Computers & Education 82 (2015) 460–485

Contents lists available at ScienceDirect

Computers & Education

journal homepage: www.elsevier.com/locate/compedu

Connection making between multiple graphical representations: A multi-methods approach for domain-specific grounding of an intelligent tutoring system for chemistry

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A R T I C L E I N F O

Article history:
Received 21 August 2014
Received in revised form
4 December 2014
Accepted 5 December 2014
Available online 18 December 2014

Keywords:
Connection making
Multiple representations
Perceptual learning
Intelligent tutoring systems
Chemistry

A B S T R A C T

Making connections between graphical representations is integral to learning in science, technology, engineering, and mathematical (STEM) fields. However, students often fail to make these connections spontaneously. Intelligent tutoring systems (ITSs) are suitable educational technologies to support connection making. Yet, when designing an ITS for connection making, we need to investigate what concepts and learning processes play a role within the specific domain. We describe a multi-methods approach for grounding ITS design in the specific requirements of the target domain. Specifically, we applied this approach to an ITS for connection making in chemistry. We used a theoretical framework that describes potential target learning processes and conducted a series of four empirical studies to investigate what role graphical representations play in chemistry knowledge and to investigate which learning processes related to connection making play a role in students' learning about chemistry. These studies combined multiple methods, including knowledge testing, eye tracking, interviews, and log data analysis. We illustrate how our findings inform the design of an ITS for chemistry: Chem Tutor. Results from two pilot studies done in the lab and in the field with altogether 99 undergraduates suggest that Chem Tutor leads to significant and large learning gains on chemistry knowledge.

1. Introduction

Multiple graphical representations are ubiquitous in science, technology, engineering, and mathematics (STEM) domains. For instance, line graphs, coordinate systems, pie and bar charts, and sets are used in mathematics (Arcavi, 2003; Cheng, 1999; Noss, Healy, & Hoyles, 1997); Lewis dot structures, electrostatic potential maps, and ball-and-stick figures are used in chemistry (Kozma, Chin, Russell, & Marx, 2000; Stieff, Hegarty, & Deslongchamps, 2011; Zhang & Linn, 2011); diagrams, charts, and graphs are used in physics (Larkin & Simon, 1987; Lewalter, 2003; Urban-Woldron, 2009). In all of these domains, learning of the domain knowledge depends on students' ability to make connections between representations (Ainsworth, 2006; Gobert et al., 2011; de Jong et al., 1998), and many students struggle doing so (Ainsworth, Bibby, & Wood, 2002; Rau, Rummel, Aleven, Pacilio, & Tunc-Pekkan, 2012). Multiple graphical representations can enhance learning of the domain knowledge because different representations emphasize complementary conceptual aspects of the learning material and have different effects on mental processing (Kozma et al., 2000; Larkin & Simon, 1987; Schnotz & Bannert, 2003). However, students' benefit from multiple representations depends on their ability to make connections between them (Ainsworth, 2006; Bodemer & Faust, 2006; Bodemer, Ploetzner, Bruchmüller, & Häcker, 2005; Bodemer, Ploetzner, Feuerlein, & Spada, 2004; Brünken, Seufert, & Zander, 2005; Butcher & Aleven, 2008; Gutwill, Frederiksen, & White, 1999; van der Meij & de Jong, 2006; Seufert & Brünken, 2006; Taber, 2001). For instance, to learn about chemical bonding, students need to make connections between Lewis structures, ball-and-stick figures, space-filling models, and electrostatic potential maps (EPMs; see Fig. 1). Connection making is a difficult task that students often do not engage in spontaneously, even though it is critical to their learning (Ainsworth et al., 2002; Rau, Rummel, et al., 2012). Hence, they need

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http://dx.doi.org/10.1016/j.compedu.2014.12.009
0360-1315/

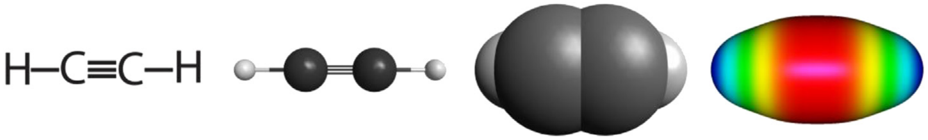

Fig. 1. Graphical representations of ethyne: Lewis structure, ball-and-stick figure, space-filling model, electrostatic potential map (EPM).

support to make these connections. Prior research shows that connection-making support can enhance students' learning outcomes in STEM domains (Bodemer & Faust, 2006; van der Meij & de Jong, 2006; Seufert, 2003).

