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Effects of audio support on multimedia learning processes and outcomes in students with dyslexia

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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 process and learning outcomes in students with and without dyslexia can shed light on this issue and helps 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 time 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.

On a daily basis, students with dyslexia are provided with audio support to aid their reading (Ghesquière, Boets, Gadeyne, & Vandewall, 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 is (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, Lai, & Chuang, 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

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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.

1. 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 at the same time, 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 evidenced: people learn more when information is presented auditory (Jamet & Le Bohec, 2007; Kalyuga, Chandler, & Sweller, 1999; Moreno & Mayer, 2002). Some studies, however, found reversed redundancy effects. For example, Ari et al. (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, Segers, and Verhoeven (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, Van Hooijdonk, & Lagerwerf, 2017). When the degree of redundancy between written and narrated content was manipulated (Roscoe, Jacovina, Harry, Russell, & McNamara, 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, Whitley, & Vila, 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) that explains the effects via working memory overload. The instructional orientated Cognitive Load Theory (Sweller, Ayres, & Kalyuga, 2011) addresses this discrepancy issue from a slightly different angle and focusses on the limitations of the working memory. This theory indicates that there are three different ways to (over)load working memory: via intrinsic, extrinsic and germane load (Sweller, Van Merriënboer, & Paas, 1998). The redundancy effect -with its two similar information sources-specifically involves increased extrinsic cognitive load (Van Merriënboer & Sweller, 2010). As reducing one of these sources should result in lower extrinsic 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 extrinsic 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.

2. 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 et al. (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 accompanied 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, Szarkowska, Krejtz, Walczak, & Duchowski, 2012). Krejtz et al. (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 (e.g., Koć-Januchta, Höffler, Thoma, Prechtl, & Leutner, 2017; Mason, Pluchino, & Tornatora, 2016; Ponce, Mayer, Loyola, Lopez, & Mendez, 2018; Tsai, Huang, Hou, Hsu, & Chiou, 2016) instead of directly relating the two to each other. The field is thus in need of studies that make the direct link between process measures and outcomes.

3. 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, is the group of students with dyslexia. These students have phonological deficits and experience reading difficulties (Lyon, Shaywitz, & Shaywitz, 2003). Even though they can acquire reading comprehension skills, their graphene-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, Tønnessen, Ersland, & Hugdahl, 2010) which potentially also increases the problems of the extrinsic 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, Boets, Gadeyne, & Vandewall, 2010, pp. 41–58). 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 extrinsic cognitive overload but also decreases 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, Segers, and Verhoeven (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, Leuwers, & Hilton, 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, pp. 24–48) 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, Silvestri, Allingham, Parrila, & La Fave, 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, Donnadieu, and Valdois (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 to graph and text comprehension, showed that students with dyslexia needed more time for processing both text as well as graphs (Kim, Lombardino, Cowles & Altman, 2014). In addition, Schmidt-Weigand, Kohnert, and Glowalla (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 added 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.

4. 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:

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?
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 amount 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, Lombardino, Cowles & Altman, 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.

5. Method

5.1. 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, graphene-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 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 to have ADHD for which they effectively took medication, one other had ADD, and one an autism spectrum disorder. All four university students indicated to 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, $t(60.29) = 7.22$, $p < .001$, $d = 1.64$.

6. Materials

6.1. 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 ecological validity. The pictures are mainly interpretational illustrations which are most effective for learning (Carney & Levin, 2002). Some pictures contained words: these words where 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 Fig. 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).

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

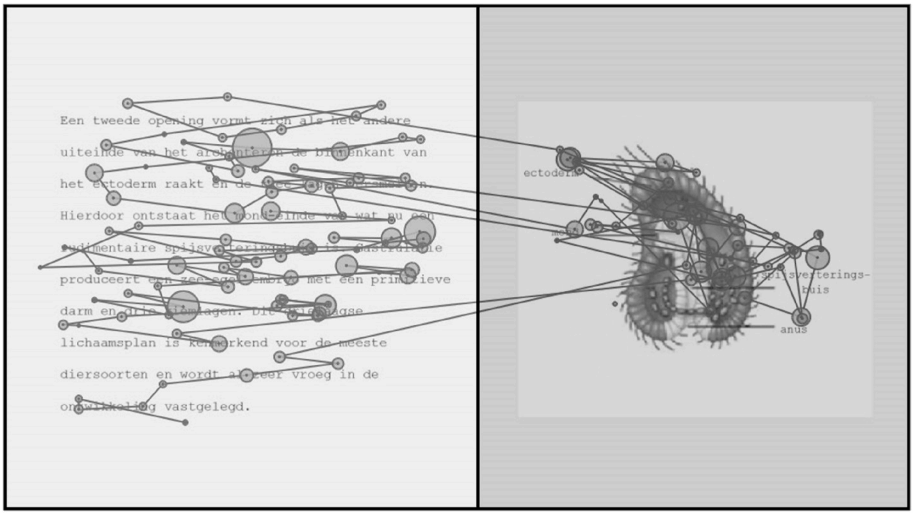

Fig. 1. Areas of Interest (left Text-AOI, right Picture-AOI).

students could start the lesson by moving to the first lesson-slide.

