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How Revisions to Mathematical Visuals Affect Cognition: Evidence from Eye Tracking

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ABSTRACT

Mathematics curricula are frequently rich with visuals, but these visuals are often not designed for optimal use of students' limited cognitive resources. The authors of this study revised the visuals in a mathematics lesson based on instructional design principles. The purpose of this study is to examine the effects of these revised visuals on students' cognitive load, cognitive processing, learning, and interest. Middle-school students (N = 62) read a lesson on early algebra with original or revised visuals while their eye movements were recorded. Students in the low prior knowledge group had less cognitive load and cognitive processing with the revised lesson than the original lesson. However, the reverse was true for students in the middle prior knowledge group. There were no effects of the revisions on learning. The findings are discussed in the context of the expertise reversal effect as well as the cognitive theory of multimedia learning and cognitive load theory.

Keywords: Cognitive Load, Instructional Design Principles, Cognitive Processing, Multimedia Learning, Multiple Representations

INTRODUCTION

Eye-tracking measures may provide important insight into the design of learning materials (i.e., instructional design; Hyönä, 2010; Mayer, 2010; van Gog & Scheiter, 2010). This view is based on the *eye-mind assumption* (Just & Carpenter, 1980), which states that the eye fixates on what the mind is processing (Just & Carpenter, 1976; Rayner, 1998). By examining what a student's eyes fixate on, one can discern what that student is focusing on, and this information may be useful for understanding how students use instructional materials.

One distinct benefit of eye-tracking measures is their spatial precision, which allows for understanding how information in different regions of a lesson is processed (e.g., Chang & Choi, 2014; She & Chen, 2009). For this reason, eye-tracking measures are particularly valuable for understanding how different representations, such as visuals and text, are processed (e.g., Mason et al., 2013; Scheiter & van Gog, 2009; Schwonke, Berthold, & Renkl, 2009). In this research, we used eye tracking to examine how variations in visuals affect students' processing of a lesson.

Researchers and curriculum designers have articulated *instructional design principles* (also called evidence-based principles and cognitive principles) that specify how visuals should be integrated with text (Mayer & Moreno, 1999; Mayer, 2008). The broad aim of these principles is to optimize learning (e.g., Mayer, 2009; Sweller, Ayres, & Kalyuga, 2011). In this work, we used eye tracking to examine students' processing of a lesson that was either well aligned or less well aligned with these principles.

To address this issue, we used a lesson from *Connected Mathematics 2* (*CMP2;* Lappan, Fey, Fitzgerald, Friel, & Phillips, 2006), which is rich with visuals, such as pictures, diagrams, and other spatial representations (Clinton, Cooper, Alibali & Nathan, 2012). However, the ways visuals are used in the lessons and activities do not always make effective use of students' cognitive resources. In a separate, large-scale study, a team of researchers has revised the visuals based on instructional design principles, and is testing the revised version of the *CMP2* curriculum in a nation-wide randomized control trial in order to determine the effectiveness of the revisions on learning (Davenport, Kao, & Schneider, 2013).

Building on previous research findings on instructional design principles and eye tracking (e.g., Johnson & Mayer, 2012; Ozcelik, Karakus, Kursun, & Cagiltay, 2009; Ozcelik, Arslan-Ari, Cagiltay, 2010), we conducted an eye-tracking experiment with students who read a lesson derived from the *CMP2* curriculum with original visuals or with visuals that were revised on the basis of instructional design principles. The aim was to assess the effects of the revised visuals on students' processing of the different representations and on their subsequent learning. Specifically, we were interested in how eye-tracking measures could reveal the moment-by-moment effort in working memory, referred to as *cognitive load*, as well as the amount of time spent viewing representations, referred to as the *amount of cognitive processing* (see Ozcelik et al., 2010 for a similar approach).

BACKGROUND

The instructional design principles that guided the revisions are grounded in the *cognitive theory of multimedia learning* (Mayer, 2009; Mayer & Moreno, 2003) and in *cognitive load theory* (e.g., Paas, Renkl & Sweller, 2003; Plass, Moreno, & Brünken, 2010). A central idea of both theories is that the structure of the cognitive system imposes limits on the processing of information presented to auditory, linguistic, and visual sensory processing channels that influence how learners integrate information. The cognitive theory of multimedia learning holds that visual and verbal information (i.e., text or speech) are processed in different pathways, and the theory emphasizes the need for the information in these two pathways to be integrated (Mayer, 2014a). In addition, the cognitive theory of multimedia learning prescribes guidance for instructional design, namely the reduction of extraneous (i.e., unnecessary) processing to improve learning (Mayer, 2009). In sum, implementing these theory-based principles in a lesson should reduce the amount of cognitive processing necessary to understand a lesson.

In contrast to the cognitive theory of multimedia learning, cognitive load theory emphasizes the different types of cognitive load (i.e., effort in working memory) a student may experience (Sweller et al., 2011). Cognitive load theory builds on the idea that inherent (i.e., biological) constraints on working memory limit the amount of information one can process at a given time (Chandler & Sweller, 1991). If a student has too much information to process or information is difficult to understand, limited working memory capacity can be overloaded, thereby impairing comprehension and diminishing learning (Sweller, 1994). Much of this research has shown superior problem-solving performance and learning with manipulations that reduce the cognitive load required to integrate information across visuals and text (e.g., Chandler & Sweller, 1991; Kalyuga, Chandler, & Sweller, 1999; see Mayer & Moreno, 2009; Pashler et al., 2007 for reviews).

Cognitive load can be intrinsic or extrinsic to the learning goal (Sweller et al., 2011). Intrinsic cognitive load (this includes what used to be referred to as "germane load"; Kalyuga, 2011) consists of the information in working memory relevant to the task. In contrast, extrinsic cognitive load consists of information in working memory irrelevant to the instructional task. The general aim of instructional design principles is to reduce extrinsic cognitive load so that students can focus their cognitive resources to best manage the lesson content (Mayer & Moreno, 2003).

Instructional design principles

Three instructional design principles guided the revisions to the curricular materials: signaling, contiguity, and coherence.

According to the *signaling principle*, learning is promoted by cues, such as color codes and labels (Mayer, 2009), to important information. Cues may promote learning both by directing students' attention to relevant information and by connecting corresponding information across different representations (e.g., text and visuals; Berthold & Renkl, 2009; Florax & Ploetzner, 2010; Kalyuga, Chandler & Sweller, 1999; de Koning, Tabbers, Rikers, & Paas, 2009; for a meta-analysis see Richter, Scheiter & Eitel, 2016). These cues may reduce the extraneous processing and the extrinsic cognitive load needed to discern the importance of information or integrate corresponding information across representations (Lin & Lin, 2014; Mayer & Moreno, 2003). The use of signaling may increase cognitive processing of the visual, especially in the signaled areas of the visual (de Koning, Tabbers, Rikers, & Paas, 2010). However, previous eye-tracking findings have not indicated a reduction in cognitive load due to signaling (de Koning et al., 2010; Ozcelik et al., 2010).

