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Reading in print versus digital media uses different cognitive strategies: evidence from eye movements during science-text reading

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Abstract
Comparing comprehension outcomes in print and digital reading is an active area of research but little is known about the reading processes that these media entail. This study involved an eye-tracking experiment with 50 undergraduate students to investigate the differences in reading processes in print and digital media. The participants were randomly assigned to read the same six-page popular science article that included several diagrams either in print or on a tablet computer and then answer reading comprehension questions. The results showed that comprehension was better when reading in print. Eye-movement data indicated that the print and digital groups spent about the same amount of time processing the article, texts, diagrams, and diagram statements, but the time was not divided evenly between the first pass and the rereading stages. The digital group spent more time reading the article at the first-pass reading stage and seldom reread it. In contrast, the print group first skimmed the article and then reread the important parts, exhibiting both longer total fixation durations in the rereading stage and a higher number of rereading instances across pages. In sum, the findings indicate that reading in print versus digital media employs different cognitive strategies with those reading in print showing more selective and intentional reading behavior.

Keywords Digital reading · Eye movements · Science text · Print reading · Cognitive strategies

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Introduction

Technological developments can have a great impact on reading. Besides books, students use various reading media (e.g., tablets, smartphones) in their daily lives. Reading text from screens is also called digital reading or reading electronic text (Clinton, 2019). Although the reading opportunities and preferences for print reading may not be replaced by digital reading for most people (Baron, 2020), a new medium may attract readers who subsequently revert in whole or part to traditional media choices such as books (De Waal & Schoenbach, 2010). Therefore, knowing the pros and cons of reading in print and digital media and discovering what cognitive strategies are involved while reading in different media are important topics of interest.

So far, we have some knowledge regarding the advantages and disadvantages of reading on digital media. Reading from screens is advantageous due to lower costs, accessibility, and faster transportation of the reading materials compared to physical books (Baron, 2020). However, some critics such as Dillon et al. (1988) point out that reading on screen is slower, less accurate, more fatiguing, leads to poorer comprehension, and feels subjectively less effective than reading in print. Recent research indicated that readers did not derive positive reading experiences and pleasant engagement from digital reading similar to print reading (Kazanci, 2015; Mangen & Kuiken, 2014). The existing research (see reviews by Clinton, 2019, and Singer & Alexander, 2017) indicates that reading from screens involves poorer self-regulation (Ackerman & Goldsmith, 2011; Ackerman & Lauterman, 2012; Liu, 2005). Most of the research have reported that reading in print results in better reading comprehension than digital media (Ackerman & Goldsmith, 2011; Ackerman & Lauterman, 2012; Lenhard et al., 2017; Mangen et al., 2013; Singer et al., 2017). However, some studies have reported the opposite results, or that the type of media had no significant effect on reading comprehension (Daniel & Woody, 2013; Dundar & Akcayir, 2012; Margolin et al., 2013). In sum, the empirical studies examining reading comprehension and reading time of print versus digital reading have reported that reading on the screen is quicker, but comprehension is poorer; that reading on screen is quicker and comprehension is the same as reading in print; and that reading on screen takes longer, but there are no differences in reading comprehension as compared to reading in print.

For the first result, Singer et al. (2017) postulated that print and digital mediums played a different role in the way students comprehended and spent their time reading texts. They recruited undergraduate students to read print and digital (PDF files) forms of two expository articles. The length of time that participants spent reading each text was recorded. The results showed that there was a significant advantage of print reading on reading comprehension, especially for recalling key points and other relevant information. However, the participants read significantly faster on computer than on paper. Lenhard et al. (2017) asked elementary-school students to complete a standard reading comprehension test either on screen or on paper and found that the students were quick to complete the task on the screen, but comprehension was poor. This result corresponds to the effect of the speed accuracy trade-off (Wickelgren, 1977) that has been demonstrated in a number of domains, including reading tasks (Dyson & Haselgrove, 2000).

Other studies have found no differences between print and digital reading. Margolin et al. (2013) asked undergraduate students to read narrative and expository texts either on an e-reader, a computer screen, or on paper, and then answer multiple-choice questions that required thought and reflection rather than simply memorizing content. The results suggested that the type of reading media did not differentially affect the comprehension of narrative or expository texts, or reading rate. Similarly, Eden and Eshet-Alkalai (2013) found that undergraduates detected and corrected mistakes (including mistyped words, homophonic, morphological, semantic, and syntactic errors) in science texts quicker on digital media, but the accuracy did not differ across the two media. Finally, Dundar and Akcayir (2012) found no significant differences in reading comprehension of fifth graders reading textbooks in print or on digital media.

Finally, Daniel and Woody (2013) asked undergraduates to read textbooks and found that students exhibited longer processing times while reading e-textbooks, but the level of reading comprehension was similar to that of reading the textbook in print. In other words, the efficiency of reading comprehension was worse for digital reading. Daniel and Woody attributed this result to possible feelings of fatigue from reading on digital media, and concluded that the students need to be given more time to study textbook contents.

Although the above studies compared reading comprehension and processing time in print versus digital media during expository text reading, illustrated texts have rarely been used as reading materials in this research. As many expository text (e.g., scientific texts) have multiple representations (e.g., words, diagrams, diagram statements), digital literacy involves not only word processing but also the ability to acquire information from diagrams (Eshet-Alkalai & Chajut, 2009). Therefore, it is necessary to investigate whether reading comprehension and reading processes differ between print and digital media during reading of illustrated texts. Further, texts and diagrams have different functions in cognitive processes (Jian & Wu, 2021; Schnotz & Bannert, 2003; Schnotz et al., 2014). Text usually serves as a conceptual guide for initial comprehension (Schnotz & Wagner, 2018), while pictures are used as a mental scaffold to facilitate mental model construction (Eitel et al., 2013). Hence, it is worth examining if readers spend different amount of time processing these parts while reading in print and digital media.

Eye movements in print and digital reading

Eye tracking is a suitable tool for exploring online reading processes as it provides rich information of “when/time” and “where/location” readers pay attention to when reading materials (Just & Carpenter, 1980; Reichle et al., 1999). Many studies have demonstrated that eye tracking data is helpful to uncover readers’ processing strategies during reading (Chen & Chen, 2020; Jian, 2018, 2019, 2021; Kim et al., 2018; Liao et al., 2020; Mason et al., 2013; Tsai et al., 2019; 2021).

