimedia learning environments is no longer efficient? For all learners, but especially the ones with dyslexia, the practical necessity is eminent; children and adults are more and more learning digitally in multimedia learning environments.

To conclude, this dissertation shows that audio-support in multimedia environments affects **what** learners learn, **how** learners learn, and that there are certain **boundary conditions** that apply to learning with audio-support. By combining the results on process measures with multimedia learning outcomes, argumentation for efficient learning can be made. After all, individuals can come to the same (correct) outcomes in various ways, but they can also provide different responses using similar approaches. Efficient learning is about being able to accurately and quickly absorb and retrieve the learning material. This dissertation shows that audio-support may indeed support children in doing so, but also that it is ineffective in adult learners, even those with dyslexia.

References

Alemdag, E., & Cagiltay, K. (2018). A systematic review of eye tracking research on multimedia learning. *Computers & Education, 125*, 413–428. https://doi.org/10.1016/j.compedu.2018.06.023

Azevedo, R. (2014). Multimedia learning of metacognitive strategies. In R.E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 647–672). Cambridge University Press. https://doi.org/10.1007/s11409-014-9123-1

Azevedo, R., & Cromley, J. G. (2004). Does training on self-regulated learning facilitate students' learning with hypermedia? *Journal of Educational Psychology, 96*(3), 523–535. https://doi.org/10.1037/0022-0663.96.3.523

Baddeley, A. (1995). *Working memory.* Oxford Psychology Series No. 11. Oxford: Clarendon Press.

Beacham, N. A., & Alty, J. L. (2006). An investigation into the effects that digital media can have on the learning outcomes of individuals who have dyslexia. *Computers & Education, 47*(1), 74–93. https://doi.org/10.1016/j.compedu.2004.10.006

Breznitz, Z., & Misra, M. (2003). Speed of processing of the visual–orthographic and auditory–phonological systems in adult dyslexics: The contribution of "asynchrony" to word recognition deficits. *Brain and language, 85*(3), 486-502. https://doi.org/10.1016/S0093-934X(03)00071-3

Byrom, G. (1998). If you can't read it then audio read it. *Reading, 32*(2), 3-7. https://doi.org/10.1111/1467-9345.00081

Caccamise, D., Friend, A., Littrell-Baez, M. K., & Kintsch, E. (2015). Constructive theory as a framework for instruction and assessment of reading. In S. R. Parris & K. Headley (Eds.), *Comprehension instruction: Research-based best practices* (3rd ed., pp. 88-104). Guilford Press.

Calisir, F., Eryazici, M., & Lehto, M. R. (2008). The effects of text structure and prior knowledge of the learner on computer-based learning. *Computers in Human Behavior, 24*(2), 439-450. https://doi.org/10.1016/j.chb.2007.01.032

Calisir, F., & Gurel, Z. (2003). Influence of text structure and prior knowledge of the learner on reading comprehension, browsing and perceived control. *Computers in Human Behavior, 19*(2), 135-145. https://doi.org/10.1016/S0747-5632(02)00058-4

Caute, A., Cruice, M., Marshall, J. Monnelly, K., Wilson, S., & Woolf, C. (2018). Assistive technology approaches to reading therapy for people with acquired dyslexia. *Aphasiology, 32*, 40-42. https://doi.org/10.1080/02687038.2018.1489119

Cho, B. Y., Woodward, L., Li, D., & Barlow, W. (2017). Examining adolescents' strategic processing during online reading with a question-generating task. *American Educational Research Journal, 54*(4), 691-724. https://doi.org/10.3102/0002831217701694

De Jong, T., & van Joolingen, W. R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research, 68*(2), 179–201. https://doi.org/10.3102/00346543068002179

Diao, Y., & Sweller, J. (2007). Redundancy in foreign language reading comprehension instruction: Concurrent written and spoken presentations. *Learning and Instruction, 17*(1), 78–88. https://doi.org/10.1016/j.learninstruc.2006.11.007

Dunsworth, Q., & Atkinson, R. K. (2007). Fostering multimedia learning of science: Exploring the role of an animated agent's image. *Computers & Education, 49*(3), 677–690. https://doi.org/10.1016/j.compedu.2005.11.010

Gerjets, P., Scheiter, K., Opfermann, M., Hesse, F. W., & Eysink, T. H. (2009). Learning with hypermedia: The influence of representational formats and different levels of learner control on performance and learning behavior. *Computers in Human Behavior, 25*(2), 360–370. https://doi.org/10.1016/j.chb.2008.12.015

Ghesquière, P., Boets, B., Gadeyne, E., & Vandewalle, E. (2011). Dyslexie: een beknopt wetenschappelijk overzicht. In A. Geudens, D. Baeyens, K. Schraeyen, K. Maetens, J. De Brauwer, & M. Loncke (Eds.), *Jongvolwassenen met dyslexie: diagnostiek en begeleiding in wetenschap en praktijk* (pp. 41-58). Acco Uitgeverij.