The *contiguity principle* states that information should be arranged such that relevant information in different representations is in close proximity. This reduces the cognitive load of reading and connecting corresponding verbal and visual information (e.g., Ginns, 2006; Renshaw, Finlay, Tyfa, & Ward, 2004). Labels place relevant text in close proximity to visuals, making the information in the two representations more spatially contiguous, thereby facilitating integration between the two representations (Florax & Ploetzner, 2010; Holsanova, Holmberg, & Holmquist, 2009; Johnson & Mayer, 2012). Previous eye-tracking findings have indicated that integrating relevant text with visuals does not affect the amount of cognitive processing of the visual, but does reduce the amount of cognitive processing of the text, perhaps due to the reduction in extraneous processing (Johnson & Mayer, 2012). However, there has been limited empirical investigation of the contiguity principle on cognitive load (see Altan & Cagiltay, 2015, for preliminary work with a small sample).

The *coherence principle* states that learning is fostered when interesting, but irrelevant information, such as decorative pictures, is removed (Harp & Mayer, 1997; Mayer, 2009; for a review, see Rey, 2012). This type of information has been found to distract learners and diminish comprehension, a phenomenon referred to as the *seductive details effect* (e.g., Lehman, Schraw, McCrudden, & Hartley, 2007). Irrelevant visuals may interfere with learning because they increase the amount of information in the lesson (Sanchez & Wiley, 2006). This potential increase in extraneous cognitive processing and extrinsic cognitive load appears to be particularly problematic for learning from written lessons in which verbal information is conveyed through text (visually) compared to oral presentations in which verbal information is conveyed through narration (auditorily; Park, Moreno, Seufert, & Brünken, 2011). This difference in modalities is presumably due to irrelevant visuals overloading cognitive resources when all of the information in a lesson is presented visually (Park, Flowerday, & Brünken, 2015). Previous eye-tracking findings have indicated that irrelevant visuals in statistics lessons caused less cognitive processing of instructional text and visuals compared to lessons without irrelevant visuals, likely because of the extra information and distraction of the irrelevant visuals (Rey, 2014). Surprisingly, one study found that self-reports of cognitive load were lower for lessons with irrelevant visuals, despite lower comprehension scores (Park, Korbach, & Brünken, 2015. It is possible that the irrelevant visuals gave students the impression the lesson was easier than it actually was. For this reason, an eye-tracking measure of cognitive load may be particularly valuable (van Gog, Kester, Nievelstein, Giesbers, & Paas, 2009) for materials such as these. An eye-tracking measure would be collected as the lesson is being viewed and would be a more objective measure of the demand imposed by the lesson (e.g., Amadieu, Van Gog, Paas, Tricot, & Mariné, 2009).

In past research, the signaling, contiguity, and coherence principles have typically been examined in isolation (e.g., Florax & Ploetzner, 2010; Mason et al., 2013; Ozcelik et al., 2009, 2010; Scheiter & Eitel, 2015). However, in the revisions of the CMP curriculum, these principles were all applied in the following ways: (1) additional signaling was added; (2) contiguity of visuals and related text was increased, and (3) math-irrelevant visuals were removed. Multiple principles were applied based on a "less is more" approach; *less* extrinsic cognitive load and extraneous processing (through the removal of math-irrelevant visuals and increased contiguity and signaling) was expected to yield *more* learning (see Mayer, 2014b). This approach is novel and examines whether benefits to the process and products of learning can be maximized by applying multiple principles simultaneously.

Instructional design principles can interact with prior knowledge

Generally speaking, the cognitive load and cognitive processing involved when learning from lessons with text and visuals varies with both the design of the material (as previously discussed) and the prior knowledge of the student (Kalyuga et al., 2003; Kirschner, Paas, Kirschner, & Janssen, 2011; Moreno, 2004). Some evidence suggests that the implementation of instructional design principles may be most effective for students with low levels of prior knowledge (Mayer, 2001). This is because the less prior knowledge a student has, the more intrinsic cognitive load the task imposes (Kalyuga, 2011; Leahy, Hanham, & Sweller, 2015). An increase in intrinsic cognitive load could consume working memory capacity, leaving little capacity for handling extrinsic cognitive load (Paas, Renkl, & Sweller, 2003). For these reasons, if a task is high in intrinsic cognitive load, reductions in extrinsic load should yield more benefits compared to tasks low in intrinsic load (Seufert, Jänen, & Brünken, 2007). Therefore, the reduction of extraneous processing and extrinsic cognitive load through the application of the instructional design principles may foster greater learning in students with low levels of prior knowledge than in students with high levels of prior knowledge (e.g., Magner, Schwonke, Aleven, Popescu & Renkl, 2014; see Moreno & Mayer, 2007; Schnotz, 2002, for discussions). It is also possible that efforts to lower cognitive load may actually make learning more difficult for students with higher levels of prior knowledge (Kalyuga, 2007). This phenomenon, known as the *expertise reversal effect*, arises because the information added to guide processing is redundant with what students with high prior knowledge already know, thereby increasing the cognitive load of the lesson (Sweller et al., 2011).

Much of the previous work on prior knowledge and instructional design techniques has involved separating students into two groups: high and low (e.g., Mayer & Gallini, 1990; Mayer, Steinhoff, Bower, & Mars, 1995). However, recent research findings have indicated that separating students into three groups allows a more nuanced understanding of interactions between instructional design techniques and prior knowledge (Magner et al., 2014).

THE CURRENT STUDY

The purpose of the current study is to use eye-tracking methodology to examine the effects of revisions to visuals based on instructional design principles (specifically, the signaling, contiguity, and coherence principles) on the process of reading a mathematics lesson and on subsequent learning from that lesson. Eye tracking was the methodology of choice because the data from eye tracking can be used to infer the moment-by-moment processes involved in reading (Just & Carpenter, 1980; Rayner, 1998). Because of the spatial precision of eye tracking, the data afford valuable insight into the processing of different representations in written lessons with visual representations (e.g., Mason et al., 2013; Rau, Michaelis, & Fay, 2015; Scheiter & Eitel, 2015; see Hyönä, 2010 for review). In other words, eye tracking allows an examination of how visuals and text are processed.

Specific to this study, we were interested in how eye tracking could yield information about the cognitive load and amount of cognitive processing involved in viewing the text and visuals. To assess cognitive load, average fixation length (i.e., pause in eye movement) was used. *Average fixation length* is thought to be a positive indicator of cognitive load (i.e., as cognitive load increases, average fixation length increases; Ozcelik et al. 2010; van Gog et al., 2009; Paas, 2009; van Gog & Scheiter, 2010). This is because cognitive load is essentially the mental effort involved in working memory, and fixations typically increase as more effort is exerted while viewing the fixated material (van Gog et al., 2009). Thus, average fixation length can be used to infer the effectiveness of the revisions in reducing cognitive load. In contrast, the amount of cognitive processing is how much time one spends thinking about something. Given the eye-mind assumption (Just & Carpenter, 1980), the time spent viewing a representation, calculated by summing the fixation durations on that representation, is considered to be the amount of cognitive processing involved with the representation (e.g., Graesser, Lu, Olde, Cooper-Pye, & Whitten, 2005; Rayner, 1998; Ozcelik et al., 2009). In other words, the amount of time a student viewed a section of a lesson provides a measure of how much that student cognitively processed that section (e.g., Kaakinen, Olkoniemi, Kinnari, & Hyönä, 2014). The amount of cognitive processing differs from cognitive load because cognitive processing is the overall time spent on a representation whereas cognitive load is the mental effort in working memory at a given moment (Ozcelik et al., 2010).