However, most existing studies have examined reading behaviors by using reading material presented on a screen due to technical difficulties in collecting, recording, and analyzing eye movement data while reading a book. Pages in a book usually have relatively curved surfaces that hinder the match of the exact eye fixation locations required for software calculations. Nonetheless, highly developed software has gradually resolved this problem. According to a literature review by Singer and Alexander (2017), only two studies (Siegenthaler et al., 2011; Zambarbieri & Carniglia, 2012) have investigated the reading processes of print and digital text using eye-tracking technology. Siegenthaler et al. (2011) asked college participants to read a 12-page novel and recorded their eye fixations, but the students read one page on each reading device (including one book and five e-book devices) in two test sessions. This experimental procedure may inherently produce inconsistent results, as readers had to change to a new device after completing one page of reading, which is an unnatural process that may break the semantic coherence of the reading material. In the study by Zambarbieri and Carniglia (2012), undergraduate students were asked to read a comic novel in print and digital media. The result revealed similar eye movement patterns in print and digital reading. However, reading comprehension outcomes were not measured in their study.

Although these two studies used eye trackers to investigate the reading processes of print and digital text reading, they used fiction and comics as reading materials. Text genre (e.g., narrative and expository) affects the way the readers process the texts (Best et al., 2008; Kraal et al., 2017), and readers show different eye movement patterns for reading narrative and expository texts (Kraal et al., 2017). Some studies reviewed above used expository learning materials (e.g., Ackerman & Goldsmith, 2011; Daniel & Woody, 2013; Davis & Neitzel; Eden & Eshet-Alkalai, 2013; Mangen et al., 2013; Margolin et al., 2013), but did not collect eye movement data to examine the cognitive processes in print and digital reading. In addition, many expository texts (e.g., scientific texts) contain diagrams, and diagram diversity is a fundamental characteristic of scientific articles. Therefore, the present study combines online (i.e., eye movements) and offline (i.e., comprehension tests) data to investigate the potential differences between reading a scientific article in print and digital media.

Reading strategies and metacognitive regulation of print versus digital reading

Readers' metacognition (e.g., comprehension monitoring, self-regulation) has a great influence on adopting a specific reading strategy, and results in differences in the reading processes (Ackerman & Goldsmith, 2011; Ackerman & Lauterman, 2012; Goldsmith, 2011; Liu, 2005). Reading strategy and metacognition are closely related and therefore are jointly discussed in this section. Ackerman and Goldsmith (2011) compared undergraduates' cognitive (e.g., encoding, information storage) and metacognitive (e.g., self-regulated study time, prediction of performance) processes when they read expository texts in print or on digital media, and found that the primary differences between print and digital reading lay in the metacognitive regulation rather than in the cognitive processes. Liu (2005) asked undergraduate students to think aloud while they read on a screen, and found that they spent a lot of time browsing and scanning the text, keyword spotting, one-time rereading rather than back-and-forth reading, and non-linear reading. The participants also reported that it was harder for them to maintain their attention on the text displayed on screens, and therefore, they did not spend enough time concentrating on the information to ensure deep processing. This response implied that readers invested less cognitive effort on processing the information when reading from digital media.

In contrast, Davis and Neitzel (2012) found that middle-school students were more strategic in digital than in print reading. They asked sixth- and seventh-graders to read expository articles in paper and computer formats and discuss their content. They collected video and screen recording data and found that students reading collaboratively from paper with their peers displayed "covering text" behaviors (reading the text silently or aloud, or listening to a partner read the text aloud). In contrast, students reading texts on the computer were more likely to engage in "previewing" (skimming an article or set of hyperlinks before deciding where to begin reading), and "process monitoring" (making a plan for how to approach the reading, asking about or evaluating the progress a dyad was making towards accomplishing this plan, or giving explicit directions to a partner about how to proceed with the work), but no differences in reading comprehension were found between the two conditions. In sum, the research on learning strategies involved in reading texts in print versus digital format is inconclusive.

The present study

This study investigates the reading processes and comprehension outcomes of reading an illustrated scientific text in print or on a tablet computer. Scientific diagrams have multiple functions. According to the classification provided by Carney and Levin (2002), a decorative diagram, such as a photograph, has a less cognitive function. In contrast, a representational diagram has a more cognitive function as it comprises labels and spatial structures to represent an abstract description of a text. In turn, an explanatory diagram shows a series of steps involved in performing an action. Finally, statistical diagrams are commonly used in scientific texts for conveying the findings of relationships between variables. Therefore, this study used these four types of diagrams in the reading material and investigated if there were differences in viewing or reading processes of these diagrams in print and digital reading. In addition, readers' preferences for reading either in print or on digital media (Ackerman & Lauterman, 2012; Lenhard et al., 2017; Margolin et al., 2013), prior knowledge (Jian & Ko, 2014; Tobias, 1994; Song et al., 2016; Wade & Kidd, 2019), and reading interest (Tobias, 1994; Song et al., 2016; Wade & Kidd, 2019) may influence their performance. Therefore, their possible effects were controlled.

The first research question addressed in this study is: Does reading an illustrated scientific text in print and on digital media result in differences in reading comprehension? On the basis of the existing findings (Ackerman & Goldsmith, 2011; Ackerman & Lauterman, 2012; Lenhard et al., 2017; Mangen et al., 2013; Singer et al., 2017), it was expected that reading comprehension would be better in print reading.

The second research question is: Does reading an illustrated scientific text in print and on digital media involve different reading processes and strategies? This question is examined using eye movement data. Because of inconsistent reading time results in previous studies (Daniel & Woody, 2013; Lenhard et al., 2017; Singer et al., 2019), no specific predictions were made regarding the total processing time of the article. However, the print group was expected to use scientific diagrams strategically which would result in longer processing time in viewing these diagrams, especially representational and explanatory diagrams, that involve a cognitive function (Carney & Levin, 2002). Further, previous studies have indicated that reading on a screen entails surface processing strategies (e.g., memorization information) instead of deep processing strategies (e.g., organization, elaboration, and monitoring of information) (Liu, 2005), and participants reading in print have shown better comprehension-monitoring and self-regulation (Ackerman & Goldsmith, 2011). Therefore, it was expected that print and digital groups would show different eye movement patterns. Specifically, the print group was expected to show more selective and intentional reading behaviors, such as spending time on rereading important sections of the text and diagrams.

Methods

Participants

Sixty-four undergraduate students ($M_{age} = 20.88$ years, $SD = 1.69$) were recruited from a wide range of disciplines but excluding the departments of geography and earth science because these students might have had prior knowledge of the reading materials used. Participants were native speakers of Chinese, which was the language used in the reading material, and had normal or corrected-to-normal vision. All participants volunteered to take part in the experiment and provided written consent.

