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Exploring the characteristics of an optimal design of digital materials for concept learning in mathematics: Multimedia learning and variation theory

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ABSTRACT

Design principles emerging from the cognitive theory of multimedia learning can be applied to engage cognitive processing, and teaching methods that have evolved from variation theory can encourage thinking through comparisons in mathematics education. Applying these principles and teaching methods in designing digital material should be a sound proposition. However, there is a disconnection between research in digital educational material and classroom practices. Teachers often have doubts about the effectiveness of the materials. Thus, this paper presents a design-based research of developing a digital material for algebra concept learning. We collaborated with two experienced teachers and a subject expert from a university, and designed some digital learning material that was presented to 68 students through an iterative redesign development cycle; the effectiveness of the final product was tested on another group of 66 students the following year. Characteristics of an optimal design generated from the data collected are presented in this paper. The characteristics may have useful practical implications for instructional designers and teachers and contribute to improvements in the design of digital learning materials.

1. Introduction

Digital educational materials for mathematics learning currently used in schools often incorporate mainstream teaching methods that focus primarily on improving procedural knowledge. These materials provide students with great learning opportunities through online exercises and quizzes that instantly reward responses with answers and solutions; further, teachers receive detailed analysis of student performance. While this timely feedback for students and teachers is useful, the materials offer training platforms focusing on assessment rather than learning. Balanced mathematics learning encompasses another type of knowledge – conceptual (CDC & HKEAA, 2007; Rittle-Johnson, Siegler, & Alibali, 2001). Conceptual knowledge comprises ideas retrieved from conceptual understanding (Rabinowitz, 1988). Due to the different nature of procedural and conceptual knowledge, digital educational materials that foster the development of conceptual knowledge are therefore often considered as cognitive tools to improve students' active involvement in the learning process – that is, active learning (Churchill, 2007, 2011, 2013, 2014; Mayer, 2009). These materials are designed to elicit thinking, and focus on understanding rather than memorizing (Churchill, 2011, 2013, 2014). The design of tools influences learning processes and outcomes (Ainsworth, 2006; Churchill, 2007; Mayer, 2009). Therefore, targeting the design to engage learners' cognitive processing is important (Churchill, 2011; Mayer, 2009). The present study focused on this issue. Multimedia learning design principles suggested by Mayer (2009) were primarily used to cater for learners' cognitive processing needs; and the way learning messages in the content were presented evolved from variation theory (Gu,

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Huang, & Marton, 2004; Marton et al., 2004). The main goal of this study was to explore the optimal design of mute digital material for concept learning in algebra, resulting in design characteristics. Moreover, many studies often focus on investigating the effects of Mayer's multimedia learning principles in design (Harskamp, Mayer, & Suhre, 2007; Moreno & Mayer, 1999; Moreno & Mayer, 2000). Design recommendations in the literature on the application of multimedia learning principles are scarce (Churchill, 2013). This paper also exemplifies the application of a combination of the multimedia learning principles including mute in the design of digital educational materials.

1.1. Digital material in school algebra

Conceptual understanding is considered to be a hard-to-teach mathematical idea (Hoyles, Noss, Vahey, & Roschelle, 2013). Teachers lack of effective learning strategies for developing deeper understanding of mathematics concepts in students (Wong, 2007). The use of digital materials in school mathematics can support students in developing conceptual understanding (Churchill, 2011; Churchill & Hedberg, 2008; Hoyles et al., 2013). Computer aided algebra resources whose core comprises symbolic manipulators, were originally designed to complete algebraic procedures accurately and quickly. These resources let students observe the relationship between quantities and graphs, and support different views and representations of the mathematical concept (Heid, 1995; Yerushalmy & Chazan, 2008). However, most of the materials typically neglect mathematical and instructional issues (Yerushalmy, 1999; Yerushalmy & Chazan, 2008), and cognitive processing when visual representation is applied (Churchill, 2013). For examples, Churchill and Hedberg (2008) designed the material for concept learning by representing one or more related mathematical ideas in an interactive and visual way. The material allowed students to explore mathematics properties by manipulation; Caglayan (2014) suggested the materials should visualize algebraic expressions or numbers to construct mathematical formulas meaningfully; and Vahey, Knudsen, Rafanan, and Lara-Meloy (2013) developed a system called SimCalc and suggested the materials should provide dynamic representation environments which embed mathematical relationships. The SimCalc system linked algebraic expression, tabular expression, narrative and graphical representation through a visualization of motion. These materials focused on how to visualize mathematical ideas, but not on student cognitive processing and a domain specific instructional strategy. These may not result in optimal learning outcomes.