Graesser, A. C. (2007). An introduction to strategic reading comprehension. In D. S. McNamara (Ed.), *Reading comprehension strategies: Theories, interventions, and technologies* (pp. 3-26). Lawrence Erlbaum Associates Publishers.

Greer, D. L., Crutchfield, S. A., & Woods, K. L. (2013). Cognitive theory of multimedia learning, instructional design principles, and students with learning disabilities in computer-based and online learning environments. *Journal of Education, 193*(2), 41-50. https://doi.org/10.1177/002205741319300205

Grusky, M., Taft, J., Naaman, M., & Azenkot, S. (n.d.). Measuring and understanding online reading behaviors of people with dyslexia [Manuscript submitted for publication]. Cornell Tech, Cornell University.

Gyselinck, V., Jamet, E., & Dubois, V. (2008). The role of working memory components in multimedia comprehension. *Applied Cognitive Psychology, 22*(3), 353–374. https://doi.org/10.1002/acp.1411

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Knoop-van Campen, C. A. N., Doest, D. ter, Verhoeven, L., & Segers, E, (2021). The impact of audio on reading strategies in students with dyslexia. Annals of Dyslexia. http://doi.org/10.1007/s11881-021-00246-w

Koehler, M. J., & Mishra, P. (2005). Teachers learning technology by design. *Journal of Computing in Teacher Education, 21*(3), 94–102.

Krebs, M. C., Schüler, A., & Scheiter, K. (2019). Just follow my eyes: The influence of model-observer similarity on Eye Movement Modeling Examples. *Learning and Instruction, 61*, 126–137. https://doi.org/10.1016/j.learninstruc.2018.10.005

Krejtz, I., Szarkowska, A., Krejtz, K., Walczak, A., & Duchowski, A. (2012, March). Audio description as an aural guide of children's visual attention: Evidence from an eye-tracking study. *Proceedings of the symposium on eye tracking research and applications* (pp. 99–106). ACM. https://doi.org/10.1145/2168556.2168572

Larson, L. C. (2015). E-books and audiobook: extending the digital reading experience. *The Reading Teacher, 69*(2), 169-177. https://doi.org/10.1002/trtr.1371

MacArthur, C. A. (1996). Using technology to enhance the writing processes of students with learning disabilities. *Journal of Learning Disabilities, 29*(4), 344–354. https://doi.org/10.1177/002221949602900403

Mayer, R. E. (2005). *The Cambridge Handbook of Multimedia Learning*. Cambridge University Press. https://doi.org/10.1017/CBO9780511816819

Mayer, R. E., & Fiorella, L. (2014). 12 principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (Vol. 279, pp. 279-315). Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.015

Mead, S. E., Spaulding, V. A., Sit, R. A., Meyer, B., & Walker, N. (1997). Effects of age and training on World Wide Web navigation strategies. *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 41, No. 1, pp. 152-156). SAGE Publications. https://doi.org/10.1177/107118139704100135

Nelson, J. R., Balass, M., & Perfetti, C. A. (2005). Differences between written and spoken input in learning new words. *Written Language & Literacy, 8*(2), 25–44. https://doi.org/10.1075/wll.8.2.04nel

Paans, C., Molenaar, I., Segers, P. C. J., & Verhoeven, L. T. W. (2020). Children's macro-level navigation patterns in hypermedia and their relation with task structure and learning outcomes. *Frontline Learning Research, 8*(1), 76 – 95. https://doi.org/10.14786/flr.v8i1.473

Paivio, A. (1986). *Mental representations: A dual coding approach.* Oxford University Press.

Perfetti, C. A. (1997). *The psycholinguistics of spelling and reading.* Lawrence Erlbaum Associates.

Rahman, F. A., Mokhtar, F., Allas, N. A., & Umar, R. S. (2010). Interactive multimedia learning object (IMLO) for dyslextic children. *Procedia – Social and Behavioral Sciences, 47*, 1206-1210. https://doi.org/10.1016/j.sbspro.2012.06.801

Reinwein, J. (2012). Does the modality effect exist? And if so, which modality effect?. *Journal of psycholinguistic research, 41*(1), 1-32. https://doi.org/10.1007/s10936-011-9180-4

Ruf, A. P., Seckler, M., & Opwis, K. (2014). Long-term modality effect in multimedia learning. *Proceedings of the 8th Nordic Conference on Human–Computer Interaction: Fun, Fast, Foundational*, 963-966. https://doi.org/10.1145/2639189.2670251

Schmidt-Weigland, F., Kohnert, A., & Glowalla, U. (2010). A closer look at split visual attention in system-and self-paced instruction in multimedia learning. *Learning and Instruction, 20*(2), 100–110. https://doi.org/10.1016/j.learninstruc.2009.02.011

Seufert, T., Schutze, M., & Brunken, R. (2009). Memory characteristics and modality in multimedia learning: An aptitude–Treatment–Interaction study. *Learning and Instruction, 19*(1), 28–42. https://doi.org/10.1016/j.learninstruc.2008.01.002

Sidhu, M. S. & Mazura, E. (2011). An effective conceptual multisensory multimedia model to support dyslexic children in learning. *International Journal of Information and Communication Technology Education, 7*(3), 34-50. https://doi.org/10.4018/jicte.2011070104

