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Abstract

Visual representation has been recognized as a powerful learning tool in many learning domains. Based on the assumption that visual representations can support deeper understanding, we examined the effects of visual representations on learning performance and cognitive load in the domain of mathematics. An experimental condition with visual representations was compared to a control condition without visual representations among primary school students. The hypothesis that learning with visual representations would result in higher learning performance and lower cognitive load than learning without visual representations was confirmed by the results. Theoretical and practical implications of the findings are discussed.

Keywords

computer, visual, representation, mathematics, learning, effects, cognitive, load

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Effects of Computer-Based Visual Representation on Mathematics Learning and Cognitive Load

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ABSTRACT

Visual representation has been recognized as a powerful learning tool in many learning domains. Based on the assumption that visual representations can support deeper understanding, we examined the effects of visual representations on learning performance and cognitive load in the domain of mathematics. An experimental condition with visual representations was compared to a control condition without visual representations among primary school students. The hypothesis that learning with visual representations would result in higher learning performance and lower cognitive load than learning without visual representations was confirmed by the results. Theoretical and practical implications of the findings are discussed.

Keywords

Visual representation, Cognitive load, Learning

Introduction

In elementary mathematics, arithmetic operation on integers is generally learned through solving mathematics word problems. It requires students to master number reasoning and number abstraction skills, which are necessary skills for the ability to apply number representation in arithmetical operation on integers (Butterworth, 2006). However, mathematics textbooks do not clearly express how addition and subtraction are related (Van de Walle, 2004; Verschaffel, Greer, & De Corte, 2000). Especially, with regard to arithmetic operation on integers word problems, multiplication and division are highly complex, and without visual representation support, the mathematics concepts tend to be more difficult in addition and subtraction for elementary school children (Múñez, Orrantia, & Rosales, 2013). As a consequence, students are often confused about the relational terms, tend to use all the numbers of word problems, apply the wrong operations principles to reach a final solution, and only possess an instrumental understanding of arithmetic operation on integers principles without relational and logical understanding (Skemp, 1976).

An appropriate instructional approach to promote relational and logical understanding of learning arithmetic operation on integers is using visual representation to emphasize specific relations and promote cognitive functions, such as knowledge construction. Indeed, Barmby, Harries, Higgins, and Suggate (2007) found that the process of understanding can be mediated through visual representations by focusing on relevant information and promoting relational and logical understanding. Visual representation, such as diagrams and pictures, is an externalized form of mathematics concepts and has been recognized as a powerful tool in mathematics learning and problem solving (Ainsworth & VanLabeke, 2004; Gagatsis & Shiakalli, 2004; Zimmermann & Cunningham, 1991). It supports learners' visualization and interpretation of quantitative data and supports inferences if it contains complementary information that facilitates learners' cognitive processing (Ainsworth & VanLabeke, 2004). Ainsworth (2006) proposed a conceptual framework and defined three critical functions of multiple external representation including complementary processes, constraining interpretation and construction of deeper understanding. Firstly, the complementary function means that multiple external representations can provide different types of information and facilitate different types of learning processes (Meyer, Shinar, & Leiser, 1997). Different studies on the use of external representations in multimedia learning have shown that they can support learners' knowledge construction (Ainsworth & VanLabeke, 2004; Ainsworth, 2006). Secondly, the constraining function of multiple external representations holds that familiar representations can be employed to support the interpretation of other representations. Thirdly, multiple external representations can lead to deeper understanding when the information of different representations is integrated. The purpose of using multiple external representations is to provide rich information of a domain and construct references across representations to extend domain knowledge. Based on the above analysis of the functions of multiple external representations and the domain of mathematics, we hypothesized that providing learners with visual representations with rich and meaningful information would support them to construct deeper understanding.