1.2. Design for cognitive processing

Presentation using words and images to promote active learning should be considered when designing digital educational materials to foster concept learning (Churchill, 2007, 2011, 2013, 2014; Mayer, 2009, 2014). Designs promoting active learning effectively facilitate a level of understanding that can be referred to as mental representation (Mayer, 2009). During active learning, learners utilize three types of cognitive processing when engaging with learning messages (Mayer, 2009, 2014): generative, essential and extraneous processing (Mayer, 2009). Mayer and colleagues (2009) developed the cognitive theory of multimedia learning to explain what is involved in processing, and suggest twelve design principles to apply when presenting learning messages using words and images. Generative processing functions to build relationships among learning messages, and is closely related to the learner's motivation level. Presenting words and images together can enhance this processing (Mayer's multimedia principle refers), and better enable learning than through use of words alone (Mayer, 2009; Plass, Chun, Mayer, & Leutner, 1998), while also catering for different learning styles (Cole et al., 1998; Plass et al., 1998). Moreover, essential processing helps learners to select thinking-related learning messages from the presentation (Mayer, 2009). Allowing learners to learn at their own pace (Mayer's segmenting principle refers) and naming the key messages can engage essential processing (Mayer's pre-training principle refers). Furthermore, extraneous processing does not contribute to the learning process and wastes learners' cognitive capacity (Mayer, 2009); the heavier the processing required by the learning material, the more likely the learning will fail. They suggest ways to reduce extraneous processing: (1) deleting irrelevant words and graphics (Mayer's coherence principle refers); (2) highlighting important words and graphics (Mayer's multimedia principle refers); and (3) presenting words next to corresponding graphics simultaneously (Mayer's spatial and temporal contiguity principles refer). These principles are intended to maximize the available cognitive capacity of learners and engage cognitive processing when learning with written words and images. Thus, presentation of learning materials should be designed to free cognitive capacity by engaging generative and essential processing, and consuming less extraneous processing.

Moreover, other research-based recommendations on design presentation in digital materials for concept learning draw on ideas similar to Mayer's (2009). For example, recommendations to present learning information visually (Churchill, 2007, 2011, 2014; Seufert, 2003) draw on the notion of generative processing. Recommendations to involve interactive features (Churchill, 2011, 2014; Collins, 1996; Salomon, Perkins, & Globerson, 1991) relate to essential processing. Mindfulness of extraneous processing informs recommendations to use a single screen, the same font style (so as not to distract learners), moderate color and a holistic scenario, to divide the screen area logically (Churchill, 2011, 2014), and to avoid decorative pictures and words (Churchill, 2011, 2014; Collins, 1996).

1.3. Multimedia messages in mathematics

What are the words and images in mathematics? Words comprise signs describing learning messages in content. Consider, for example, the sentence “Concepts are abstract.” The noun and adjective are entities, the verb shows how they connect to each other. Correspondingly, in the equation $z = x + 2y + 1$, the variables x, y and z are entities, while the operators $=$ and $+$ connect the variables (Schnotz, 2002; Schnotz & Bannert, 2003; Schnotz & Kürschner, 2008). Moreover, images have no signs to describe the relations among different learning messages in the content. For example, a curve presented in a coordinate plane shows how the value of x relates to that of y and nothing in the curve explicitly points out the relationships (Schnotz, 2002; Schnotz & Bannert, 2003; Schnotz & Kürschner, 2008). In the mathematics domain, equations, expressions, numbers and symbols, theorems, notation, symbolic expressions, formulas and figures are classified as words; graphical representation, diagrams, tables and lines are classified as images (Schnotz & Bannert, 2003).