Snowling, M. J., Hayiou-Thomas, M. E., Nash, H. M., & Hulme, C. (2020). Dyslexia and Developmental Language Disorder: comorbid disorders with distinct effects on reading comprehension. *Journal of Child Psychology and Psychiatry, 61*(6), 672-680. https://doi.org/10.1111/jcpp.13140

Song, H. S., Kalet, A. L., & Plass, J. L. (2016). Interplay of prior knowledge, self-regulation and motivation in complex multimedia learning environments. *Journal of Computer Assisted Learning, 32*(1), 31-50. https://doi.org/10.1111/jcal.12117

Van den Broek, G. S. E., Segers, E., & Verhoeven, L. (2014). Effects of text modality in multimedia presentations on written and oral performance. *Journal of Computer Assisted Learning*, *30*, 438–440. https://doi.org/10.1111/jcal.12058
Van Merrienboer, J. J., & Sweller, J. (2010). Cognitive load theory in health professional education: Design principles and strategies. *Medical Education*, *44*(1), 85–93. https://doi.org/10.1111/j.1365-2923.2009.03498.x
Wiebe, E., & Annetta, L. (2008). Influences on visual attentional distribution in multimedia instruction. *Journal of Educational Multimedia and Hypermedia*, *17*(2), 259–277. https://eric.ed.gov/?id=EJ786627
Witteman, M. J., & Segers, E. (2010). The modality effect tested in children in a user-paced multimedia environment. *Journal of Computer Assisted Learning*, *26*, 132–142. https://doi.org/10.1111/j.1365-2729.2009.00335.x
Wittrock, M. C. (1989). Generative processes of comprehension. *Educational psychologist*, *24*(4), 345-376. https://doi.org/10.1207/s15326985ep2404_2
Zimmerman, B. (2000). Attaining self-regulation: A social cognitive perspective. In M. Boekaerts, P. Pintrich, & M. Zeidner (Eds.), *Handbook of self–regulation* (pp. 13–39). San Diego, CA: Academic. https://doi.org/10.1016/B978-012109890-2/50031-7

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APPENDICES

SUMMARY
SAMENVATTING
DANKWOORD
AUTHOR BIOGRAPHY
PUBLICATIONS

Summary

Rationale for this Dissertation

Multimedia learning environments are becoming more and more common in education. In these environments, information is presented in pictorial, written, and/or auditorial form. A specific form of a multimedia learning environment is the audio-support children and adults with dyslexia often use to compensate for their reading problems. However, while audio-support may compensate reading problems, it may also impact learning.

According to the Cognitive Theory of Multimedia Learning (CTML) two multimedia principles are particularly relevant for explaining the impact of audio-support on learning: the modality principle and the redundancy principle. The modality principle states that people learn less from pictures-with-written-text as compared to pictures-with-audio due to offloading the working memory. The redundancy principle states that presenting the same content simultaneously as written text and as audio would hamper learning, due to overloading the working memory. Thus, theoretically, audio-support as an addition to written text could be debatable.

For students with dyslexia, on the one hand it can be hypothesized that adding audio to written text could enhance learning since it compensates for their reading difficulties. On the other hand, working memory in students with dyslexia is often found to be impaired, and they also seem to process information differently than typically developing peers. Both on fine-grained as on larger-grained learning processes, students with dyslexia show differences in the way they process (multimodal) information. Indeed, existing research is inconclusive regarding the extent to which audio-support impacts learning in learners with dyslexia.

In addition, existing research on audio-support mostly focuses on high functioning typically developing adults in system-paced environments with direct learning effects as main interests of study. While in educational practice, learning occurs at an individual pace (user-paced) and the goal is to retain knowledge in the long term. The few available multimedia studies that do investigate learning in user-paced environments and/or learning outcomes measured in the long term, indicate that there are certain boundary conditions (or so-called moderators) to efficient multimedia learning. This indicates that the Cognitive Theory of Multimedia Learning may not apply to all situations and all learners similarly.

Therefore, the main goal of the current dissertation is to examine how audio-support affects learning of learners with and without dyslexia.

Research Questions

Audio-support is often used in education to compensate for reading problems, even though this may theoretically hamper knowledge acquisition (learning). It is by no means clear what the effect of audio-support is on **what** and **how** adults and children with dyslexia learn in multimedia environments and what the **boundary conditions** are for efficient multimedia learning.

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Therefore, the aim of the present dissertation is to provide insights into the learning behavior and short- and long-term learning outcomes of adults and children with dyslexia as compared to their typically developing peers in multimedia learning environments. The following three research questions were addressed:

RQ 1 To what extent does audio-support impact **what** these learners learn?
RQ 2 To what extent does audio-support impact **how** these learners learn?
RQ 3 What are **boundary conditions** for efficient multimedia learning?

Research Design

These research questions were addressed in four experimental studies with similar set-ups. Two studies involved university students and two studies included primary school children from grade 5. A total of 146 adults (42 with dyslexia and 104 controls) and 106 children (47 with dyslexia and 59 controls) participated in the studies.