Given the importance of the visual representation in learning, considerable research attention has been focused on the role of representations in building abstractions in mathematics understanding and problem-solving ability (Gagatsis & Shiakalli, 2004; Múñez et al., 2013). For example, Gagatsis and Elia (2004) argued that organizational pictures can signal the important information and express the similarities between internal and external forms of the same concepts. In mathematics education, representations are widely used in paper-based form, such as mathematics picture books, in order to develop the story plot, contribute to the text's coherence and serve as mental scaffolding (Fang, 1996). Levin and Mayer (1993) have proposed four factors that need to be considered when using visual representations in text; the desired performance outcomes, the nature of the representation, the nature of the text and the learner characteristics. Although visual representations can provide rich information and allow learners to go beyond the words, empirical studies have indicated that representations in the form of storybooks may hamper learning, because students have difficulty in extracting and integrating the meaning between words and pictures (Arcavi, 2003; Carney & Levin, 2002). Berends and Van Lieshout (2009) also confirmed that visual representations in a book can negatively impact students' arithmetic performance, because students not only need to map the elements in the text and representation, but also need to integrate the two sources of information. As a result, additional cognitive load is imposed on learners' cognitive capacity. Several empirical studies have examined how visual representation in computer-based environments can support students in learning and communicating mathematics concepts efficiently. Ainsworth, Wood, and O'Malley (1998) used a computer based learning environment to teach students multiplication and found that students who learned with representations produced multiple solutions and advanced their understanding.

Learning mathematical operation on integers, such as solving multiplication and division operations word problems, is considered a complex cognitive task, which imposes a high load on students' working memory, because it involves the representation of the word problem with concrete images, irrelevant information of the problem, selection of an appropriate solution strategy, and application of arithmetic operation principles to arrive at the answer (Dowker, 2005; Múñez et al., 2013; Willis & Fuson, 1988). Zhang and Norman (1994) have shown that visual representations can lead to deeper understanding, because they can relieve some of the limited working memory resources that can be used to establish relationships between abstract mathematic concepts and its underlying functions.

Although several studies related to visual representation have shown that visual representation can improve conceptual understanding in mathematics learning, little is known about the specific effect of visual representation on learning arithmetic operation on integers (Gagatsis & Elia, 2004; Koedinger, Alibali, & Nathan, 2008). Researchers have suggested that using visual representations could enhance learning and reduce working memory load (Elia, Gagatsis, & Demetriou, 2007; Mayer, 2005). Cognitive load theory (Paas, Renkl, & Sweller, 2003; Sweller, Ayres, & Kalyuga, 2011; Sweller, van Merriënboer, & Paas, 1998) provides a solid framework for examining the effectiveness of visual representations and how they can support learners' cognitive processing (Kalyuga, 2009). Recent studies have shown that visual representation may reduce cognitive load and allow students to redirect the freed resources to processes that can enhance understanding of the problem (Carlson, Chandler, & Sweller, 2003; Kalyuga, 2013).

In light of the analysis above, the present study aimed to examine the effects of the use of visual representation on learning arithmetic operations of integers and the associated cognitive load. Based on cognitive load theory, it was hypothesized that supporting students understanding with visual representation would reduce their cognitive load, enable them to better process the learning materials, and achieve higher learning performance.

Method

Participants

The participants were 46 fourth-grade students, who were taught by the same mathematics teacher at a public elementary school of Taiwan. All participants were volunteers. Twenty-two of these students were male and twenty-four were female. The mean age of the participants was 10.2 years (*SD* = 11.3 months). Students had been acquainted with basic addition, subtraction, multiplication, and division functions of integer from the third grade.

Instructional materials

In this study the instructional materials were based on elementary arithmetic operations of integer including addition, subtraction, multiplication, division, bracket (subtraction formula), bracket (multiplication formula), and two-step addition and subtraction. The goal of the computer-based instruction was to teach the students relational and logical understanding of arithmetic operation on integers and develop their ability to apply the order of operations rules with brackets while solving two-step word problems. The instruction was developed in a story format named "Saving the little Doggy," which has three main characters and ten scenarios with ten mathematics two-step word problems in a computer-based learning environment. The situated learning scenarios were intertwined with real-life experiences and operation of integer functions, ranging from buying food to dividing goods. The aim of the study was to provide the visual representation of the story-based instruction in a computer-based environment to promote meaningful learning and gradually build relational and logical understanding while solving mathematics problems. As Geary (1995) argued, to build students' conceptual knowledge of mathematics domain, instruction should involve presenting problems in real world contexts so that students can relate the contents to their own personal experiences. Especially, solving story context problems requires attention for specific information, interpretation and integration of different mathematics operations (Van de Walle, 2004).