Materials

The reading material was a popular science article from the magazine *Scientific American,* describing slow earthquakes triggered by typhoons (written by Liu, 2009). This topic was chosen because the country where the participants lived experiences typhoons often, so they could be interested in this topic. The article was six pages long, contained nine diagrams (three decorative, two representational, one organizational, and three statistical), and several paragraphs in each of the sections, divided under four subtitles: The hidden energy of seismology; Discovering slow earthquakes in Taiwan; How do typhoons trigger slow earthquakes?; and Changes in atmospheric pressure.

The size of the pages for both the print and digital groups was approximately 26.67 cm × 20.3 cm. PDF format was used for the digital media. Participants in the digital group used their finger to swipe right or left for turning pages on a tablet computer, with one page being displayed on the screen at a time. To ensure consistency in the eye movement analysis, enlarging or reducing font size was not allowed. Thus, the font sizes were equal for both groups and could not influence the results of the eye movement analyses.

Measures

Demographic survey

The participants completed a demographic questionnaire that included questions on age, gender, preferences for print or digital reading, and science-reading habits (1 = almost never; 2 = sometimes/about 3–4 times per month; and 3 = very often/more than 5 times per month).

Test of prior knowledge

To ascertain the relative novelty of the topic for participants and to ensure equal prior knowledge in the print and digital groups, a knowledge test about atmospheric pressure and earthquakes was conducted. It included ten multiple-choice questions, which were examined by two experts who taught earth science in middle school and had master's degrees in science education or earth science.

Reading comprehension test

To measure different dimensions of comprehension, the comprehension test consisted of a free-recall question ("Please, recall the article content as much as possible"), a main-idea question ("What is the main idea of this article?"), two text retrieval questions ("Please explain what a "slow earthquake" is," and "Describe the characteristics of a slow earthquake") that measured memorization of specific information, and two questions that required making inferences ("The earthquake frequency and Richter magnitude scale of eastern Taiwan are lower than Japan, but the relative reduction of the plate is higher than that of Japan, reaching 8 cm per year. Does this energy disappear? Please provide explanations," and "Please explain why an ordinary seismograph cannot record slow earthquakes"). A "concept" was used as a scoring unit rather than a "sentence," so including one "concept" was awarded one point. A scoring example is shown in the Appendix. All questions and pre-established answers were confirmed by two PhD science experts to ensure the validity. Participants' responses were rated by two independent raters. The Cohen's Kappa coefficient was 0.84 and disagreements were resolved by a discussion. Since each type of question was one-of-its-kind, test scores are not reported separately, but summed across all questions.

Apparatus

Eye movements were recorded using Tobii Pro Glasses 2 at a sampling rate of 100 Hz. A bridle was used to fix the eye tracker system to participants' head. Participants who were assigned to the digital condition used a 13-inch ASUS Surface tablet computer.

To record the eye fixation data with precision, the reading material was placed on a vertical bookrack that was fixed to the experimental desk. Participants were asked to place themselves in a way that allowed for the reading material to be at 30–50 cm from their eyes. This step was taken because if the reading material had been placed on the desk and participants had read it from the corner of their eye, the eye tracker would not be able to record their eye fixations.

Procedure

The experiment was conducted with one participant at a time. Participants were randomly assigned to one of the two groups: print or digital. Before reading the article, participants completed the prior knowledge test. Next, they were requested to read the scientific article—with no time limit—and told that they could turn the pages at their will. They were also informed that they would complete a reading comprehension test afterwards and that they would not be able to access the article while answering the questions. After reading the article, they completed the paper-and-pencil reading comprehension test. Participants rated their interest in the article on a 5-point scale (1 = "very interesting" to 5 = "very boring") and the difficulty of the article (1 = "very easy" to 5 = "very difficult"). This procedure lasted for approximately 60 min.

Data selection and eye-fixation indicators

Data from 14 participants were excluded for the following reasons: poor eye calibration (one participant), substantial changes in pupil position and failed data transfer (three participants), the eye-tracking computer crashed or recording failed (three participants), gaze-samples were lower than 70% (four participants), and the total article reading time was 2 standard deviations above or below the mean (four participants). Therefore, data was analyzed from 50 participants.

Eye movement indicators

Total fixation duration refers to the total duration of fixations on the areas of interest (AOIs). Text sections, diagrams, and diagram statements were used as AOIs in this study. This index represents cognitive effort in processing the reading material. Generally, the higher the total fixation duration on a specific AOI, the more intense the cognitive processing of the material (Hegarty & Just, 1993; Jian, 2021; Miller, 2015; Wu & Liu, 2021).

First-pass fixation duration was calculated as the total duration of all fixations on the AOI during the initial reading and before exiting it. This index represents the initial reading process, which is more automatic and includes the decoding of words or objects and the preliminary extraction of meaning from a text (Hyönä et al., 2003; Jian et al., 2019; Kaakinen et al., 2003; Mason et al., 2013; Henderson et al., 1999).

Rereading (or second-pass) fixation duration was calculated as the duration of all fixations returning to a target region that has already been processed after its initial reading. It reflects a more intentional and deeper processing, such as reading again to solve doubts from the initial reading, or to reselect important information to ensure deeper processing (Henderson et al., 1999; Hyönä et al., 2003; Jian et al., 2019; Kaakinen et al., 2003; Mason et al., 2013).

Number of rereading instances across pages was calculated as the number of instances in which readers turned the pages (i.e., previous, next, and one or several pages) and made more than one saccade between two fixations (each longer than 100 ms) on a page. If readers were reading the same text and suddenly jumped from page 2 to page 1, or from page 4 to page 3, these movements were not regarded as rereading across pages. Regardless of the reading media, if the fixations did not last longer than 100 ms, they were not calculated as rereading across pages (e.g., page scrolling might lead to several fixations of less than 100 ms on more than two pages, but these were not calculated as a rereading). Besides, in the print reading condition, readers saw two pages when they turned one page. Thus, to ensure consistency for the two groups, one rereading instance was defined as the rereading of one page once (i.e., a page that had fixations on it). For example, if a reader turned one page backwards to reread information, and there were fixations on both displayed pages, the number of rereading instances was two. The same calculation was used for the digital condition.

Results

Participants' characteristics and demographic measures

To confirm that participants' characteristics and demographic measures were comparable, five variables were analyzed with *t*-tests: age, science reading habit, prior knowledge, article interest, and article difficulty. The means and standard deviations are presented in Table 1. Two categorical variables were analyzed using chi-squares: gender (58% in the print group were female, and 61% in the digital group were female) and reading preferences for print or digital reading (67% in the print group preferred print text reading, and 65% in the digital group preferred print text reading). The results showed that the two groups did not differ significantly in any of the seven variables (all $ps > 0.05$).