Recent research indicates that intelligent tutoring systems (ITSs) can be effective in supporting connection making (Rau, Aleven, Rummel, & Rohrbach, 2012). ITSs support step-by-step problem solving (VanLehn, 2011) and provide adaptive instructional support (Corbett, Koedinger, & Hadley, 2001; Koedinger & Corbett, 2006). Adaptive support in ITSs typically includes feedback upon the diagnosis of a student's misconception (e.g., based on certain errors he/she makes while solving a problem), hints on demand (e.g., the student requests help on solving a step), and problem selection (e.g., based on the student's diagnosed knowledge level, the tutor selects a new problem that is considered to be of appropriate difficulty).

A key open question we face when designing connection making support is how to identify what specific learning processes play a role within the given target domain; that is, how to *ground* the design of support in the domain-specific requirements. The goal of this paper is to describe a multi-methods approach for grounding the design of an ITS in a particular domain. We describe how we applied our approach to the design of an ITS for connection making in chemistry: Chem Tutor. We conducted four empirical studies. Studies 1 and 2 focused on the role connection making plays in how chemistry knowledge is structured. Studies 3 and 4 focused on the role of connections between graphical representations in how students learn about chemistry. Across these studies, we pursued the following research goals:

1. Identify learning processes that are important for connection making between multiple graphical representations in chemistry;
2. Identify visual attention behaviors that indicate productive learning processes as students make connections between multiple graphical representations in chemistry;
3. Improve students' learning of important concepts in chemistry.

We conclude this paper by arguing that, even though we address these goals within the chemistry domain, our approach is applicable to other STEM domains than chemistry and to other educational technologies than ITSs. Furthermore, we believe that our approach can fundamentally improve STEM education by helping students take better advantage of multiple graphical representations that are ubiquitous in their learning materials.

2. Theoretical background

As mentioned, prior research shows that learning of domain knowledge critically depends on the students' ability to make connections between multiple representations (Ainsworth, 2006; Ainsworth et al., 2002; Cook, Wiebe, & Carter, 2007; Eilam & Poyas, 2008; Gutwill et al., 1999; de Jong et al., 1998; Özgün-Koca, 2008; Schnotz & Bannert, 2003; Schwonke, Ertelt, & Renkl, 2008; Schwonke & Renkl, 2010; Taber, 2001). We distinguish between the broader category of external representations (which includes symbolic and graphical representations), and the more specific category of graphical representations. Symbolic representations, such as text, are composed of features that have arbitrary relation to the real-world aspects they describe. Symbolic representations are interpreted based on their semantic meaning that we encode based on previously learned conventions (e.g., "1" stands for a quantity of one of something). Graphical representations are composed of perceptual features that have identifiable correspondence to the real-world aspects they depict. Therefore, graphical representations can be encoded based on their perceptual meaning (e.g., the ball-and-stick figure for ethane in Fig. 1 shows four spheres because ethane is composed of four atoms). To use graphical representations to learn about domain content, students have to learn which perceptual features of the graphical representations to attend to, how to interpret these features, and how to map these features to other representations (i.e., in the case of multiple external representations to symbolic representations, or in the case of multiple graphical representations to other graphical representations). For example, to understand the graphical representations shown in Fig. 1, students need to learn that the color in ball-and-stick figures and space-filling models denotes the identity of the atom, whereas that the color (in web version) in EPMs denotes regions of high electron density. Thus, learning with graphical representations involves a considerable amount of perceptual learning (Kellman & Massey, 2013; Kellman, Massey, & Son, 2009).

Most research on representations has focused on the broader category of learning with multiple *external* representations (Ainsworth & Loizou, 2003; Bodemer et al., 2005; Butcher & Aleven, 2007; Magner, Schwonke, Aleven, Popescu, & Renkl, 2014; Rasch & Schnotz, 2009), but only few studies have focused on learning with multiple *graphical* representations. Yet, multiple graphical representations are ubiquitous in STEM domains (Arcavi, 2003; Cook et al., 2007; Kordaki, 2010; Kozma et al., 2000; Lewalter, 2003; Nathan, Walkington, Srisurichan, & Alibali, 2011) and can significantly enhance learning outcomes compared to text and one additional graphical representation (Rau, Aleven, & Rummel, 2014).

A critical difference between multiple external and multiple graphical representations is that multiple external representations typically involve text as a dominant representation. One may assume that students are highly fluent in processing text. When students make connections between multiple external representation, the text guides their visual attention as they process the graphical representation (Rayner, Rotello, Stewart, Keir, & Duffy, 2001; Schmidt-Weigand, Kohnert, & Glowalla, 2010). By contrast, in the case of multiple graphical representations, there is no dominant text representation that we can assume students to be highly fluent with because they may not yet be fluent in processing graphical representations. To make connections between multiple graphical representations, students need to map relevant perceptual features across different representations. This task is not straightforward, because different graphical representations