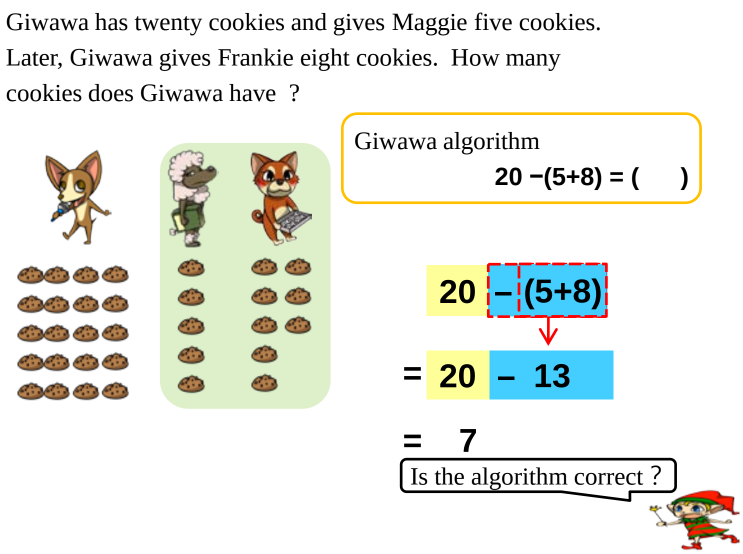

Figure 1a. An example of the story scenario problem for the experimental group

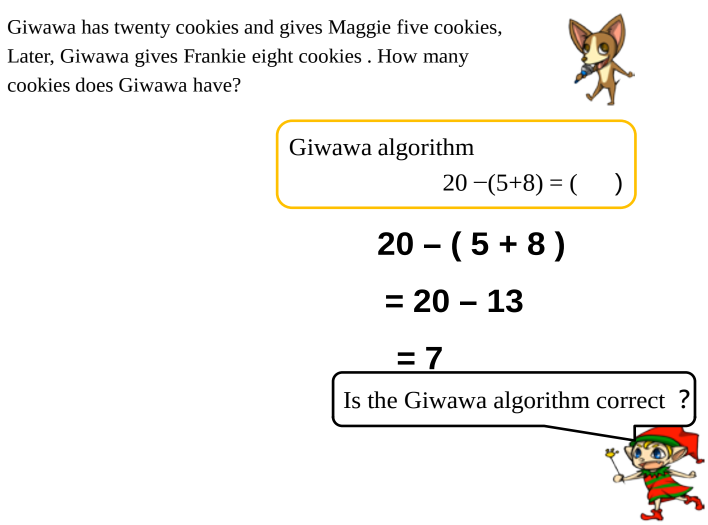

Figure 1b. An example of the story scenario problem for the control group

An example of the semi-animated story scenario and scenario problem procedures, showing that Giwawa bought cookies and shared his cookies with two friends, for the experimental and control group is presented in Figure 1a and lb, respectively. Both conditions received the story-based instruction and had the same scenario problems followed by the same problem solving procedures. The only difference between two groups was that the experimental group had the computer-based visual representation and used the arrow to limit learners' split-attention effect and matching problem between the solving procedures.

Prior knowledge test

Numerous studies have shown that learner expertise is a critical factor for instructional design in mathematics (Butterworth, 2006; Kalyuga, 2009). Despite the fact that the participants in this study can be expected to have the same prior knowledge, we used a prior knowledge test and used the score on this test as a covariate in the data analyses to control for possible differences.

A total of 10 computational problems and 10 two-step word problems in paper-and-pencil form were developed for the prior knowledge test. The 10 computational problems involved five multiplication and division operations, and five addition and subtraction operations with brackets. The two-step word problems included mixed multiplication and division functions. To determine the prior knowledge test score, each answer on the prior knowledge test was scored as correct or incorrect based on the final answer. Five points were given for correct answers to each of the 10 computational problems. Five points were given for correct answers to the two-step word problems. If the steps were correct but the final calculation was wrong, three points were given. The maximum score was 100 points. This resulted in the following means and standard deviations for the different conditions: high prior knowledge participants in the experimental group (M = 87.93, SD = 6.05), low prior knowledge participants in the experimental group (M = 67.50, SD = 12.67), high prior knowledge participants in the control group (M = 81.67, SD = 6.80), and low prior knowledge participants the control group (M = 65.76, SD = 6.80). The Cronbach's alpha for the prior knowledge test was 0.76.

Learning performance test

The learning performance test was designed to examine students' comprehension of the arithmetic operations of integer problems. The paper-and-pencil learning performance test consisted of 10 computational problems and 10 two-step word problems. The 10 computational problems involved (1) two-step addition and subtraction with brackets, (2) two-step mixed multiplication and division functions, (3) two-step mixed addition and subtraction and multiplication functions, and (4) questions mixed with a two-step addition and subtraction.