Table 1 Means and standard deviations of the print and digital groups' characteristics and the reading test scores

	Print Group ($N=24$)		Digital Group ($N=26$)	
	M	*SD*	*M*	*SD*
Age	21.08	1.84	20.69	1.54
Science-reading habits	1.35	0.49	1.46	0.65
Prior knowledge test	5.88	1.70	6.00	1.47
Article interest	3.08	0.88	2.92	1.41
Article difficulty	3.75	0.53	3.80	0.74
Total scores of reading test	12.04	3.83	9.69	3.55

Reading comprehension

To answer the first research question of whether reading media (print versus digital) affected reading comprehension, an ANOVA was first conducted with group as an independent variable and the reading comprehension test score as the dependent variable. The result (the bottom of Table 1) showed that the print group had significantly higher total scores in the reading comprehension test than the digital group ($F(1, 48)=5.07$, $p<0.05$, $\eta^2=0.10$). To confirm if the difference in reading comprehension test scores was influenced by the reading time, an ANCOVA was conducted with the total fixation durations for the whole article (the top of Table 2) as the covariate. The result showed that the article reading time affected the reading comprehension test scores ($F(1, 47)=7.68$, $p<0.01$, $\eta^2=0.14$), and that the print group still had significantly higher total scores in the reading comprehension test compared to the digital group ($F(1, 47)=4.21$, $p<0.05$, $\eta^2=0.08$).

Table 2 Means and standard deviations of total fixation durations for the two groups

	Print Group ($N=24$)		Digital Group ($N=26$)	
	M	*SD*	*M*	*SD*
Fixation durations				
Whole article	1090.59	543.50	955.78	355.01
Texts				
First-pass reading	436.58	205.21	515.87	226.70
Rereading	433.11	360.20	235.94	199.47
Total texts	869.69	455.96	751.81	276.62
Diagrams				
First-pass reading	42.24	18.96	52.29	34.13
Rereading	59.82	57.66	33.44	37.34
Total diagrams	102.06	66.58	85.73	52.26
Diagram Statements				
First-pass reading	55.18	34.62	81.39	55.41
Rereading	63.66	54.68	36.85	35.35
Total diagram statements	118.84	63.89	118.24	66.85

Analysis of eye movements

To answer the second research question—whether reading media (print versus digital) affected reading processes during illustrated science text reading—several eye movement measures for the text, diagrams, and diagram statements were analyzed. A two-way MANOVA was conducted with the eye movement measures as the dependent variables and group (print or digital) and reading stage (first-pass or rereading) as the independent variables.

The total fixations durations

The results in Table 2 show that the print and digital groups spent about the same amount of time in processing the whole article, texts, diagrams, and diagram statements ($p > 0.05$). However, the time was not divided evenly between the first-pass and rereading stages, with the digital group spending more time during the first and the print group during the second. The detailed results from the subsequent ANOVAs are reported below.

For the eye movements in the *texts* sections, there was a main effect of reading stages ($F(1, 48) = 8.34$, $p < 0.01$, $\eta^2 = 0.15$), no main effect of group ($p > 0.05$), and an interaction effect of group by reading stages ($F(1, 48) = 7.94$, $p < 0.01$, $\eta^2 = 0.14$) on the total fixation duration. Table 2 indicates that the digital group showed a large difference between the two reading stages whereas the print group did not. In addition, both groups had similar total fixation durations while reading text sections in the first-pass stage; however, the print group spent more time reading text sections in the rereading stage than the digital group.

For the *diagrams*, there was no main effects of group or reading stage on the total fixation duration ($p > 0.05$), but the interaction effect was significant ($F(1, 48) = 6.25$, $p < 0.05$, $\eta^2 = 0.12$). Table 2 indicates that the digital group spent more time examining the diagrams on the first-pass than on the rereading stage, whereas the opposite was true for the print group. Figure 1 indicates that there was a tendency for the digital group to spend more time in the first-pass stage for all types of diagrams and for the print group to spend more time in the rereading stage especially for decorative and representational diagrams. The group by reading stage interactions effect was significant for the decorative diagrams ($F(1, 48) = 8.18$, $p < 0.01$, $\eta^2 = 0.15$) and the representational diagrams ($F(1, 48) = 16.57$, $p < 0.001$, $\eta^2 = 0.26$). In addition, there was a main effect of reading stage for the statistics diagrams ($F(1, 48) = 7.02$, $p < 0.05$, $\eta^2 = 0.13$), indicating that the readers spent significantly more time on viewing the statistical diagrams in the first-pass than the rereading stages. There were no significant main or interaction effects on the total fixation durations of the explanatory diagrams ($ps > 0.05$).

For the *diagram statements*, there were no main effects for groups or reading stages on the total fixation duration ($p > 0.05$), but the interaction effect was significant ($F(1, 48) = 8.29$, $p < 0.01$, $\eta^2 = 0.15$). Table 2 indicates that the digital group spent significantly more time reading diagram statements on the first-pass than on rereading stage, but the print group had similar fixation durations on the diagram statements on both reading stages. In addition, on the first-pass stage, the digital group spent more time processing the diagram statements than the print group whereas the opposite was true

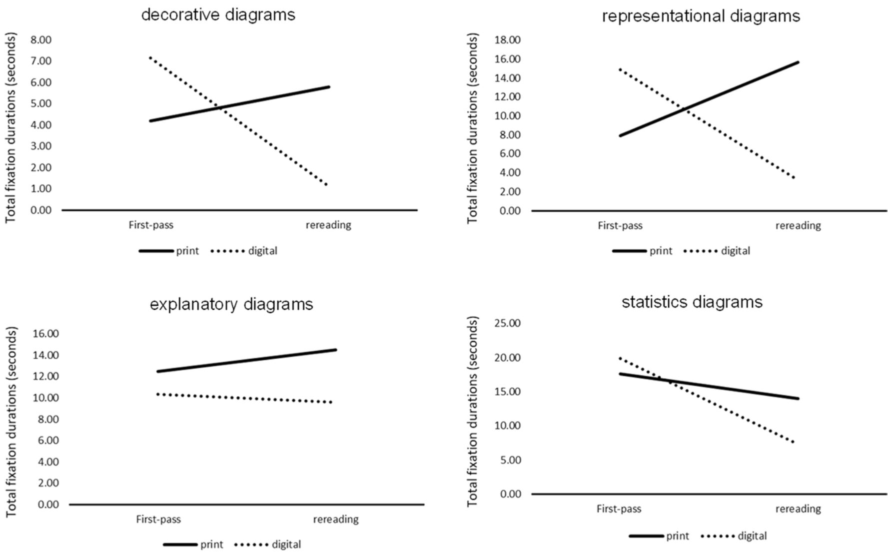

Fig. 1 Total fixation durations on different diagram types for the two groups during the first-pass and rereading stages

for the rereading stage. As for different types of diagram statements (see Fig. 2), the results showed a significant main effect of reading stage on decorative diagram statements ($F(1, 47) = 4.42$, $p < 0.05$, $\eta^2 = 0.09$), and group by reading stage interaction effects for the decorative ($F(1, 47) = 19.05$, $p < 0.001$, $\eta^2 = 0.29$), and representational ($F(1, 47) = 12.11$, $p < 0.01$, $\eta^2 = 0.21$) diagram statements. In addition, there was a main effect of reading stage on the statistics diagram statements ($F(1, 48) = 7.02$, $p < 0.05$, $\eta^2 = 0.13$), indicating that the groups spent significantly more time processing the statistics diagram statements during the first-pass than the rereading stage. However, there were no main effects or interaction effects of group and reading stage on the fixation durations for the representational and explanatory diagram statements.