6.2. 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 times calibrating (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 ($SD = 0.23$).

6.3. 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.

6.4. 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, Lee, & Peebles, 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).

6.5. 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, Spelberg, Scheepsma, & De Vries, 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.

7. 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 the test protocol describing into detail the procedure, instructions, eye tracker set-up, calibration, and the tasks.

8. 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 1).

To relate learning processes to outcomes and thus answering 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 $p < .05$.

9. Results

9.1. 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. To provide insight in the distribution of the measures, untransformed scores are presented in dot plots in Figs. 2 and 3.

9.2. 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.

9.3. 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.

Table 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

Table 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.

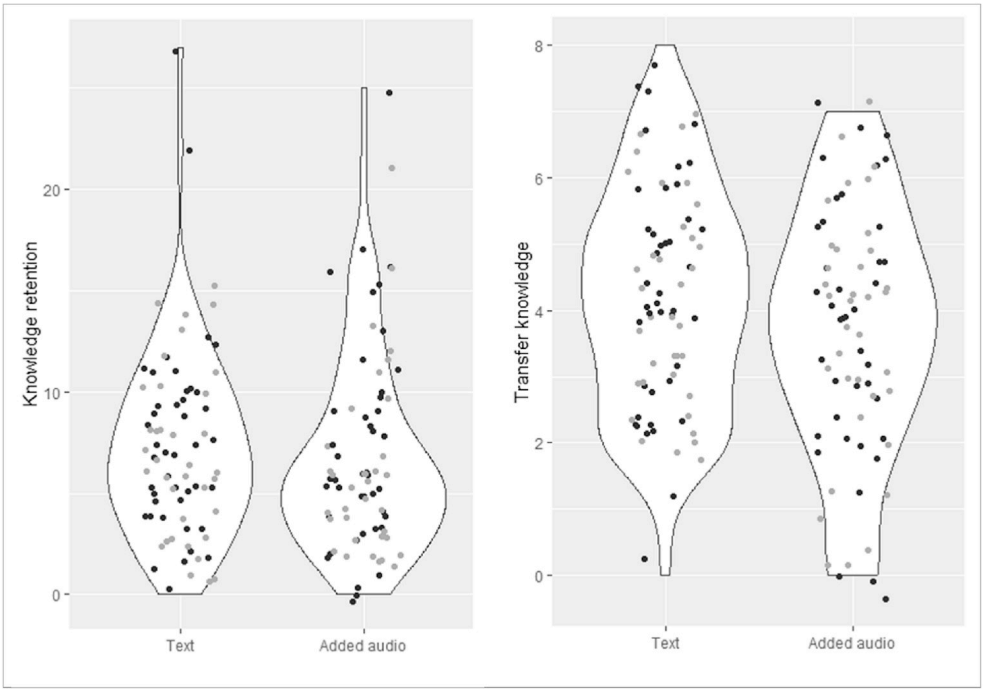

Fig. 2. Overview of the distribution of the learning outcomes on retention knowledge (left panel) and transfer knowledge (right panel) (grey = dyslexia/black = controls).