We address three main research questions. First, what were the effects of the revisions on cognitive load while reading the lesson? Because the revisions were designed to reduce cognitive load, average fixation length was expected to be shorter for the revised lesson than the original lesson (e.g., Amadieu et al., 2009). In this way, average fixation length can be used to evaluate the effectiveness of the revisions. Further, this finding might be strongest for students with low levels of prior knowledge, compared to students with higher levels of prior knowledge (Mayer, 2001). Moreover, because of the expertise reversal effect (Kalyuga, 2007), it is possible that the revisions would increase the cognitive load for students with middle and high levels of prior knowledge. It should be noted that some previous eye-tracking work examining a single instructional design principle has not revealed effects on average fixation length (Altan & Cagiltay, 2015; de Koning et al., 2010; Ozcelik et al., 2010). However, because our study applies multiple principles, the cumulative effects of these principles may be powerful enough to reduce average fixation length, at least for students with low levels of prior knowledge.

Second, what were the effects of the revisions on the amount of cognitive processing for different representations? These amounts can be assessed via *total fixation time*, which is the summed duration of all fixations within an area of interest (e.g., a visual or a section of text;). With this measure, it can be determined whether students differed in how much they processed the original and revised visuals. Given that the revised visuals provide additional guidance for processing, students may need to engage in less cognitive processing with them, thereby needing less total fixation time compared to the original visuals. In addition, it can be determined whether students processed the text in the lesson differently depending on the type of visuals used. Students with revised visuals may have less total fixation time on the text compared to students with original visuals because students with revised visuals may need less help from the text to understand the mathematical content. Finally, to assess the amount of cognitive processing of the entire lesson, we examined the total fixation duration for the entire lesson. It was expected that students with the revised lesson would spend less time with the lesson than students with the original lesson.

As with cognitive load, the effects of the revisions on the amount of cognitive processing would likely be most pronounced for students with low levels of prior knowledge. However, prior knowledge is especially important to consider given that the amount of cognitive processing of visuals is negatively associated with prior knowledge (i.e., the less prior knowledge a student has, the longer the visual is viewed; Hegarty & Just, 1993; Schwonke et al., 2009). This may be because students with high prior knowledge primarily use the visuals to confirm what they already know, rather than to learn from them (Rasch & Schnotz, 2009).

Third, did the revisions of the visuals affect students' learning from the lesson? The instructional design principles were intended to reduce cognitive load and extraneous processing so that students could focus their limited cognitive resources on the content presented in the lesson (Mayer, 2009; Sweller et al., 2011). For these reasons, students may perform better on a post-lesson test after reading the revised lesson than the original lesson. However, the learning benefits from the revisions may be strongest for students with low levels of prior knowledge (Mayer, 2001).

One benefit of eye tracking is that it can reveal whether the revisions affected how students viewed the lesson, even if there is no observable effect on learning. For example, previous eye-tracking findings have revealed that replacing text with narration in a multimedia presentation reduced average fixation lengths when viewing the presentation, but did not affect learning from the presentation (Liu, Lai, & Chuang, 2011). This is because eye-tracking measures are more sensitive than many other measures. Furthermore, the amount of cognitive processing of the representations in the lesson could be used to examine if students compensate for the lack of guidance in the original visuals by spending more time on different representations in the lesson as well on the lesson overall. Finally, if the revisions had no effect on eye movements or learning, it can be assumed that the application of the instructional design principles was ineffective and other techniques should be explored (e.g., Lowe & Boucheix, 2011).

These questions were addressed using a lesson about how to graph independent and dependent variables on a coordinate grid. In addition to being visually rich, this topic is of particular interest because of its importance in scientific literacy (Padilla, McKenzie, & Shaw, 1986) and algebraic reasoning (Nathan & Kim, 2007).

Method

Participants

Participants were 62 (26 female, 36 male) middle-school students entering sixth or seventh grade (ages 10 – 12 years; *M* = 11.12 years, *SD* = .33 years). Because of apparatus malfunction, eye-tracking data were collected for only 57 participants. However, all 62 participants read the lesson in the same manner and completed the self-report of prior knowledge and the post-lesson test (see Measures). Participants were compensated with a $15 gift card for an online retailer.

Apparatus

An EyeLink 1000 Desk-Mounted System, manufactured by SR Research Ltd. (Toronto, Ontario, Canada), was used to collect eye movement data. This eye tracker uses an infra-red video camera for monocular tracking, and the video camera was focused on the participant's pupil. The video camera sampled real-time fixations at a 1000 Hz sampling rate. Head position was stabilized with a chin and forehead rest 70 cm from the computer monitor displaying the lesson. Pupil diameter was recorded with centroid pupil tracking.

Materials

The lesson, derived from *CMP2* (Lappan et al., 2006), covered the skills necessary to record data with independent and dependent variables in a table and then construct a graph from those data. The skills were presented in the context of a story in which a person was planning a long-distance bike trip and needed to know her biking pace. The original lesson included a variety of visuals including a map, graphs, tables, and math-irrelevant pictures.

The lesson consisted of nine pages, with identical text in both the original and revised conditions but changes made to the visuals on eight of the revised pages. The first page was the same for both groups, with text that reiterated the instructions for reading the lesson (e.g., read at your own pace, please sit still). The introduction to the lesson discussed the person's plans for her trip and included a map that had decorative features in the original materials, but, based on the coherence principle, did not have decorative features in the revised materials. In the remaining 7 pages, there were 3 pages in which the signaling and contiguity principles were applied to the revised visuals. Specifically, color coding, labels, and call-out boxes were added to the math-relevant visuals of tables and graphs (see Figure 1). There were 2 pages in which the math-relevant visuals were the same in the original and revised materials, but the original materials also contained math-irrelevant visuals and, following the coherence principle, these were deleted in the revised materials (see Figure 2). Finally there were 2 pages in which the original materials contained a math-irrelevant visual and, following the signaling, contiguity, and coherence principles, the revised materials contained a math-relevant visual with labeling and call-out boxes (see Figure 3).

As one would likely see in *CMP2*, the arrangement of the visuals in relationship to the text varied on each page. On some pages the visuals were below the text and on other pages the visuals were beside the text. This created more variability in the design of the materials across the lesson than is typically seen in eye-tracking experiments of lessons with visuals (e.g., Scheiter & Eitel, 2015). However, the aim was to make materials as authentic as possible to enhance the ecological validity of the results (see Holsanova, 2014).

Original	Revised

Original

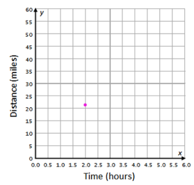
Step 4 Plot the data points.

At 2 hours, Celia had biked 22 miles.

You can see this in the table.

Time (hours)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
Distance (miles)	0	7	12	18	22	26	30	34	40	45	49	52	58

To plot this information on a coordinate graph, start at the *x*-value of 2 on the *x*-axis (time) and follow a line straight up. On the *y*-axis (distance), start at the *y*-value of 22 and follow a line straight across. Make a point where the two lines intersect. You can describe this point with the **coordinate pair** (2, 22). The first number in a coordinate pair is the *x*-coordinate, and the second number is the *y*-coordinate.



Revised

Step 4 Plot the data points.

At 2 hours, Celia had biked 22 miles.

You can see this in the table.

Time (hours)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
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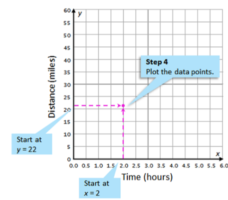


Figure 1. Example of revisions based on the signaling and contiguity principles

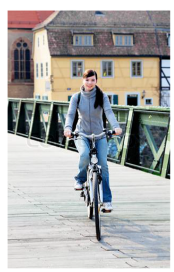
Original

Recording Data and Making Tables

Celia took a practice ride in her hometown of Atlantic City. She used an app on her smart phone that recorded how far she had biked every half hour. She made the table below of the distance in miles she had biked every half hour.