Participants took part in multimedia biology lessons suitable for their age (adult or child version). In order to resemble educational practice, participants attended one lesson per week. After each lesson, participants immediately filled out the first posttest to measure the learning effect in the short-term. A second version of the posttest was administered a week later to measure long-term effects. All the lessons included pictorial information accompted by written text and/or audio-support. Adults were presented with one lesson in which information was presented as written-text-with-pictures, and one lesson in which written-text-with-pictures was also accompanied by audio-support reading the text aloud. The children received the same two types of lessons as the adults. However, as in educational practices, children sometimes also use audio-support without reading along. Therefore, children were also presented with one additional lesson in which information was presented as pictures with audio-only.

To measure fine-grained learning processes, eye-tracking was used. Eye-tracking measured the eye movements of a student during learning. To measure larger grained learning processes, log files were tracked. Log files indicated when a participant moved to the next/previous page within the multimedia environment.

Results & Conclusions

Research Question 1: Multimedia Learning Outcomes

The first research question concerned the extent to which audio-support impacts **what** learners with dyslexia learn compared to their typically developing peers. Therefore, it focused on short and long-term learning outcomes in multimedia environments and included both the recall of facts (retention) and application of the learned knowledge in a new situation (transfer knowledge).

Audio-support leads to lower learning outcomes and longer study times in adults with and without dyslexia (Chapters 2 and 6). In this group audio-support thus leads to lower learning efficiency. In children with dyslexia, however, audio-support does not negatively affect learning outcomes and by reducing study time, increases efficiency (Chapters 4 and 5).

Research Question 2: Multimedia Learning Processes

The second research question focused on the extent to which audio-support impacts **how** learners with and without dyslexia learn. Both fine-grained (adults) and larger-grained (adults and children) learning processes were considered.

Audio-support affects learning processes similarly in learners with and without dyslexia. In adults, it affects both fine-grained (Chapter 2) and larger-grained learning processes (Chapter 3), even though the exact relation with learning outcomes could not yet be established. Chapter 3 also shows that in children, audio-support does not impact the way they navigate through multimedia environments (larger-grained learning processes).

Research Question 3: Boundaries of Multimedia Learning

The third and last research question addressed the **boundary conditions** for efficient multimedia learning. Several possible boundary conditions were taken into account: time of testing, working memory, and pacing of the material.

Time of testing seems to be an important moderator for multimedia learning (Chapters 4, 5, and 6). Despite their theoretical importance, pacing (Chapter 6) and working memory (Chapters 4, 5, and 6) do not seem to impact learning with audio-support and therefore may not be boundary conditions.

The differences between children, whose learning efficiency is improved by audio-support (Chapters 4 and 5), and adult learners, whose learning is hindered by audio-support (Chapter 6), point toward a developmental constraint. Results from Chapter 3 suggest that this developmental constraint could be (self-)regulation capacities. Audio may more strongly impact learners with more developed regulation capacities, as audio would interrupt the personalized regulation strategies, while younger learners may easily lean on "external steering" (like audio-support).

Implications for Theory

The present dissertation aimed to shed more light on multimedia learning and dyslexia. Overarching the three research questions, the more general question was: how does audio-support affect learning? As such, this dissertation highlights the effect of verbal redundancy on learning outcomes in multimedia assignments. The results provide some guidance for refining the theory on multimedia learning. Three modifications to the original Cognitive Theory of Multimedia Learning are put forward:

a) The visual and verbal channels are more interconnected;
b) Integration of information is more important;
c) Integration depends on both person and system characteristics.

Regulation capacities are proposed to be a limiting factor of efficient multimedia learning (within-person element), while the efficiency of information integration seems also dependent on type of knowledge, time of testing, and pacing (within-system element). This extended model of the CTML (see Figure 7.1 in Chapter 7) highlights the need for integration of information and acknowledges the fact that this depends on both person and system characteristics.

Implications for Practice

Generally speaking, audio-support has many advantages for learners. However, from this dissertation some drawbacks of audio-support emerge also, especially for adult learners. In that light, three recommondations for educational practice are suggested.

First, publishers and creators of educational materials should be motivated to include the possibility of audio-support in their materials for children, as it decreases their study time. Second, learners who use audio-support should receive explanation and instruction about the possible impact audio-support can have on their learning process and outcomes. This way, they can learn how to use audio-support effectively. Finally, teachers can play an important role in supporting their students with regard to actively using the available audio-support. It is therefore recommended to incorporate the possibilities and drawbacks of audio-support in teacher education.

General Conclusion

The findings in this dissertation show that theoretical models can certainly not be applied on a one-to-one basis to authentic learning environments. It also highlights the importance of a developmental perspective when constructing theoretical models.

In addition, they show that audio-support in multimedia environments affects **what** learners learn, **how** learners learn, and that there are certain **boundary conditions** that apply to learning with audio-support. This dissertation shows that audio-support may support children in efficient multimedia learning, but that it is ineffective in adult learners, even those with dyslexia.