Rereading instances across pages

T-tests were used to examine between-group difference in eye movement measures. To ensure that our calculations were based on a criterion that corresponded to that of the digital group, participants' eye fixations across pages 1 and 2, 3 and 4, and 5 and 6 were calculated as turning page behaviors. If there were paragraphs that extended across two continuous pages but belonged under the same subtitle, eye fixations across these two pages were not calculated as turning page behaviors.

Except for page 5 that included three statistical diagrams and their statements, the print group had significantly more rereading instances across pages than the digital group: page 1 (t $(48) = 4.19$, $p < 0.001$), page 2 (t $(48) = 3.18$, $p < 0.01$), page 3 (t $(48) = 3.01$, $p < 0.01$), page 4 (t $(48) = 2.94$, $p < 0.01$), and page 6 (t $(48) = 3.19$, $p < 0.01$) (Fig. 3).

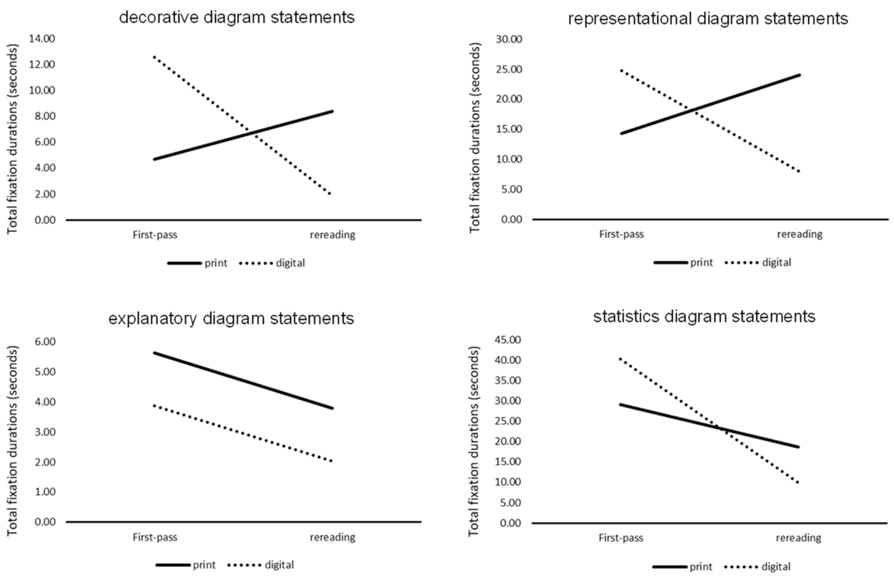

Fig. 2 Total fixation durations on different diagram statements for the two groups during the first-pass and rereading stages

Discussion

This study utilized eye tracking to examine the differences in reading processes and reading comprehension when undergraduate students read a scientific text either in print or on digital media. Moreover, this study used illustrated text as the reading material, thereby extending the findings of previous research that used text without illustrations to compare reading in print and digital media (e.g., Lenhard et al., 2017; Zambarbieri & Carniglia, 2012).

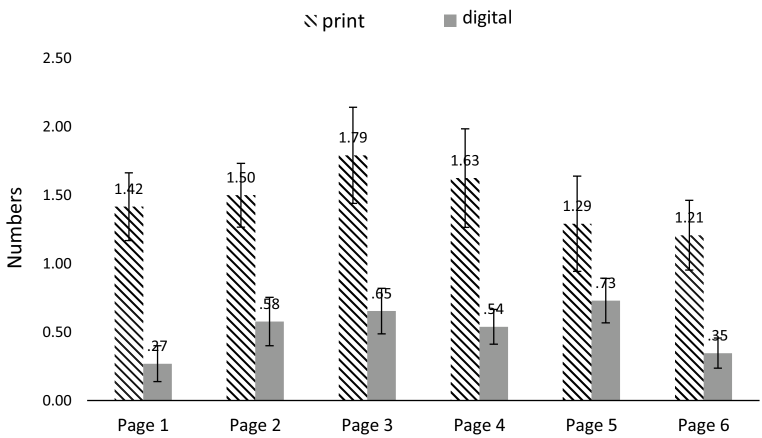

Fig. 3 Bar chart of the number of rereading instances across pages for both groups

Regarding the first research question, as expected, the participants in the print condition showed better reading comprehension outcomes than those in the digital condition, even after controlling for the total fixation durations for the article. This result is in line with previous studies conducted with younger children (e.g., Kerr & Symons, 2006; Lenhard et al., 2017), adolescents (e.g., Mangen et al., 2013), and using non-illustrated texts as reading material (e.g., Singer et al., 2019; Singer & Alexander, 2017; Stoop et al., 2013). The benefits of print reading were significant, supporting studies that used expository texts (Ackerman & Lauterman, 2012; Singer et al., 2019) and comics (Hou et al., 2017; Zambarbieri & Carniglia, 2012) as reading materials. One possible explanation for this result can be based on the theory of textual landscapes (Jabr, 2013), which suggests that the human brain prefers print to digital reading because the former helps readers to construct a better mental representation of a text, thereby allowing better recall of content details and information locations. Another explanation may be that print reading leads to better comprehension due to the absence of visual fatigue, which may be induced differently by print and digital media. Benedetto et al. (2013) found that LCD (Kindle Fire HD) may trigger higher visual fatigue than both an E-ink (Kindle Paperwhite) or a paper book.