Time (hours)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
Distance (miles)	0	7	12	18	22	26	30	34	40	45	49	52	58

After the first half hour (0.5 hours), she had biked for seven miles. At four hours, she had biked for 40 miles. At the end of the day, she had biked six hours for a total of 58 miles.



Revised

Recording Data and Making Tables

Celia took a practice ride in her hometown of Atlantic City. She used an app on her smart phone that recorded how far she had biked every half hour. She made the table below of the distance in miles she had biked every half hour.

Time (hours)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
Distance (miles)	0	7	12	18	22	26	30	34	40	45	49	52	58

After the first half hour (0.5 hours), she had biked for seven miles. At four hours, she had biked for 40 miles. At the end of the day, she had biked six hours for a total of 58 miles.

Figure 2. Example of revisions based on the coherence principle (image from Shutterstock©, used with permission)

Original	Revised

Step 5 Finish plotting the data points. Continue plotting the information in the data table on the coordinate graph.

Step 5 Finish plotting the data points. Continue plotting the information in the data table on the coordinate graph.

Time (hours)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
Distance (miles)	0	7	12	18	22	26	30	34	40	45	49	52	58

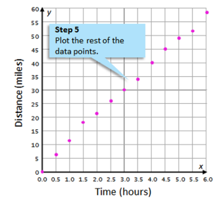


Figure 3. *Example of revisions based on the coherence, signaling, and contiguity principles (image in original lesson from Getty Images©, used with permission)*

Procedure

Participants took part individually, and the experimenter calibrated the eye tracker for each participant. Participants then read the lesson one page at a time, at their own pace, while their eye movements were recorded. Prior to reading each page, participants gazed at a single dot on the screen to correct for drifts in eye gaze that may have occurred since calibration. After reading the lesson, participants reported their familiarity with the math content and then completed the post-lesson test.

Measures

Similar to Mautone and Mayer (2001), prior knowledge was assessed through self-reports of familiarity with the mathematical content of the lesson on a Likert scale from 1-5 (M = 3.74, SD = 1.20). Based on these responses, participants were divided into three prior knowledge groups: low (responses between 1-3; n = 22), middle (response of 4; n = 16), and high (response of 5; n = 19). Self-reports were used instead of pretests to prevent pretest sensitization, in which treatment effects may be inflated by priming knowledge with assessments prior to the lesson (Willson & Putnam, 1982; Willson & Kim, 2010).

The post-lesson test consisted of three parts. The first part directly assessed individual skills covered in the lesson, such as reading data values from a table and graph, identifying independent and dependent variables, identifying appropriately scaled axes, using appropriate axis units and scales, and locating the x- and y-axes. Answers on the first part were scored for accuracy (0 for incorrect answers; 1 for correct answers). The second part asked participants to construct a graph based on a table of data points. Students' graph construction was scored out of 5 points based on variable and axis placement, consistent use of scale on each axis, variable labels, and plotting points. The third part assessed preparation for future learning (see Bransford & Schwartz, 1999) by presenting a short, novel lesson that students read and answered questions about. The preparation for future learning questions asked students to take their reasoning a step further and to match a graph's pattern to a description of a data scenario. As with the first part, accuracy for question answers was dichotomously scored. A total score was determined by summing scores on all three parts (maximum of 27 points).

RESULTS

For all analyses, the Type I error rate was set at $\alpha = .05$, with Bonferroni corrections for multiple comparisons.

What were the effects of the revisions on cognitive load while reading the lesson?

We first examined the cognitive load incurred while reading the text, as indicated by average fixation length. Eye-tracking measures were extracted from text at the sentence level. Following Blozis and Traxler (2007), linear mixed-model analyses with condition and prior knowledge group as fixed factors, participant as a random factor, sentence as a repeated effect, and average fixation length as the dependent variable were conducted (see Schonberg, Sandhofer, Tsang, & Johnson, 2014, for similar analyses). All lesson text after the first page of instructions was used in these analyses.

As predicted, there was an interaction between condition and prior knowledge group, $F(2, 51) = 47.27$, $p < .001$ (see Figure 4). Participants in the low prior knowledge group had longer average fixation lengths on the text in the original condition than the revised condition, $F(1, 21) = 45.42$, $p < .001$. In contrast, participants in the middle prior knowledge group had shorter average fixation lengths on the text in the original condition than the revised condition, $F(1, 15) = 71.15$, $p < .001$. Participants in the high prior knowledge group also had shorter average fixation lengths on the text in the original condition than the revised condition, but this difference did not reach significance, $F(1, 18) = 3.613$, $p = .06$. These findings indicate that the cognitive load involved when reading the text varies as a function of both prior knowledge and revisions to the visuals.

In addition to the significant interaction, there was also a main effect for condition, $F(1, 51) = 7.75$, $p = .01$. Average fixation length was *shorter* overall while viewing text in the original condition than the revised condition, because participants in both the middle and high prior knowledge groups had shorter average fixation lengths in the original condition. There was also a main effect for prior knowledge, $F(2, 51) = 52.41$ $p = .01$, with participants in the high prior knowledge group having shorter average fixation lengths than both participants in the middle prior knowledge group, $p = .001$, and participants in the low prior knowledge group, $p < .001$. In addition, participants in the middle prior knowledge group had shorter average fixation lengths than did participants in the low prior knowledge group, $p < .001$. Overall, the decrease in average fixation duration with higher levels of prior knowledge indicated that cognitive load was lower for students with more knowledge. This relationship between prior knowledge and cognitive load is consistent with previous findings (Kalyuga, 2011) and validates the use of self-reports for assessing prior knowledge.

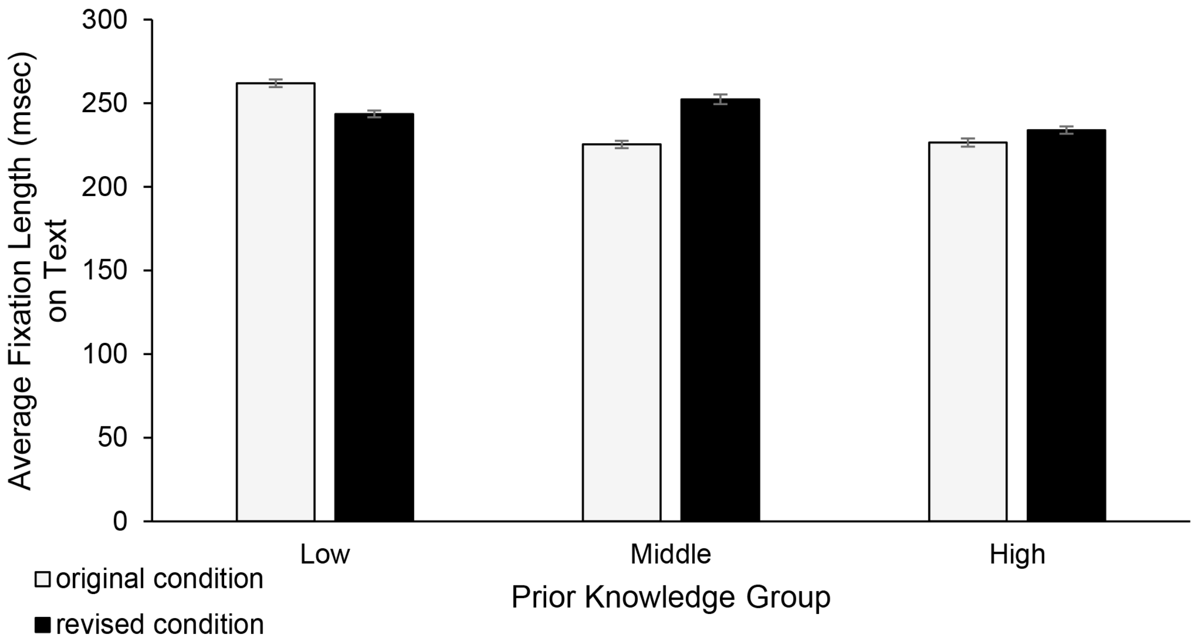


Figure 4. Average fixation length (means and +/1 SE) by condition and prior knowledge group while reading the lesson text