Samenvatting

Aanleiding voor dit Proefschrift

Multimediale leeromgevingen worden steeds meer gebruikt in het onderwijs. In zulke leeromgevingen wordt informatie gepresenteerd in beeldende, geschreven en/of auditieve vorm. Zo maken kinderen en volwassenen met dyslexie vaak gebruik van audio-ondersteuning als compensatie voor hun leesproblemen. Het gebruik van audio-ondersteuning kan echter ook gevolgen hebben voor het leren.

Volgens de Cognitieve Theorie van Multimedia Leren (CTML) zijn in het bijzonder twee multimedia-principes relevant om het effect van audio-ondersteuning op het leren te begrijpen: het modaliteitsprincipe en het redundantieprincipe. Het modaliteitsprincipe stelt dat mensen minder leren van plaatjes-met-geschreven-tekst in vergelijking met plaatjes-met-audio doordat het werkgeheugen wordt ontlast. Het redundantieprincipe stelt dat het gelijktijdig presenteren van dezelfde informatie, zoals geschreven tekst en audio, het leren zou belemmeren door overbelasting van het werkgeheugen. Theoretisch gezien kan audio-ondersteuning bij geschreven tekst aldus ter discussie worden gesteld.

Specifiek voor leerlingen met dyslexie kan enerzijds verondersteld worden dat het toevoegen van audio aan geschreven tekst het leren zou kunnen verbeteren, omdat het hun leesproblemen compenseert. Anderzijds blijkt het werkgeheugen bij leerlingen met dyslexie vaak verminderd te zijn, en lijken zij informatie ook anders te verwerken dan typisch ontwikkelende leeftijdgenoten. Zowel bij het fijnmazige als bij het grofmazige leerproces vertonen leerlingen met dyslexie verschillen in de manier waarop zij (multimodale) informatie verwerken. Bestaand onderzoek is dus niet eenduidig wat betreft de mate waarin audio-ondersteuning invloed heeft op het leren bij leerlingen met dyslexie.

Bovendien is bestaand onderzoek naar audio-ondersteuning meestal gericht op hoog-functionerende, typisch ontwikkelende volwassenen in systeem-gestuurde omgevingen met directe leereffecten als onderwerp van studie. Terwijl in de onderwijspraktijk het leren plaatsvindt op individueel tempo (user-paced) en het doel is om kennis op de lange termijn te behouden. De weinig beschikbare multimediastudies die het leren in user-paced omgevingen en/of de leerresultaten op de lange termijn onderzoeken, geven aan dat er bepaalde randvoorwaarden (of zogenaamde moderatoren) zijn voor efficiënt multimedia leren. Dat betekent dat de Cognitieve Theorie van Multimedia Leren mogelijk niet op alle situaties en alle mensen in gelijke mate van toepassing is. Het hoofddoel van dit proefschrift is daarom om te onderzoeken hoe audio-ondersteuning het leren van leerlingen en studenten met en zonder dyslexie beïnvloedt.

Onderzoeksvragen

Audio-ondersteuning wordt in het onderwijs vaak gebruikt ter compensatie van leesproblemen, ook al kan dit theoretisch gezien de kennisverwerving (het leren) belemmeren. Het is nog lang niet duidelijk wat het effect van audio-ondersteuning is op **wat** en **hoe** volwassenen en kinderen met dyslexie leren in multimedia-omgevingen en wat de **randvoorwaarden** zijn voor efficiënt multimediaal leren.

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Om deze redenen is het doel van het huidige proefschrift om inzicht te verschaffen in het leergedrag en de korte- en lange-termijn leerresultaten van volwassenen en kinderen met dyslexie in vergelijking met typisch ontwikkelende leeftijdsgenoten, in een multimediale leeromgeving. De volgende drie onderzoeksvragen werden onderzocht:

Vraag 1 In welke mate heeft audio-ondersteuning invloed op **wat** deze leerlingen leren?
Vraag 2 In hoeverre heeft audio-ondersteuning invloed op **hoe** deze leerlingen leren?
Vraag 3 Wat zijn de **randvoorwaarden** voor efficiënt multimediaal leren?

Onderzoeksopzet

De bovengenoemde onderzoeksvragen werden onderzocht in vier experimentele studies, vergelijkbaar van opzet. Twee studies betroffen universiteitsstudenten en twee studies zijn uitgevoerd bij basisschoolkinderen uit groep 7. In totaal participeerden er 146 volwassenen (42 met dyslexie en 104 zonder dyslexie) en 104 kinderen (47 met dyslexie en 59 zonder dyslexie).

De participanten kregen de opdracht verschillende multimediale biologielessen (volwassen of kinderversie) te leren. Om gelijkenis met de onderwijspraktijk te creëren, werd elke week één les aangeboden. Direct na een les vulden de participanten de eerste nameting waardoor het leereffect op korte termijn kon worden gemeten. Een tweede versie van de nameting werd een week later afgenomen om de langetermijneffecten te meten. Alle lessen hadden plaatjes met geschreven tekst en/of gesproken tekst (audio-ondersteuning). Volwassenen kregen één les waarin de informatie werd gepresenteerd als geschreven-tekst-met-plaatjes, en één les met geschreven-tekst-met-plaatjes met audio-ondersteuning. Aangezien kinderen in het onderwijs soms ook gebruik maken van audio-ondersteuning zonder mee te lezen, kregen de kinderen drie multimedialessen. Naast dezelfde twee type lessen als de volwassenen, kregen ze ook een les waarin de informatie werd gepresenteerd als enkel audio met plaatjes.