Regarding the second research question, the processing time of the whole article did not differ significantly between the groups, which corresponds to the findings of some previous studies (Clinton, 2019; Dundar & Akcayir, 2012). However, when the processing time was divided into first-pass and rereading stages, the results indicated that the group by reading stage interaction effects were significant for texts, diagrams, and diagram statements. Specifically, the digital group spent about twice the amount of time studying the material during the first-pass than during the rereading stage, whereas the print group split their time evenly between the two reading stages. As a result, the print group returned to earlier information much more frequently than the digital group. Rereading reflects more intentional processing, such as reading again to solve doubts from the initial reading or reselecting important information for deeper processing (Henderson et al., 1999; Hyönä et al., 2003; Jian et al., 2019; Kaakinen et al., 2003; Mason et al., 2013). This implies that the reading strategies of the print group were more selective and adjustable. One possible explanation for this result can be based on the metacognitive self-regulation and how learners activate and sustain their cognitive, affective, and behavioral capabilities to achieve personal goals (Zimmerman, 1986). The results of this study suggest that readers in the print group were more capable of adjusting their reading strategies to spend more effort and time on some specific sections (e.g., representational diagrams and their statements, cause-and-effect paragraphs relative to the core concept of the article) to reach better reading comprehension. This result is consistent with previous findings (Ackerman & Goldsmith, 2012) showing that readers who read expository text in print have better metacognition (e.g., self-regulated study time, prediction of performance) than those who read on digital media. Another possible explanation is that undergraduate readers are socio-historically and culturally informed and may still prefer reading long academic articles in print rather than on digital media (Foasberg, 2014; Gao & Isaia, 2017). They might think that since they were handed a printed document, they must study it closely because that is what people usually do with printed articles, especially with scientific expository texts.

A detailed analysis of eye movement data on specific areas of interests (see Figs. 1 and 2) revealed a few interesting findings. Compared with the digital group, the print group fixated longer on the representational diagrams and their statements. It may indicate that the print group used diagrams more strategically than the digital group given that the representational diagrams mirror part or all of the text content and have a cognitive function (Carney & Levin, 2002). The two representational diagrams included in this study included many scientific concepts; one explained the plate tectonics of coast mountains and continents and the different movement speed and crash energy of plate tectonics whereas the other explained the internal structure of a subsurface equipment and the flow ability of silicone oil. Texts and diagrams have different functions in cognitive processes (Jian & Wu, 2021; Schnotz & Bannert, 2003; Schnotz et al., 2014), where the text usually serves as a conceptual guide for initial comprehension (Schnotz & Wagner, 2018), while diagrams are used as a mental scaffold to facilitate mental model construction (Eitel et al., 2013). Therefore, decoding the information in these diagrams deeply may help readers to comprehend the important scientific concepts in the article and may result in better reading comprehension. This result is also in line with previous studies showing that readers who had better scores on the reading comprehension test spent more time processing the diagrams than readers who had poorer test scores (Jian, 2017; Mason et al., 2013).

In addition, the results showed that the readers spend less time examining the statistics diagrams, and most of that time was spent during the first-pass stage rather than the rereading stage. Comprehending statistics diagrams is difficult for most undergraduates (Cooper & Shore, 2008; Glazer, 2011), and the results of this study indicate that the readers had limited will to review the statistics diagrams, even though these diagrams contained plenty of important information.

This study had two limitations. The areas of interest used in this study were already present in the original scientific article and not designed for the study. Thus, the size and concept density of the diagrams was not equal. Moreover, since the analysis was exploratory, the interpretation of the results should be treated with caution. Further research is needed to investigate possible explanations and causes for the results by controlling the diagram characteristics for each type.

In sum, although the print and digital groups spent about the same amount of time on processing the article, texts, diagrams, and diagram statements, the time was not divided evenly between the first-pass and the rereading stage. The digital group spent much more time reading the article in the first-pass stage, but seldom reread it. In contrast, the print group first skimmed the article and then went back to check and carefully reread the important parts of the article. As a result, they exhibited higher total fixation durations in the rereading stage, and a higher number of rereading instances across pages. To conclude, the above findings indicate that reading media affects the cognitive strategies employed, and that readers who read in print show more selective and intentional reading behaviors, likely reflecting self-regulation and metacognition to ensure better comprehension.

Appendix

See Table 3.

Table 3 A scoring example of the reading test

	Answers	Score
Correct answer	Slow earthquakes refer to the earthquakes in which the faults rupture gradually or those that occur over a long time period (1 point represents events such as fault rupture and plate collision) Slow earthquakes take up to several minutes, hours, days, or even weeks to release the accumulated energy (1 point represents a long time period) However, they cannot be recorded on seismic instruments (1 point indicates that they cannot be recorded), though their formation mechanism is similar to that of the ordinary earthquakes	3
Subject 01	Unlike ordinary earthquakes that release energy rapidly (in a few seconds), slow earthquakes release energy gradually, perhaps in weeks or even months (1 point represents a long time period). Moreover, they do not release large amounts of energy at once but release the accumulated energy gradually	1
Subject 02	Slow earthquakes, unlike the commonly occurring earthquakes that last few seconds, have a duration ranging from several minutes to even days (1 point represents a long time period), thereby releasing the pressure of plate collision (1 point represents events such as fault rupture and plate collision)	2
Subject 03	Slow earthquakes are distinct from the ordinary earthquakes that are defined by the Central Weather Bureau and can be recorded by at least three detection instruments (1 point indicates that they cannot be recorded); however, like ordinary earthquakes, they are also caused by plate dislocation (1 point represents plate or stratum changes) As these earthquakes take longer to form and occur than the ordinary earthquakes, they are designated as slow earthquakes. Ordinary earthquakes take only a few seconds to occur, while slow earthquakes need several minutes, days, or even weeks to form the momentum (1 point represents a long time period)	3

Item: "Please explain what "Slow Earthquake" is? And describe the characteristics of Slow Earthquake"

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References

Ackerman, R., & Goldsmith, M. (2011). Metacognitive regulation of text learning: On screen versus on paper. *Journal of Experimental Psychology: Applied, 17*(1), 18–32. https://doi.org/10.1037/a0022086

Ackerman, R., & Lauterman, T. (2012). Taking reading comprehension exams on screen or on paper? A metacognitive analysis of learning texts under time pressure. *Computers in Human Behavior, 28*(5), 1816–1828. https://doi.org/10.1016/j.chb.2012.04.023

Baron, N. S. (2020). Digital reading: A research assessment. In E. B. Moje, P. P. Afflebrach, P. Enciso, & N. K. Lesaux (Eds.), *Handbook of reading research* (Vol. V, pp. 116–136). Routledge Press.