We next examined the effects of the revisions on the cognitive load incurred while processing math-relevant visuals (i.e., graphs and tables). To do this, the average fixation lengths on the math-relevant visuals that were present in both the original and revised lessons were examined (see Table 1 for an example of math-relevant visuals). The same analyses as with text were conducted, except the dependent variable was the average fixation length on math-relevant visuals. Similar to the text analyses, there was an interaction of condition and prior knowledge on average fixation length on the math-relevant visuals, $F(2, 51) = 8.58$, $p < .001$ (see Figure 2). For participants in the low prior knowledge group, the average fixation length for math-relevant visuals was longer in the original condition than in the revised condition $F(1, 21) = 5.53$, $p = .02$. In contrast, for the middle prior knowledge group, the average fixation length for math-relevant visuals was shorter in the original condition than in the revised condition, $F(1, 15) = 9.77$, $p = .003$. Finally, for the high prior knowledge group, the average fixation length for math-relevant visuals was longer in the original condition than in the revised condition, $F(1, 18) = 9.29$, $p = .003$. There was no overall main effect of condition, and there was a marginally significant main effect of prior knowledge, $F(2, 51) = 2.80$, $p = .06$, with average fixation length generally being shorter with higher levels of prior knowledge.

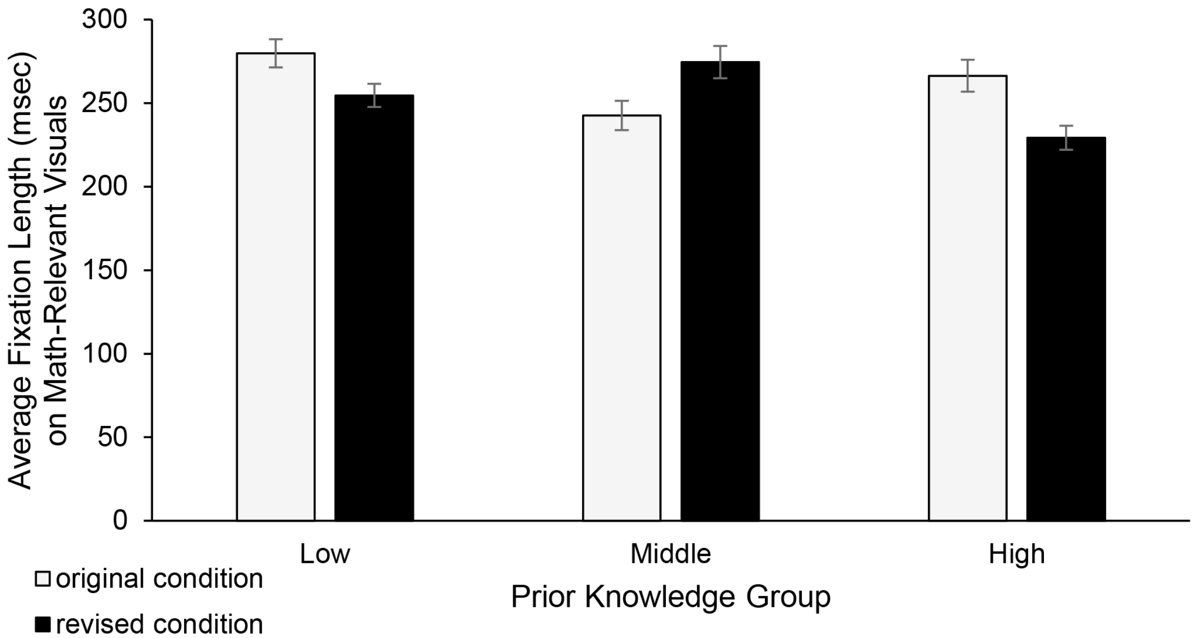


Figure 5. *Average fixation length (means and +/1 SE) by condition and prior knowledge group while viewing original or revised math-relevant visuals*

What were the effects of the revisions on the amount of cognitive processing for different representations in the lesson?

The effects of the revisions to the visuals on the amount of cognitive processing of the text and the visuals were examined. Total fixation duration (i.e., the sum of all fixations on a region of interest) was the measure of amount of cognitive processing. Prior to analyses, total fixation time was logarithmically transformed to improve normality (e.g., Mason, Tornatora, & Pluchino, 2015). Analyses were similar to those for cognitive load except the dependent variable was the total fixation duration on the region of interest.

We also examined the effects of the revisions on the cognitive processing of the text. Results are shown in Figure 6 (actual, non-transformed total fixation time is presented in the graphs to provide the reader with meaningful descriptive statistics). There was an interaction between condition and prior knowledge group for total fixation duration on the text, $F(2, 51) = 23.63$, $p < .001$. Participants in the low prior knowledge group had greater total fixation duration on the text in the original conditions than the revised condition, $F(1, 21) = 74.88$, $p < .001$. In contrast, participants in the middle prior knowledge group had less total fixation duration on the text in the original condition than the revised condition, $F(1, 15) = 9.82$, $p = .002$. There was no effect of condition on total fixation duration on the text for participants in the high prior knowledge group.

In addition to this interaction, there was also a main effect of condition, $F(1, 51) = 7.58$, $p = .01$, with greater total fixation duration on the text in the original condition than the revised condition, which is likely due to the reading behavior of participants in the low prior knowledge group. In addition, there was a main effect of prior knowledge, $F(2, 51) = 49.02$, $p < .001$. Participants in the low prior knowledge group had greater total fixation duration on the text than did both participants in the middle prior knowledge group, $p < .001$, and participants in the high prior knowledge group, $p < .001$.