Om de leerprocessen fijnmazig te meten, werd gebruik gemaakt van *eye-tracking*. *Eye-tracking* meet de oogbewegingen van een leerling tijdens het leren. Om leerprocessen ook grofmazig te meten, werden logbestanden bijgehouden. Logbestanden gaven aan wanneer een deelnemer naar een volgende/vorige pagina ging binnen de multimedia-omgeving.

Resultaten & Conclusies

Onderzoeksvraag 1: Leeruitkomsten van Multimedia Leren

Met behulp van de eerste onderzoeksvraag is onderzocht in hoeverre audio-ondersteuning invloed heeft op **wat** mensen met dyslexie leren in vergelijking met mensen zonder dyslexie. Zodoende richtte het huidige onderzoek zich op leerresultaten op korte en lange termijn in multimedia-omgevingen en omvatte het zowel het herinneren van feiten (retentie) als het toepassen van de verworven kennis in een nieuwe situatie (transfer).

In volwassenen met en zonder dyslexie leidt audio-ondersteuning tot lagere leerresultaten en lagere efficiëntie (Hoofdstukken 2 en 6). Bij kinderen met dyslexie heeft audio-ondersteuning echter geen negatief effect op de leerresultaten, en kan het de efficiëntie verhogen door de studietijd te verkorten (Hoofdstukken 4 en 5).

Onderzoeksvraag 2: Het Proces van Multimedia Leren

De tweede onderzoeksvraag richtte zich op hoe audio-ondersteuning van invloed is op **hoe** mensen met en zonder dyslexie leren in multimediale leeromgevingen. Zowel fijnmazige (volwassenen) als grofmazige (volwassenen en kinderen) leerprocessen werden meegenomen.

Audio-ondersteuning beïnvloedt op vergelijkbare wijze het leerproces bij mensen met en zonder dyslexie. Bij volwassenen beïnvloedt audio-ondersteuning zowel de fijnmazige (Hoofdstuk 2) als grofmazige leerprocessen (Hoofdstuk 3), hoewel de precieze relatie met leerresultaten nog niet vastgesteld kon worden. Hoofdstuk 3 laat bovendien zien dat audio-ondersteuning bij kinderen geen invloed heeft op de manier waarop zij door multimediale leeromgevingen navigeren (grofmazige leerprocessen).

Onderzoeksvraag 3: Randvoorwaarden van Multimedia Leren

De derde en laatste onderzoeksvraag betreft de **randvoorwaarden** voor efficiënt multimedia leren. Verschillende mogelijke randvoorwaarden werden onderzocht: moment van testen, werkgeheugen en het tempo van het materiaal.

Het moment van testen blijkt een belangrijke moderator te zijn voor multimedia leren (Hoofdstukken 4, 5 en 6). Tempo (Hoofdstuk 6) en werkgeheugen (Hoofdstukken 4, 5 en 6) lijken, ondanks hun theoretisch belang, geen invloed te hebben op leren met audio-ondersteuning. Deze vindingen geven aan dat tempo en werkgeheugen wellicht geen randvoorwaarden zijn van multimedia leren.

De verschillen tussen kinderen - bij wie de leerefficiëntie wordt verbeterd door audio-ondersteuning - en volwassen - bij wie het leren wordt belemmerd door audio-ondersteuning - zijn een indicatie dat er sprake kan zijn van een ontwikkelingsperspectief. De resultaten uit Hoofdstuk 3 suggereren dat het kan gaan om (zelf)regulatievaardigheden. Audio kan een grotere invloed hebben op mensen met een beter ontwikkeld reguleringsvermogen, aangezien audio individuele regulatiestrategieën kan verstoren, terwijl kinderen met een minder ontwikkeld regulatievermogen makkelijker kunnen leunen op “externe sturing” (zoals audio-ondersteuning).

Implicaties voor de Wetenschap

Het doel van het huidige proefschrift was om meer inzicht te krijgen in multimedia leren en dyslexie. Onderliggend aan de drie onderzoeksvragen was de meer algemene vraag hoe audio-ondersteuning het leren beïnvloedt, om zo het effect van verbale redundantie op leerresultaten te belichten. De hierboven beschreven resultaten bieden enig houvast voor het verfijnen van de theorie over multimedia leren. Drie veranderingen betreffende de Cognitieve Theorie van Multimedia Leren worden voorgesteld:

a) De visuele en verbale informatieverwerkingskanalen zijn meer met elkaar verbonden dan voorheen werd aangenomen;
b) Er is een grotere noodzaak van integratie van informatie;
c) Integratie hangt af van zowel persoons- als systeemkenmerken.