Benedetto, S., Drai-Zerbib, V., Pedrotti, M., Tissier, G., & Baccino, T. (2013). E-Readers and Visual Fatigue. *PLoS ONE, 8*(12), e83676. https://doi.org/10.1371/journal.pone.0083676

Best, R. M., Floyd, R. G., & Mcnamara, D. S. (2008). Differential competencies contributing to children's comprehension of narrative and expository texts. *Reading Psychology, 29*(2), 137–164. https://doi.org/10.1080/02702710801963951

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

Chen, M. L., & Chen, C. H. (2020). Do readers adjust their lower- and higher-level language skills according to text structures? Evidence from eye movements in Chinese text reading. *Journal of Research in Reading, 43*(2), 180–200. https://doi.org/10.1111/1467-9817.12297

Clinton, V. (2019). Reading from paper compared to screens: A systematic review and meta-analysis. *Journal of Research in Reading, 42*(2), 288–325. https://doi.org/10.1111/1467-9817.12269

Cooper, L. L., & Shore, F. S. (2008). Students' misconceptions in interpreting center and variability of data represented via histograms and stem-and-leaf plots. *Journal of Statistics Education*. https://doi.org/10.1080/10691898.2008.11889559

Daniel, D., & Woody, W. (2013). E-textbooks at what cost? Performance and use of electronic v. print texts. *Computers & Education, 62*, 18–23. https://doi.org/10.1016/j.compedu.2012.10.016

Davis, D. S., & Neitzel, C. (2012). Collaborative sense-making in print and digital text environments. *Reading and Writing, 25*, 831–856. https://doi.org/10.1007/s11145-011-9302-2

De Waal, E., & Schoenbach, K. (2010). New sites' position in the mediascape: Uses, evaluations, and media displacement effects over time. *New Media & Society, 12*(3), 477–496. https://doi.org/10.1177/1461444809341859

Dillon, A., McKnight, C., & Richardson, J. (1988). Reading from paper versus reading from screens. *The Computer Journal, 31*, 457–464. https://doi.org/10.1093/comjnl/31.5.457

Dundar, H., & Akcayir, M. (2012). Tablet vs paper: The effect on learners' reading performance. *International Electronic Journal of Elementary Education, 4*(3), 441–450.

Dyson, M., & Haselgrove, M. (2000). The effects of reading speed and reading patterns on the understanding of text read from screen. *Journal of Research in Reading, 23*(2), 210–223. https://doi.org/10.1111/1467-9817.00115

Eden, S., & Eshet-Alkalai, Y. (2013). The effect of format on performance: Editing text in print versus digital formats. *British Journal of Educational Technology, 44*(5), 846–856. https://doi.org/10.1111/j.1467-8535.2012.01332.x

Eitel, A., Scheiter, K., Schüler, A., Nyström, M., & Holmqvist, K. (2013). How a picture facilitates the process of learning from text: Evidence for scaffolding. *Learning and Instruction*, *28*, 48–63. https://doi.org/10.1016/j.learninstruc.2013.05.002.

Eshet-Alkalai, Y., & Chajut, E. (2009). Changes over time in digital literacy. *CyberPsychology & Behavior, 12*(6), 713–715. https://doi.org/10.1089/cpb.2008.0264

Foasberg, N. M. (2014). Student reading practices in print and electronic media. *College & Research Libraries, 75*(5), 705–723. https://doi.org/10.5860/crl.75.5.705
Gao, Y., & Isaia, M. (2017). *Reading and the good life: An analysis of print and digital readers in suburban libraries* (pp. 1–18). Lincoln.
Glazer, N. (2011). Challenges with graph interpretation: A review of the literature. *Studies in Science Education, 47*(2), 183–210. https://doi.org/10.1080/03057267.2011.605307
Hegarty, M., & Just, M. A. (1993). Constructing mental models of machines from text and diagrams. *Journal of Memory and Language, 32*, 717–742. https://doi.org/10.1006/jmla.1993.1036
Henderson, J. M., Weeks, P. A., & Hollingworth, A. (1999). The effects of semantic consistency on eye movements during complex scene viewing. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 210–228. https://doi.org/10.1037/0096-1523.25.1.210
Hou, J., Rashid, J., & Lee, K. M. (2017). Cognitive map or medium materiality? Reading on paper and screen. *Computers in Human Behavior, 67*, 84–94. https://doi.org/10.1016/j.chb.2016.10.014
Hyönä, J., Lorch, R. F., & Rinck, M. (2003) Eye movement measures to study global text processing. In J. Hyo¨na¨, R. Radach, & G. Deubel (Eds.), *The mind's eye: Cognitive and applied aspects of eye movement research* (pp. 313–334). Amsterdam: Elsevier Science
Jabr, F. (2013). Why the brain prefers paper? *Scientific American, 309*(5), 48–53.
Jian, Y. C. (2017). Eye-movement patterns and reader characteristics of students with good and poor performance when reading scientific text with diagrams. *Reading and Writing, 30*(7), 1447–1472. https://doi.org/10.1007/s11145-017-9732-6
Jian, Y. C. (2018). Reading instructions influence cognitive processes of illustrated text reading not subject perception: An eye-tracking study. *Frontiers in Psychology, 9*, 2263. https://doi.org/10.3389/fpsyg.2018.02263
Jian, Y. C. (2019). Reading instructions facilitate signalling effect on science text for young readers: An eye-movement study. *International Journal of Science and Mathematics Education, 17*, 503–522. https://doi.org/10.1007/s10763-018-9878-y
Jian, Y. C. (2021). Influence of science text reading difficulty and hands-on manipulation on science learning: An eye-tracking study. *Journal of Research in Science Teaching (in Press)*. https://doi.org/10.1002/tea.21731
Jian, Y. C., & Ko, H. W. (2014). Investigating the effects of background knowledge on Chinese word processing during text reading: Evidence from eye movements. *Journal of Research in Reading, 37*(1), 71–86. https://doi.org/10.1111/j.1467-9817.2012.01534.x
Jian, Y. C., Su, J. H., & Hsiao, Y. R. (2019). Differentiated processing strategies for science reading among sixth-grade students: Exploration of eye movements using cluster analysis. *Computers and Education*. https://doi.org/10.1016/j.compedu.2019.103652
Jian, Y. C., & Wu, C. J. (2021). Conveying spatial and kinematic representations in text reading via words and pictures: An eye-movement analysis. *Chinese Journal of Psychology* (in press)
Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review, 87*(4), 329–354. https://doi.org/10.1037/0033-295X.87.4.329
Kaakinen, J. K., Hyönä, J., & Keenan, J. M. (2003). How prior knowledge, WMC, and relevance of information affect eye fixation in expository text. *Journal of Experimental Psychology Learning, Memory, and Cognition, 3*, 447–457. https://doi.org/10.1037/0278-7393.29.3.447
Kazanci, Z. (2015). University students' preferences of reading from a printed paper or a digital screen—A longitudinal study. *International Journal of Culture and History, 1*(1), 50–53. https://doi.org/10.18178/ijch.2015.1.1.009
Kerr, M. A., & Symons, S. E. (2006). Computerized presentation of text: Effects on children's reading of informational material. *Reading and Writing, 19*(1), 1–19. https://doi.org/10.1007/s11145-003-8128-y
Kim, Y.-S.G., Vorstius, C., & Radach, R. (2018). Does online comprehension monitoring make a unique contribution to reading comprehension in beginning readers? Evidence from eye movements. *Scientific Studies of Reading, 22*(5), 367–383. https://doi.org/10.1080/10888438.2018.1457680
Kraal, A., Koornneef, A. W., Saab, N., & van den Broek, P. W. (2017). Processing of expository and narrative texts by low- and high-comprehending children. *Reading and Writing, 31*(9), 2017–2040. https://doi.org/10.1007/s11145-017-9789-2
Lenhard, W., Schroeders, U., & Lenhard, A. (2017). Equivalence of screen versus print reading comprehension depends on task complexity and proficiency. *Discourse Processes, 54*(5–6), 427–445. https://doi.org/10.1080/0163853X.2017.1319653