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

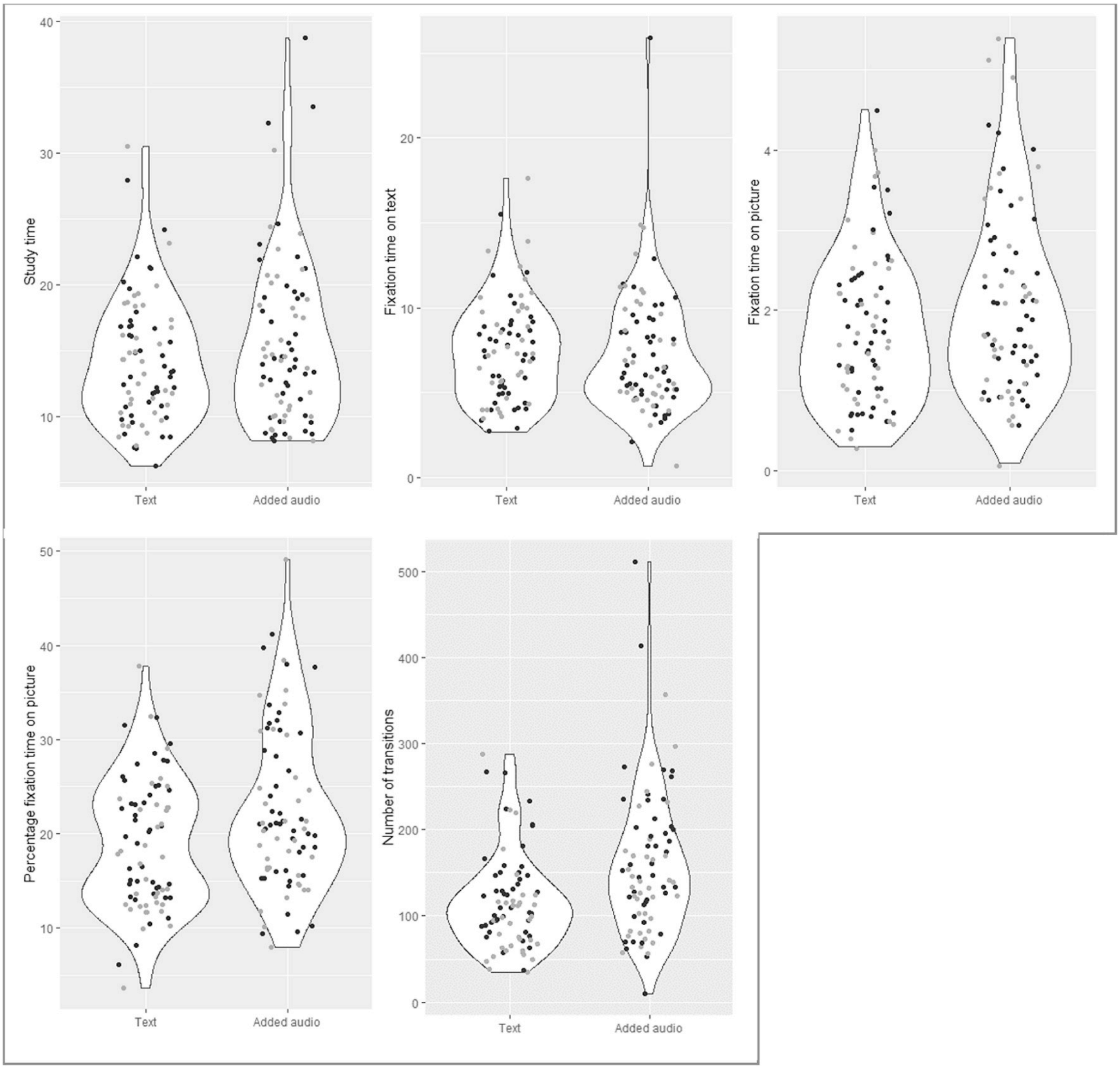

Fig. 3. Overview of the distribution of the learning processes on (from left to right and from top to bottom) study time, fixation time on the text, fixation time on the picture, percentage fixation time on the picture and the number of transitions (grey = dyslexia/black = controls).

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

Table 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.

changes the learning process: adding audio increases students' transitions between text and pictures.

9.4. 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 Tables 3 and 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.

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 evidenced 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 ($R^2 = 0.049$), focusing on the text did not predict transfer knowledge in students with dyslexia. ($R^2 = 0.007$). In the added audio condition, transfer knowledge retention knowledge was not predicted by learning outcomes.

10. 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.

10.1. 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 evidence 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 faster overloads the information processing streams which in turn hampers knowledge gain (Mayer, 2005). It is likely

Table 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.

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, Bailly, & Bosse, 2018). Gerbier, Billy and Bosse (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 added audio was found to be less efficient than written text-only (Gerjets, Scheiter, Opfermann, Hesse, & Eysink, 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.

10.2. 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 evidenced 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 et al. (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, Lombardino, Cowles & Altman, 2014). The former focus on much poorer readers, the latter provided less written text and a less ecologically validated 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.

10.3. 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 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 that 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 and 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, Landi, & Oakhill, 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 relatively) 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 at 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, Schuler, and Scheiter (2019) who evidenced 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, Schuler, & Scheiter, 2019). In the present study, audio seemed to facilitate transitions (see hypothesis 2), although not to such an extent that it changed learning outcomes.

10.4. Limitations

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, Radach, & Huber, 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 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.

10.5. 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 which 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.

11. Conclusion

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.

Author contribution

Carolien **Knoop-van Campen**: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft. Eliane **Segers**: Conceptualization, Methodology, Writing - Review & Editing, Supervision. Ludo **Verhoeven**: Conceptualization, Methodology, Writing - Review & Editing, Supervision.

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