For example, $127 \times (12 \div 3) =$. To determine the learning performance test score, each answer on the learning performance test was scored as correct or incorrect based on the final answer. Five points were given for correct answers to each of the 10 computational problems. Five points were given for correct answers to the two-step word problems. If the steps were correct but the final calculation was wrong, three points were given. The maximum score was 100 points. The Cronbach's alpha for the learning performance test was 0.75.

Cognitive load measurement

Cognitive load was measured using a 7-point scale of perceived difficulty, which is a modified version of the scale developed by Paas and van Merriënboer (1994; see also Paas, Tuovinen, Tabbers, & van Gerven, 2003). Studies have shown that perceived difficulty can be a reliable measure of cognitive load (Kalyuga, Chandler, & Sweller, 1999). Students were asked how difficult the learning material on operations on integers was for them. Cronbach's alpha for cognitive load was 0.81, which indicated a good internal consistency of the rating scale.

Procedure

The regular mathematics class was taught four times a week, using the national academic edited textbook. The operation of integer unit was taught during the regular scheduled mathematics instructional period for 45 minutes daily. Before the experiment, all students took the prior knowledge test to examine their levels of mathematics knowledge. After taking the prior knowledge test, students were randomly assigned to either the experimental group or control group. All students received the operation of integer function with multimedia story based instruction over five classes. During the instruction phase, the teacher introduced story characters and started with story scenarios. In both conditions students received the same story scenarios. During the problem solving instruction phase, all students were presented with the same 10 arithmetic two-step word problems. Five word problems required multiplication, division with bracket, the other half the word problems required addition, subtraction, multiplication, division with bracket. For example, $36 \times (9 \div 3)$. The teacher asked the students to read the problems together, and to interpret the meaning of the problem before presenting the next screen. After five minutes, the screen showed how the story characters solved two-step word problems correctly. The only difference between the two groups was that the experimental group received the two-step word problems accompanied by visual representation and the control group received two-step word problems only. After the problem solving instruction, participants were asked to rate the difficulty of the instruction for 1 minute, followed by the paper and pencil learning performance test for 45 minutes.

Results

Learning performance scores and cognitive load ratings were analyzed with one-way Analyses of Covariance (ANCOVA) with instructional condition (with visual representation vs. without visual representation) as between-subjects factor, and prior knowledge serving as a covariate. Table 1 shows the estimated means and standard deviations of learning performance scores and cognitive load ratings for the experimental and control group.

First, homogeneity of regression was determined to test the assumption of the interaction between the prior knowledge and the instructional condition in the prediction of students' learning performance. The result indicated that the interaction was not significant, $F(1, 44) = 3.57$, $p = .06$. After confirming that the data met the ANCOVA assumption, we proceeded with the ANCOVA analysis. The ANCOVA analysis revealed a significant effect for instructional condition, $F(1, 44) = 5.41$, $p = .03$, partial eta squared = .28, which indicated that students who learned with visual representations performed better on the test than students who learned without visual representations.

The ANCOVA conducted on the cognitive load ratings revealed a significant effect of instructional condition on cognitive load, $F(1, 44) = 6.11$, $p = .02$), partial eta squared = .20 ,which indicated that the students who learned with the visual representations experienced the learning tasks as less difficult than the students who learned without visual representations.

Table 1. Means and standard deviations for learning performance and cognitive load, for students in the experimental and control groups

	Experimental group (N = 23)		Control group (N = 23)	
	M	*SD*	*M*	*SD*
Learning performance	87.39	8.12	81.07	12.94
Perceived difficulty	1.92	1.04	2.84	1.55

Discussion and conclusion

The present study examined the effects of the use of computer based visual representations in the learning of arithmetic operation on integers on learning performance and cognitive load. The results confirmed the hypotheses by demonstrating that learning with visual representations resulted in higher learning performance and lower cognitive load than learning without visual representations. The results suggest that visual representation, which can convey information about numbers and relations among numbers in a simple form, allowed students to focus attention on the most essential elements. As a results, extraneous cognitive load was reduced, and students could use the freed working memory resources for constructing a coherent mental representation.

Although the perceived difficulty scores that were used as an indicator of cognitive load were differentially affected by the learning conditions, the average scores were very low. This seems to indicate that the students found the task very easy. However, several studies have shown that children generally give low scores, probably because they have the idea that saying that a task was easy, makes you look smarter than saying it was difficult. However, this speculative explanation needs to be verified in future research.