Liao, C.-N., Chang, K.-E., Huang, Y.-C., & Sung, Y.-T. (2020). Electronic storybook design, kindergartners' visual attention, and print awareness: An eye-tracking investigation. *Computers & Education, 144*, 103703. https://doi.org/10.1016/j.compedu.2019.103703

Liu, Z. (2005). Reading behavior in the digital environment. *Journal of Documentation, 61*, 700–712. https://doi.org/10.1108/00220410510632040

Liu. C. C. (2009).Slow earthquakes triggered by typhoons (in Chinese). *Scientific American, 92, October*

Mangen, A., & Kuiken, D. (2014). Lost in an iPad: Narrative engagement on paper and tablet. *Scientific Study of Literature, 4*(2), 150–177. https://doi.org/10.1075/ssol.4.2.02man

Mangen, A., Walgermo, B. R., & Brønnick, K. (2013). Reading linear texts on paper versus computer screen: Effects on reading comprehension. *International Journal of Educational Research, 58*, 61–68. https://doi.org/10.1016/j.ijer.2012.12.002

Margolin, S. J., Driscoll, C., Toland, M. J., & Kegler, J. L. (2013). E-readers, computer screens, or paper: Does reading comprehension change across media platforms? *Applied Cognitive Psychology, 27*(4), 512–519. https://doi.org/10.1002/acp.2930

Mason, L., Tornatora, M. C., & Pluchino, P. (2013). Do fourth graders integrate text and picture in processing and learning from an illustrated science text? Evidence from eye-movement patterns. *Computers & Education, 60*(1), 95–109. https://doi.org/10.1016/j.compedu.2012.07.011

Miller, B. W. (2015). Using reading times and eye-movements to measure cognitive engagement. *Educational Psychologist, 50*(1), 31–42. https://doi.org/10.1080/00461520.2015.1004068

Reichle, E. D., Rayner, K., & Pollatsek, A. (1999). Eye movement control in reading: Accounting for initial fixation locations and refixations within the E-Z Reader model. *Vision Research, 39*, 4403–4411. https://doi.org/10.1016/B978-012369374-7/50017-1

Schnotz, W., & Bannert, M. (2003). Construction and interference in learning from multiple representations. *Learning and Instruction*, *13*, 141–156. https://doi.org/10.1016/S0959-4752(02)00017-8.

Schnotz, W., & Wagner, I. (2018). Construction and elaboration of mental models through strategic conjoint processing of text and pictures. *Journal of Educational Psychology*, *110*(6), 850–863. https://doi.org/10.1037/edu0000246.

Schnotz, W., Ludewig, U., Ullrich, M., Horz, H., McElvany, N., & Baumert, J. (2014). Strategy shifts during learning from texts and pictures. *Journal of Educational Psychology*, *106*(4), 974–989. https://doi.org/10.1037/a0037054.

Siegenthaler, E., Wurtz, P., Bergamin, P., & Groner, R. (2011). Comparing reading processes on e-ink displays and print. *Displays*, *32*(5), 268–273. https://doi.org/10.1016/j.displa.2011.05.005.

Singer, L. M., & Alexander, P. A. (2017). Reading on paper and digitally: What the past decades of empirical research reveal. *Review of Educational Research, 87*(6), 1007–1041. https://doi.org/10.3102/0034654317722961

Singer Trakhman, L. M., Alexander, P. A., & Berkowitz, L. E. (2019). Effects of processing time on comprehension and calibration in print and digital mediums. *Journal of Experimental Education, 87*(1), 101–115. https://doi.org/10.1080/00220973.2017.1411877

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

Stoop, J., Kreutzer, P., & Kircz, J. (2013). Reading and learning from screens versus print: A study in changing habits: Part 1-reading long information rich texts. *New Library World, 114*, 284–300. https://doi.org/10.1108/NLW-04-2013-0034

Tsai, M. J., Wu, A. H., & Chen, Y. (2019). Static and dynamic seductive illustration effects on text-and-graphic learning processes, perceptions, and outcomes: Evidence from eye tracking. *Applied Cognitive Psychology*. https://doi.org/10.1016/10.1002/acp.3514

Wade, S., & Kidd, C. (2019). The role of prior knowledge and curiosity in learning. *Psychonomic Bulletin & Review*. https://doi.org/10.3758/s13423-019-01598-6

Wickelgren, W. A. (1977). Speed-accuracy tradeoff and information processing dynamics. *Acta Psychological, 41*(1), 67–85. https://doi.org/10.1016/0001-6918(77)90012-9

Wu, C. J., & Liu, C. Y. (2021). Eye-movement study of high- and low-prior-knowledge students' scientific argumentations with multiple representations. *Physical Review Physics Education Research, 17*(1), 010125. https://doi.org/10.1103/PhysRevPhysEducRes.17.010125

Wu, C.-J., Liu, C.-Y., Yang, C.-H., & Wu, C.-Y. (2021). Children's reading performances in illustrated science texts: Comprehension, eye movements, and interpretation of arrow symbols. *International Journal of Science Education, 43*(1), 105–127. https://doi.org/10.1080/09500693.2020.1858515

Zambarbieri, D., & Carniglia, E. (2012). Eye movement analysis of reading from computer displays, eReaders and printed books. *Ophthalmic and Physiological Optics, 32*(5), 390–396. https://doi.org/10.1111/j.1475-1313.2012.00930.x

Zimmerman, B. J. (1986). Becoming a self-regulated learner: Which are the key subprocesses? *Contemporary Educational Psychology, 11*, 307–313. https://doi.org/10.1016/0361-476X(86)90027-5