Het regulatievermogen is een nieuwe, potentiele beperkende factor voor efficiënt multimedia leren (persoonlijk element), terwijl de efficiëntie van de informatie-integratie ook afhankelijk lijkt te zijn van het moment van testen, het soort kennis en het tempo (systeemelementen). Het uitgebreide model van de CTML (zie Figuur 7.1 in Hoofdstuk 7) belicht de behoefte aan integratie van informatie en erkent dat dit afhankelijk is van zowel persoons- als systeemelementen.

Implicaties voor de Onderwijspraktijk

Over het algemeen heeft audio-ondersteuning veel voordelen, maar dit proefschrift toonde voor volwassenen ook enkele nadelen aan. Drie implicaties voor de onderwijspraktijk worden besproken.

Ten eerste zou men uitgevers en makers van onderwijsmateriaal moeten motiveren om de mogelijkheid van audio-ondersteuning op te nemen in hun lesmateriaal voor kinderen, omdat het (vooral bij kinderen met dyslexie) de leertijd verkort. Ten tweede zouden mensen die gebruik maken van audio-ondersteuning instructie en uitleg moeten krijgen over de mogelijke impact van audio-ondersteuning op hun leerproces en -resultaten. Zodoende leren zij audio-ondersteuning efficiënt in te zetten. Ten slotte kunnen leerkrachten een belangrijke rol spelen in het ondersteunen van hun leerlingen door actief gebruik te maken van de beschikbare audio-ondersteuning. Er wordt daarom gepleit om zowel de mogelijkheden als nadelen van audio-ondersteuning in de lerarenopleiding op te nemen.

Algemene Conclusies

De resultaten beschreven in dit proefschrift laten zien dat theoretische modellen zeker niet één op één toegepast kunnen worden in natuurlijke leeromgevingen. Het benadrukt daarnaast dat het belangrijk is om ontwikkelingen over tijd (en dus verschillen tussen kinderen en volwassenen) mee te nemen bij het construeren van theoretische modellen.

Dit proefschrift toont aan dat audio-ondersteuning in multimedia-omgevingen invloed heeft op **wat** leerlingen leren, **hoe** leerlingen leren, en dat er bepaalde **randvoorwaarden** zijn die gelden voor leren met audio-ondersteuning. Audio-ondersteuning kan kinderen ondersteunen bij efficiënt multimedia leren, maar is ineffectief bij volwassenen - zelfs bij volwassenen met dyslexie.

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Author Biography

Carolien Knoop-van Campen (Nijmegen, 1987) graduated from the Stedelijk Gymnasium Nijmegen, with the profiles Nature & Health and Nature & Technology in 2006. In the following years she obtained her Bachelor in Pedagogy at the Hogeschool van Arnhem en Nijmegen, and her Bachelor in Pedagogical and Educational Sciences at the Radboud University (RU) Nijmegen. To pursue both her interest in research and her ambition to be practically relevant, she first completed the two-year Research Master's degree in Behavoural Science (RU) and then obtained her diagnostic qualification as a child psychologist (*orthopedagoog*) through a practical internship in primary education.

In 2015, she started a PhD project at the Behavioural Science Institute at the Department of Learning and Development with her own research proposal. Within this project, Carolien conducted research on multimedia learning in children and adults with dyslexia. In 2018 she was nominated for the Christine Mohrmann Stipendium for promising female PhD candidates. To further specialize in learning processes, Carolien attended an international eye-tracking course at Utrecht University (UU) and went on a working visit to Prof. Dr. Ladislao Salmerón in Valencia. She is a member of the EARLI Special Interest Group 27 'Online Measures of Learning Processes'and has presented her research at various national and international conferences and symposia. She regularly presents her work to the educational field, for example at the annual National Dyslexia Conference and during training days for e.g., the Regional Institute for Dyslexia and the CED-group. Carolien taught undergraduate and graduate students of the Pedagogical Sciences and Educational Sciences programme and obtained her Basic Teaching Qualification (BKO) in 2019.

In addition to her PhD research, from 2014 onwards Carolien has been working within the Adaptive Learning Lab (RU) on research into adaptive learning environments and teacher dashboards, where she continues to work as a postdoc with dr. Inge Molenaar. She is also involved as a postdoc on the 'Tussen Wal en Schip' project of prof. dr. Evelyn Kroesbergen on twice-exceptional students. Carolien works together with dr. Ellen Kok (UU) on research into the application of eye-tracking data in reading comprehension education. She also continues her teaching at the Pedagogical Sciences and Educational Sciences programme (RU).

Publications

Scientific Publications

Knoop-van Campen*, C. A. N., Kok*, E., Doornik, R. van, Vries, P. de, Immink, M., Gog, T. van, & Jarodzka, H. (2021). How teachers interpret displays of students' gaze in reading comprehension assignments. *Frontline Learning Research, 9*(4), 116-140.
* shared first authorship

Knoop-van Campen, C. A. N., Doest., D. ter, Verhoeven, L., & Segers, E. (2021). The effect of audio-support on strategy, time, and performance on reading comprehension in secondary school students with dyslexia. *Annals of Dyslexia*, 1-20.