In addition, using visual representations could support learners to process and transform abstract mathematics concepts into concrete representations, and forming such concrete mental images (Sierpinska, 2004). This ability to construct and switch between multiple forms of the same mathematics concepts in the mathematic domain is important because it can support learners to build abstract representation of the concepts and increase the possibility for successful application to new situations, i.e., transfer (Spiro & Jehng, 1990). Therefore, the study confirmed the hypothesis that students learn more with less cognitive load in a learning environment with a visual representation than in a learning environment without a visual representation.

Only a few studies have directly examined the effects of visual representation on learning arithmetic operations of integer from cognitive load perspectives (Berends & Van Lieshout, 2009). We found empirical evidence that using visual representation is beneficial for students in the domain of mathematics. However, more fine-grained studies are needed to examine different types of representations such as dynamic visual representations. By conducting more fine-grained studies, it will be possible to determine the most important characteristics affecting learning and cognitive load. In addition, future research could explore how visual representation facilitates students understanding of abstract mathematics concepts, and how this differs as a function of the level of prior knowledge. It would also be interesting for future research to investigate how level of prior knowledge and working memory capacity mediate the effects of visual representation on learning and cognitive load.

In addition, it would be interesting for future research to disentangle cognitive and affective effects. It is possible that the positive effects of visual representation on mathematics learning were partly caused by the fact that students had more fun and were more motivated to invest mental effort in the instructional materials. In future studies students could be asked to indicate how much they like to work with the instructional materials and whether they would like to work with the same materials in the future.

The relatively small sample size can be considered a limitation of this study. In addition, one specific type of visual representation, one specific topic within a domain, and one specific domain was used in this study. Future studies need to investigate whether other types of visual representations are effective, whether similar effects can be found with other topics within the same domain, and whether similar effects can be found in other domains.

The present study contributes to the knowledge base on the effects of visual representation on learning mathematics. Although the results look promising, it is clear that more research is needed before reliable recommendations can be given for educational practice.

References

Ainsworth, S. E. (2006). DeFT: A Conceptual framework for considering learning with multiple representations. *Learning and Instruction*, *16*(3), 183-198.

Ainsworth, S. E., & VanLabeke, N. (2004). Multiple forms of dynamic representation. *Learning and Instruction, 14*(3), 241-255.

Ainsworth, S. E., Wood, D. J., & O'Malley, C. (1998). There's more than one way to solve a problem: Evaluating a learning environment to support the development of children's multiplication skills. *Learning and Instruction, 8*(2), 141-157.

Arcavi, A. (2003). The Role of visual representations in the learning of mathematics. *Educational Studies in Mathematics, 52*, 215-241.

Barmby, P., Harries, T., Higgins, S., & Suggate, J. (2007). How can we assess mathematical understanding?. In J. H. Woo, H. C. Lew, K. S. Park, & D. Y. Seo (Eds.), *Proceedings of the 31st Conference of the International Group for the Psychology of Mathematics Education* (Vol. 2, pp. 41-48). Seoul, Korea: PME.

Berends, I. E., & Van Lieshout, E. C. (2009). The Effect of illustrations in arithmetic problem-solving: Effects of increased cognitive load. *Learning and Instruction*, *19*(4), 345-353.

Butterworth, B. (2006). Mathematical expertise. In K. A. Ericsson (Ed.), *The Cambridge handbook of expertise and expert performance* (pp. 553-568). Cambridge, UK: Cambridge University Press.

Carlson, R., Chandler, P., & Sweller, J. (2003). Learning and understanding science instructional material. *Journal of Educational Psychology*, 95(3), 629-640.

Carney, R. N., & Levin, J. R. (2002). Pictorial illustrations still improve students' learning from text. *Educational Psychology Review, 14*(1), 5 - 26.

Dowker, A. (2005). *Individual differences in arithmetic: Implications for psychology, neuroscience and education*. Hove, UK: Psychology Press.

Elia, I., Gagatsis, A., & Demetriou, A. (2007). The Effects of different modes of representation on the solution of one-step additive problems. *Learning and Instruction*, *17*(6), 658-672.

Fang, Z. (1996). Illustrations, text, and the child reader: What are pictures in children's storybooks for?. *Read Horizons*, *37*, 130-142.