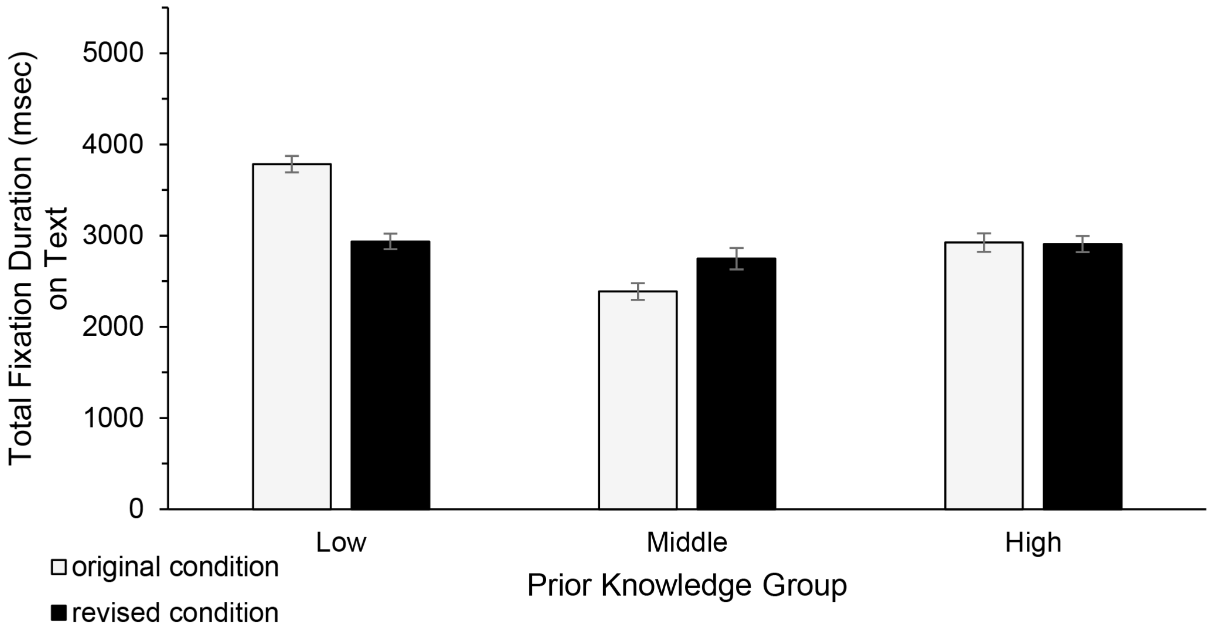


Figure 6. Total fixation duration (means and +/1 SE) by condition and prior knowledge group while reading the lesson text

We also examined the effects of the revisions on the cognitive processing of math-relevant visuals. Results are shown in Figure 4.

There was an interaction between condition and prior knowledge group for total fixation duration on the math-relevant visuals, $F(2, 51) = 6.57$, $p = .002$ (see Figure 7). Participants in the low prior knowledge group had longer total fixation duration on the math-relevant visuals in the original condition than in the revised condition, $F(1, 21) = 6.43$, $p = .01$. In contrast, participants in the middle prior knowledge group had shorter total fixation duration on the math-relevant visuals in the revised condition than in the original condition, $F(1, 15) = 9.74$, $p = .003$. There was no effect of condition on total fixation duration on the math-relevant visuals for participants in the high prior knowledge group. Therefore, revisions appeared to reduce cognitive processing for students in the low prior knowledge group, but increased cognitive processing for students in the middle prior knowledge group (explanations for these findings will be considered in the discussion). There was no main effect of condition, but there was a main effect of prior knowledge group, $F(2, 51) = 9.70$, $p < .001$. Participants in the low prior knowledge group had longer total fixation duration on math-relevant visuals than did either participants in the middle prior knowledge group, $p = .002$, or the high prior knowledge group, $p < .001$.

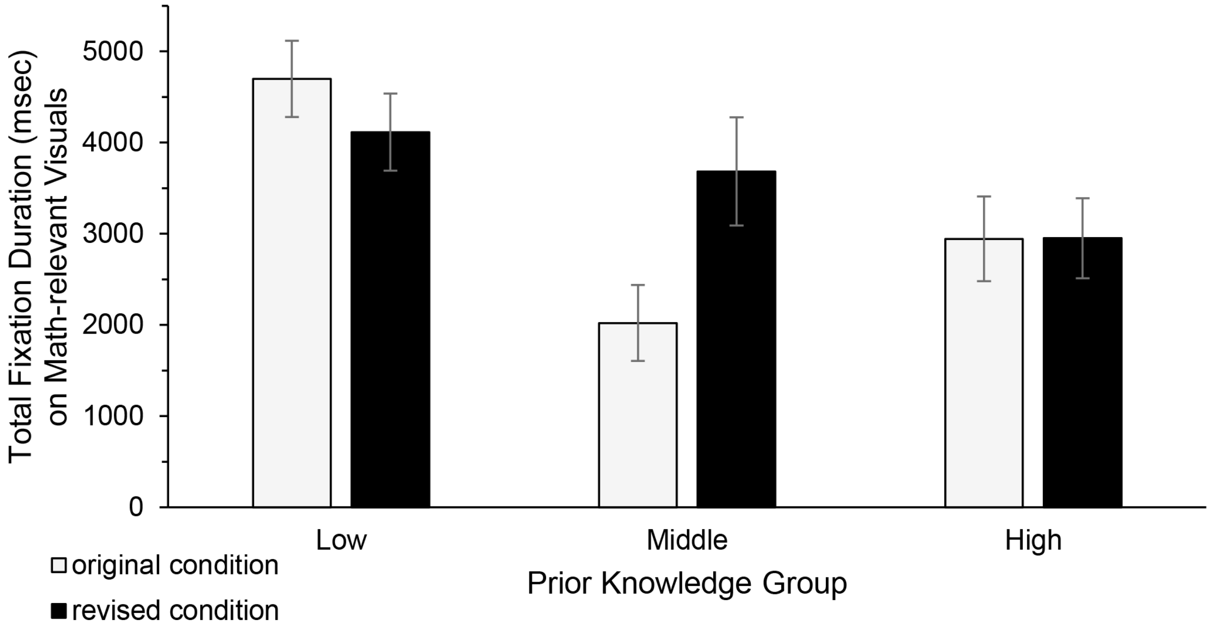


Figure 7. Total fixation duration (means and +/1 SE) by condition and prior knowledge group while viewing original or revised math-relevant visuals

Finally, the amount of cognitive processing of the entire lesson was examined (termed time spent with lesson to distinguish from previous analyses). An ANOVA with condition and prior knowledge group as independent variables and the total number of seconds spent with the lesson as the dependent variable was conducted. Results are shown in Figure 8. Condition and did not affect the time spent with the lesson, $F(1, 51) = .36$, $p = .55$ and there was a marginal effect of prior knowledge group, $F(2, 51) = 2.91$, $p = .06$, with time with the lesson generally being less with more prior knowledge. There was no reliable interaction between condition and prior knowledge group, $F(2, 51) = 2.22$, $p = .12$, although, based on the means, the revised lesson appeared to be read more quickly than the original lesson for the low prior knowledge group.