Knoop-van Campen, C. A. N., Wise, A. F., & Molenaar, I. (2021). The equalizing effect of teacher dashboards on feedback type and allocation in a K-12 classroom. *Interactive Learning Environments*, 1-17.

Leeuwen, A. van, **Knoop-van Campen**, C. A. N., Molenaar, I., & Rummel, N. (2021). How teacher characteristics relate to how teachers use dashboards: Results from two case studies in K-12. *Journal of Learning Analytics*, 8(2), 6-21.

Knoop-van Campen, C. A. N., & Molenaar, I. (2020). How teachers integrate dashboards into their feedback practices. *Frontline Learning Research*, 8(4), 37-51.

Knoop-van Campen, C. A. N., Segers, E, & Verhoeven, L. (2020). Effects of audio support on multimedia learning processes and outcomes in students with dyslexia. *Computers & Education*, 150, 103858.

Knoop-van Campen, C. A. N, Segers, E., & Verhoeven, L. (2019). Modality and redundancy effects, and their relation to executive functioning in children with dyslexia. *Research in developmental disabilities, 90*, 41-50.

Molenaar, I. & **Knoop-van Campen**, C. A. N. (2019). How teachers make dashboard information actionable. *IEEE Transactions on Learning Technologies*, *12*(3), 347-355.

Knoop-van Campen, C. A. N., Segers, E., & Verhoeven, L. (2018). The modality and redundancy effects in multimedia learning in children with dyslexia. *Dyslexia, 24*(2), 140-155.

Knoop-van Campen, C. A. N., Segers, E., & Verhoeven, L. (2018). How phonological awareness mediates the relation between working memory and word reading efficiency in children with dyslexia. *Dyslexia, 24*(2), 156-169.

Van Leeuwen, A., Rummel, N., Holstein, K., McLaren, B. M., Aleven, V., Molenaar, I., **Knoop-van Campen**, C. A. N., Schwarz, B., Prusak, N., Swidan, O., Segal, A., & Gal, K. (2018). Orchestration tools for teachers in the context of individual and collaborative learning: what information do teachers need and what do they do with it?. In Kay, J. and Luckin, R. (Eds.) *Rethinking Learning in the Digital Age: Making the Learning Sciences Count.* London, UK.

Molenaar, I. & **Knoop-van Campen**, C. A. N. (2017). Teacher dashboards in practice: usage and impact. *In European Conference on Technology Enhanced Learning* (pp. 125-138). Springer, Cham. (Best paper award EC-TEL).

Molenaar, I., **Knoop-van Campen**, C. A. N., & Hasselman, F. (2017). The effects of a learning analytics empowered technology on students' arithmetic skill development. *In Proceedings of the Seventh International Learning Analytics & Knowledge Conference* (pp. 614-615). ACM.

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Molenaar, I. & **Knoop-van Campen**, C. A. N. (2017, Sept). *How Teachers Differ in Using Dashboards: the Classroom Observation App*. Paper presented at the CROSS MMLA: Multimodal Learning Analytics Across Spaces Workshop at European Conference on Technology Enhanced Learning 2017, Tallinn, Estland.

Molenaar, I. & **Knoop-van Campen**, C. A. N. (2016). Learning analytics in practice: the effects of adaptive educational technology Snappet on students' arithmetic skills. *In Proceedings of the Sixth International Conference on Learning Analytics & Knowledge Conference* (pp. 538-539). ACM.

Professional Publications

Knoop-van Campen, C. A. N., & Segers, E. (2021). De invloed van audio-ondersteuning op leesstrategieën bij leerlingen met dyslexie. In E. Segers & R. Van Steensel (Reds.), *De nieuwe lezer.* Delft: Eburon.

Knoop-van Campen, C. A. N., Segers, E, & Verhoeven, L. (2019). Kinderen met dyslexie leren efficiënter met audio-ondersteuning. *Tijdschrift voor Remedial Teachers, 3*, 20-23.

Knoop-van Campen, C. A. N., Segers, E., & Verhoeven, L. (2017). Multimedialeren bij kinderen met dyslexie. In R. Van Steensel & E. Segers (Reds.), *Succesvol lezen in het onderwijs.* Delft: Eburon.

Molenaar, I., Bakker, M., **Knoop-van Campen**, C. A. N., & Hasselman, F. W. (2017). Onderwijsvernieuwing met een adaptief leermiddel: richting gepersonaliseerd leren. Nijmegen: The Adaptive Learning Lab, Behavioural Science Institute, Radboud Universiteit.

Molenaar, I., **Knoop-van Campen**, C. A. N., & van Gorp, K. (2016). Rapportage Kennisnet: onderzoek naar Snappet; gebruik en effectiviteit. Nijmegen: Behavioural Science Institute, Radboud Universiteit.

Position Paper (contributor)

Xhomaqi, B., Todd, A., Boivin, P., & Ramírez, J. B. (2019). *21st century learning environments*. LifeLong Learning Platform (LLLP) Position Paper. Brussels, Belgium.

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