Gagatsis, A., & Elia, I. (2004). The Effects of different modes of representations on mathematical problem solving. In M. J. Høines & A. B. Fuglestad (Eds.), *Proceedings of the 28th Conference of the International Group for the Psychology of Mathematics Education* (Vol.2, pp. 447-454). Bergen, Norway: Bergen University College.

Gagatsis, A., & Shiakalli, M. (2004). Ability to translate from one representation of the concept of function to another and mathematical problem solving. *Educational Psychology, 24*(5), 645-657.

Geary, D. C. (1995). Reflections of evolution and culture in children's cognition: Implications for mathematical development and instruction. *American Psychologist*, *50*(1), 24-37.

Kalyuga, S. (2009). *Managing cognitive load in adaptive multimedia learning.* Hershey, PA: Information Science Reference.

Kalyuga, S. (2013). Effects of learner prior knowledge and working memory limitations on multimedia learning. *Procedia-Social and Behavioral Sciences*, *83*(4), 25-29.

Kalyuga, S., Chandler, P., & Sweller, J. (1999). Managing split-attention and redundancy in multimedia instruction. *Applied Cognitive Psychology, 13*, 351-371.

Koedinger, K. R., Alibali, M. W., & Nathan, M. M. (2008). Trade-offs between grounded and abstract representations: Evidence from algebra problem solving. *Cognitive Science*, *32*(2), 366-397.

Levin, J. R., & Mayer, R. E. (1993). Understanding illustrations in text. In Britton, B. K., Woodward, A., and Brinkley, M. (eds.), *Learning from Textbooks* (pp. 95–113). Hillsdale, NJ: Erlbaum.

Mayer, R. E. (2005). Principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity. In R. E. Mayer (Ed.), *Cambridge handbook of multimedia learning* (pp. 183–200). New York, NY: Cambridge University Press.

Meyer, J., Shinar, D., & Leiser, D. (1997). Multiple factors that determine performance with tables and graphs. *The Journal of the Human Factors and Ergonomics Society*, 39(2), 268-286.

Múñez, D., Orrantia, J., & Rosales, J. (2013). The Effect of external representations on compare word problems: Supporting mental model construction. *The Journal of Experimental Education*, *81*(3), 337-355.

Paas, F., Renkl, A., & Sweller, J. (2003). Cognitive load theory and instructional design: Recent developments. *Educational Psychologist*, *38*(1), 1-4.

Paas, F., Tuovinen, J. E., Tabbers, H., & van Gerven, P. W. (2003). Cognitive load measurement as a means to advance cognitive load theory. *Educational Psychologist*, *38*(1), 63-71.

Paas, F., & van Merriënboer, J. J. G. (1994). Variability of worked examples and transfer of geometrical problem solving skills: A Cognitive-load approach. *Journal of Educational Psychology, 86*(1), 122-133.

Sierpinska, A. (2004). Research in mathematics education through a keyhole: Task problematization. *For the Learning of Mathematics*, *24*(2), 7-15.

Skemp, R. R. (1976). Relational understanding and instrumental understanding. *Mathematics Teaching*, *77*, 20-26.

Spiro, R., & Jehng, J. (1990). Cognitive flexibility and hypertext: Theory and technology for the nonlinear and multidimensional traversal of complex subject matter. In Nix, D., Spiro, R. (Eds.), *Cognition, education and multimedia: Exploring ideas in high technology* (pp. 163-205). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

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

Sweller, J., van Merriënboer, J. J. G., & Paas, F. (1998). Cognitive architecture and instructional design. *Educational Psychology Review*, *10*(3), 251-296.

Van de Walle, J. A. (2004). *Elementary and middle school mathematics: Teaching developmentally* (5th ed.). Boston, MA: Pearson Education, Inc.

Verschaffel, L., Greer, B., & De Corte, E. (2000). *Making sense of word problems.* Lisse, The Netherlands: Swets & Zeitlinger B. V.

Willis, G. B., & Fuson, K. C. (1988). Teaching children to use schematic drawings to solve addition and subtraction word problems. *Journal of Educational Psychology*, *80*(2), 192-201.

Zhang, J., & Norman, D. A. (1994). Representations in distributed cognitive tasks. *Cognitive Science*, *18*, 87-122.

Zimmermann, W., & Cunningham, S. (1991). Editors' introduction: What is mathematical visualization?. In W. Zimmermann & S. Cunningham (Eds.), *Visualization in teaching and learning mathematics* (pp. 1-7). Washington, DC: Mathematical Association of America.