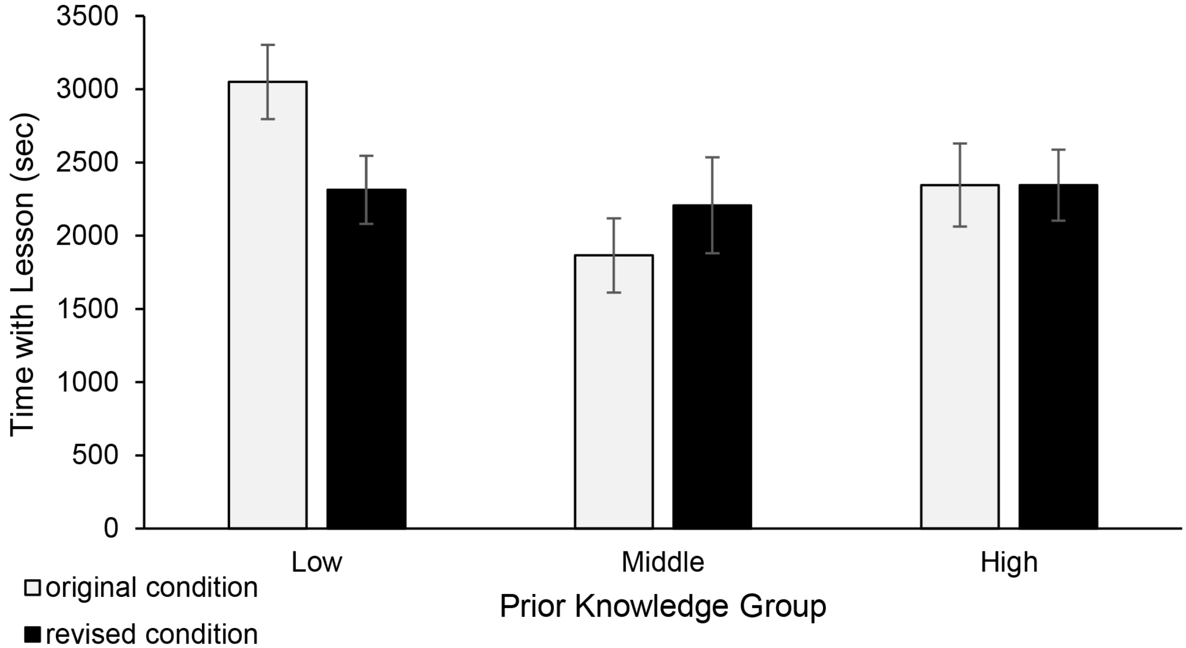


Figure 8. Time spent with lesson (means and +/1 SE) by condition and prior knowledge group

Did the revisions affect learning?

We examined the effects of the revisions on learning from the lesson. An ANOVA with condition and prior knowledge group as independent variables and score on the post-lesson test as the dependent variable was conducted. For these analyses, data from all participants, not just those for whom eye-tracking data were recorded, are reported ($N = 62$). As seen in Figure 9, condition did not affect post-lesson test scores, $F(1, 56) = .00$, $p = .96$. However, level of prior knowledge did predict post-lesson test scores, $F(2, 56) = 10.19$, $p < .001$; pairwise comparisons revealed that participants in the low prior knowledge group had lower post-lesson test performance than did participants in the high prior knowledge group, $p < .001$, Cohen's $d = 1.30$, providing validity for use of the self-report as a prior knowledge measure. There was no interaction between condition and level of prior knowledge, $F(2, 56) = .14$, $p = .87$.

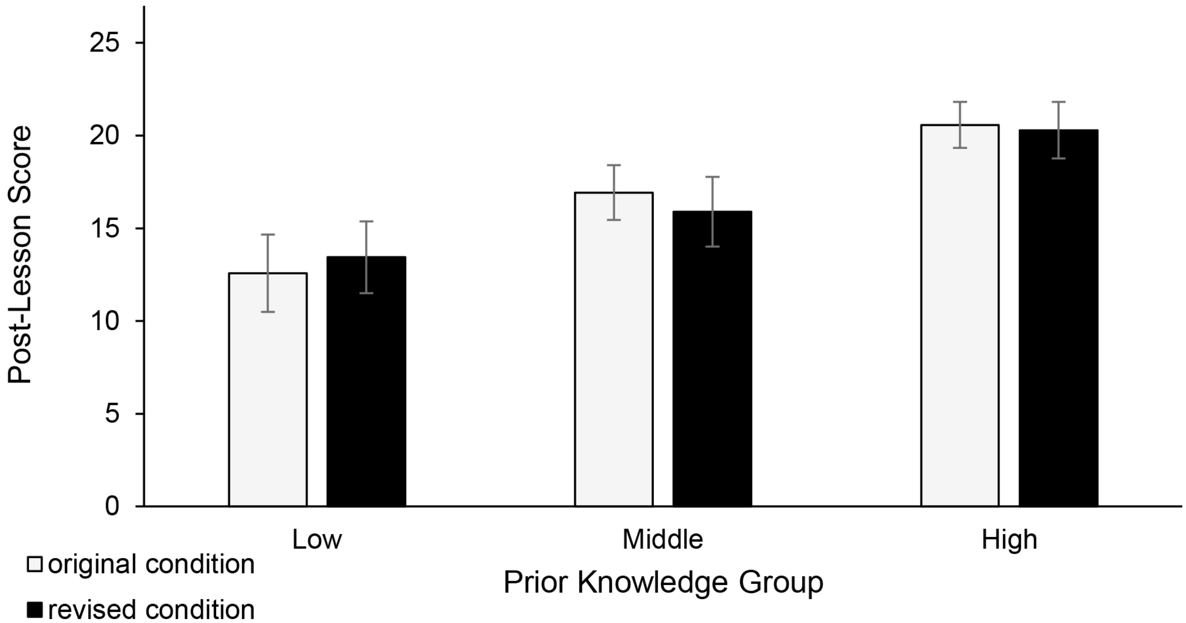


Figure 9. Post-lesson scores (means and +/1 SE) by condition and prior knowledge group

DISCUSSION

This study examined the effects of revisions of mathematical lesson materials based on instructional design principles on measures of cognitive load, amount of cognitive processing, and learning. The findings indicated that the revisions affected cognitive load and amount of cognitive processing for visuals and text, but that the effect of the revisions varied with students' level of prior knowledge. No effects of the revisions were found for amount of processing of the lesson as a whole or learning from the lesson.

Cognitive load

It was expected that the revisions would reduce cognitive load, as indicated by average fixation length, especially for students with low levels of prior knowledge. Indeed, the revisions appeared to reduce cognitive load while reading the text for students with low levels of prior knowledge. In addition, the revisions appeared to reduce cognitive load for viewing the revised visuals for students in the low prior knowledge group and high prior knowledge group. These findings support the idea that instructional design principles can reduce the cognitive load of reading text and attending to math-relevant visuals, at least for students with low levels of prior knowledge.

However, the revisions *increased* the cognitive load of reading the lesson text and viewing the math-relevant visuals for students with moderate prior knowledge. These findings are somewhat consistent with the *expertise reversal effect*, a phenomenon in which guidance intended to assist learning actually makes learning more difficult for students with higher levels of prior knowledge (Kalyuga, 2007). This is because the guidance is unnecessary information for someone who is proficient with the material. Specifically, the labeling of revised visuals may have been redundant information that required extra processing and thus increased cognitive load for the students with more knowledge (Kalyuga, Ayres, & Sweller, 2003). For students in the high prior knowledge group, this trend was reversed when these students were viewing the math-relevant visuals. One speculative explanation, based on previous work on how students with high levels of prior knowledge use visuals (Rasch & Schnotz, 2009) is that these students had such proficiency with the lesson that they were able to use the visuals to help remind them of the material they already knew. However, it is worth noting that this pattern, in which students with the highest level of prior knowledge have a reversal of the expertise reversal effect, has not been previously noted in the literature; therefore, it should be interpreted with caution.

Cognitive processing

It was expected that amount of cognitive processing of the text and visuals, as indicated by total fixation duration, would be less for the revised lesson than the original, at least for students with low levels of prior knowledge. This is because, based on the cognitive theory of multimedia learning, the revisions should have reduced extraneous processing (Mayer, 2009). Indeed, the amount of cognitive processing of the lesson text and math-relevant visuals was greater in the original condition than the revised condition for students in the low prior knowledge group. This could be because students who saw the original visuals compensated for less well-designed visuals by spending more time processing the lesson information compared to students who saw revised visuals. For students in the middle prior knowledge group, a different pattern of results was noted: The amount of cognitive processing of lesson text and math-relevant visuals was greater in the revised condition than in the original condition. As with the cognitive load findings, this could be due to the revisions adding extra information. Finally, there was no difference in the amount of cognitive processing of the lesson text and math-relevant visuals between conditions for students in the high prior knowledge group (Kalyuga, 2007). It is possible that this group had such proficiency with the material that their overall processing was not affected by the revisions. Another possibility is related to the finding that, consistent with previous findings (Hegarty & Just, 1993; Schwonke et al., 2009), students in the high prior knowledge group processed the visuals less than did students in the low and middle prior knowledge groups. It could be that students in the high prior knowledge group did not view the visuals long enough for the revisions to have an effect.

Learning

The effects of the revisions on learning were examined. Unlike previous work examining these principles in isolation with science lessons (Mayer, 2009), the revised materials did not promote greater learning than the original materials. Although the eye-tracking findings indicated an effect on cognitive load, this effect was insufficient to influence learning outcomes. However, information from the eye-tracking measures of amount of cognitive processing may explain the null effect on learning. Students in the low prior knowledge group engaged with the visuals and text in the original lesson more than with those in the revised lesson. It is possible that this additional processing compensated for the less well-designed visuals in the original lesson, to help students effectively learn from the original lesson. Although, according to the cognitive theory of multimedia learning, this additional processing would likely be extraneous and lead to less learning (Mayer, 2009), it appears that at least some of this additional processing was helpful, or at the very least not harmful, for learning. It is possible that the revisions would have yielded a benefit for learning for the students in the low prior knowledge group if there had been time-limited presentation of the materials (e.g., Amelsvoort, van der Meij, Anjewierden, & van der Meij, 2012). Such presentation may enhance the potential benefits of instructional design principles because the limited time frame may increase the need for the guidance provided by the labeling and color coding in the revised visuals, at least for students with low levels of prior knowledge.

It is also possible that the visuals served a different role in this study than in previous studies. The visuals in previous studies typically represented a scientific phenomenon described by the text (e.g., how lightning is formed; Mayer, 2009). The nature of this study's lesson content (i.e., constructing a graph) naturally prompted the integration of text and visual information. If the verbal representation provides instruction on how to construct the other representations (e.g., tables and graphs), as this lesson did, students may need less guidance through labels and color coding to connect the representations.

Implications for Curriculum Development

In this study, a "less is more" approach was embraced when revising the visuals in an authentic lesson (Clark & Elen, 2006). That is, three principles (signaling, contiguity, and coherence) were applied to reduce extraneous processing and cognitive load wherever possible (Mayer, 2009; Sweller et al., 2011). However, the findings do not support the effectiveness of the "less is more" approach in improving student learning. One reason may be that the potential benefits of increasing processing in a useful way (i.e., generative processing) were not considered. It is possible that a "focused more is more" approach, in which students are prompted to engage in generative processing and materials are designed to minimize extraneous processing, would be more beneficial for students, (Mayer, 2014b).

In this study, we applied a combination of three instructional design principles that shared common theoretical foundations in the cognitive theory of multimedia learning and cognitive load theory (Mayer, 2009; Sweller et al., 2011). This is a novel approach to instructional design, given that these principles have generally been examined in isolation (e.g., Florax & Ploetzner, 2010; Johnson & Mayer, 2012; Magner et al., 2014; Mason et al., 2013; Ozcelik et al., 2009, 2010; Scheiter & Eitel, 2015). However, one consequence of this approach is that it is uncertain how the principles individually related to the findings, but it also suggests that combining principles may not result in additive effects. In light of our findings, it may be premature to apply these principles to curriculum development on a large scale.

Theoretical Implications

The findings from this study provide limited support for the cognitive theory of multimedia learning and cognitive load theory. According to the cognitive theory of multimedia learning, students learn more if instructional materials are designed to reduce extraneous processing (Mayer, 2009). According to cognitive load theory, limited working memory capacity is best used if cognitive load unrelated to learning (i.e., extrinsic cognitive load) is minimized (Sweller et al., 2011). The applications of the three instructional design principles to the revised visuals were all intended to reduce extraneous processing and cognitive load. The revisions appeared to be effective in reducing cognitive processing and cognitive load for students in the low prior knowledge group. However, inconsistent with these theories and previous findings (e.g., Florax & Ploetzner, 2010; Holsanova et al., 2009; Johnson & Mayer, 2012; Mayer et al., 1995), the revisions did not affect student learning although they did affect cognition (similar to Liu et al., 2011). As previously discussed, it is possible that students in the low prior knowledge group engaged in compensatory cognitive processing in an effort to learn from the less well-designed, original visuals.

Limitations and Future Directions

This study applied eye-tracking methodology to understand the effects of multiple instructional design principles on cognitive load and the amount of cognitive processing of an authentic mathematics lesson. Unfortunately, because of the labor-intensive nature of eye-tracking data collection and the curvilinear patterns with prior knowledge, there was insufficient power to directly examine relationships between the eye-tracking measures reported and learning. Future work could better elucidate our understanding of how different representations are processed in relation to learning. Such work could detect relationships by targeting a specific prior knowledge group—individuals with low prior knowledge may be of particular importance given that instructional design principles appear to have the most influence for such individuals (Mayer, 2001). Such work might also consider a single instructional principle at a time. In addition, in future studies, less authentic, but more controlled placement of visuals may allow for a more fine-grained understanding of relations between eye-tracking measures and learning. The use of controlled placement of visuals would also be conducive to eye-tracking measures not reported in this chapter, such as transitions between visuals and text.

CONCLUSION

In this study, visuals were revised in a mathematics lesson based on instructional design principles to improve the integration of text and visual information, and the effects on cognitive load, cognitive processing, and learning were examined. Eye-tracking methodology was used to examine the effects of the revisions on viewing the text and the math-relevant visuals. Consistent with the cognitive theory of multimedia learning (Mayer, 2014a) and cognitive load theory (Sweller et al., 2011), the revisions appeared to reduce cognitive processing and cognitive load for students with low levels of prior knowledge, though they did not affect learning. .

Taken together, the findings emphasize the complexity of applying instructional design principles to authentic lessons. Although many instructional design principles are framed as "one size fits all," the findings indicate that their effects on student cognition may depend on students' level of prior knowledge. This study illuminates the usefulness of eye-tracking data in understanding cognitive load and cognitive processing among different groups of students learning from multiple representations.

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KEY TERMS AND DEFINITIONS

Cognitive load: The amount of effort one exerts while processing information in working memory (Sweller et al., 2011).

Cognitive processing: The amount of thinking in which one engages for a particular task or topic.

Coherence principle: Learning is facilitated when interesting, but irrelevant information is removed (Mayer, 2009).

Contiguity principle: Learning is facilitated when materials have relevant information in different representations in close physical proximity (Mayer, 2009).

Eye-mind assumption: The concept that the eye fixates on what the mind is processing (Just & Carpenter, 1980).

Instructional design principles: Approaches for the arrangement of learning materials based on theoretical understanding of human cognition. Also called cognitive principles or evidence-based principles.

Signaling principle: Learning is facilitated when materials have cues to important information (Mayer, 2009).