ARTICLE IN PRESS

Learning and Instruction xxx (2017) 1–12

Contents lists available at ScienceDirect

Learning and Instruction

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

Effectiveness and efficiency of adding drawing prompts to an interactive educational technology when learning with visual representations

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ARTICLE INFO

Article history:
Received 8 September 2016
Received in revised form
22 September 2017
Accepted 29 September 2017
Available online xxx

Keywords:
Drawing
Visual representations
Sense making
Mental models
Chemistry

ABSTRACT

This paper investigates whether prompting students to draw their own visual representations enhances students' learning from technology-based instructional activities with visual representations. Seventy-two undergraduate students were randomly assigned to receive an educational technology with (1) drawing prompts throughout instruction, (2) drawing prompts before and after instruction, or (3) no drawing prompts. We assessed learning outcomes with respect to instructional effectiveness and efficiency using immediate and delayed posttests. Results on instructional efficiency showed a significant advantage for drawing prompts. Results on instructional effectiveness showed an advantage at the delayed posttest for drawing prompts provided throughout instruction, compared to prompts before and after. Qualitative analyses suggest that adding drawing prompts throughout instruction promotes drawing quality. In sum, our findings expand theory by suggesting that drawing prompts facilitate visual sense making of concepts shown in visual representations. Furthermore, we provide practical recommendations on how best to implement drawing prompts with technology-based instructional activities.

Many concepts in science, technology, engineering, and mathematics (STEM) are visual-spatial in nature. Therefore, students' learning of domain knowledge in STEM critically depends on their ability to make sense of *visual representations* (Gilbert, 2005; Mathewson, 1999). For example, students learn about atoms in chemistry with the visual representations shown in Fig. 1. These visual representations are typically used in instructional materials such as textbooks, worksheets, and webpages. We refer to these visual representations as *traditional* because they are designed and used by STEM professionals, not *generated* by students.

Prior research shows that students have tremendous difficulties in making sense of traditional representations (Ainsworth, 2006; Rau, 2016). Therefore, an important educational goal in STEM is to support students' learning with these representations. Much prior research has investigated how to design instructional activities that support students in *verbally* making sense of traditional representations (Rau, 2016; Rau & Wu, 2015a). For example, adding self-explanation prompts to instructional activities has been shown to be particularly effective (Berthold & Renkl, 2009; van der Meij & de Jong, 2011). Such prompts can ask students to self-explain while they construct, manipulate, and reason with representations (Rau, Aleven, & Rummel, 2015b). However, a new line of research suggests that visual-spatial concepts are difficult to explain verbally (Bobek & Tversky, 2014; Vosniadou, 1994). Instead, instructional activities that prompt students to engage in *visual* sense-making processes may be more effective in supporting students' learning with representations (Leopold & Leutner, 2012; Scheiter, Schleinschok, & Ainsworth, 2017). For example, *prompting students to draw* their own visual representations has been shown to be effective (Prain & Tytler, 2012; Van Meter & Garner, 2005). Drawing prompts can simply ask students to draw on paper and thus are easy to integrate within instructional activities that support verbal sense-making processes with traditional representations. Such prompts may be effective for two reasons. First, prompts to generate drawings can help students organize visual-spatial concepts from traditional representations and activate their own mental models (Brooks, 2009; Van Meter & Garner, 2005). Second, prompts to revise their drawings can help students revise their mental models after comparing their drawings to traditional representations (Prain & Tytler, 2012; Valanides, Efthymiou, & Angeli, 2013). Yet, prior research has not investigated whether providing

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https://doi.org/10.1016/j.learninstruc.2017.09.010
0959-4752/

Please cite this article in press as: Wu, S. P. W., & Rau, M. A., Effectiveness and efficiency of adding drawing prompts to an interactive educational technology when learning with visual representations, *Learning and Instruction* (2017), https://doi.org/10.1016/j.learninstruc.2017.09.010

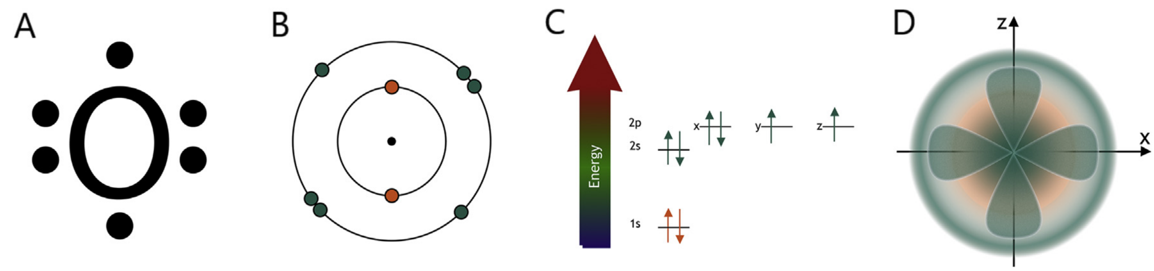

Fig. 1. Four traditional visual representations of an oxygen atom (from left): Lewis structure, Bohr model, energy diagram, and orbital diagram.

prompts to generate and revise drawings are effective when combined with typical instructional activities.

To this end, we present a controlled experiment that investigates whether adding prompts to generate and revise drawings to an educational technology enhances undergraduate students' learning of domain knowledge. We situate this experiment in undergraduate chemistry learning because success in chemistry requires learning with traditional representations and often involves drawing (Kozma & Russell, 2005; Talanquer, 2013).

1. Theoretical background

In the following, we first review prior research on how students learn with traditional visual representations and typical instructional activities that support *verbal* sense-making processes as well as recent findings on instructional activities that support *visual* sense-making processes. Then, we highlight gaps in prior research on visual sense-making supports, which we investigate in our experiment.

1.1. Learning with traditional visual representations in STEM

Prior research shows that students have difficulties in making sense of how visual representations depict domain-relevant concepts (Ainsworth, 2006; Rau, 2016). Students often focus on irrelevant surface features and fail to make connections among representations (Cook, Wiebe, & Carter, 2008; Kozma & Russell, 2005; Rau, Aleven, Rummel, & Pardos, 2014). For example, when students use Lewis structures and Bohr models (Fig. 1a and b) to learn about electrons in atoms, they may focus on irrelevant features such as color while failing to attend to relevant features such as the number and location of dots. Making such connections is particularly difficult for students with low spatial skills (Höffler, 2010) because it requires students to mentally rotate representations (Stieff, 2007).

A large body of research has investigated how best to help students overcome difficulties with visual representations. This research shows that effective instructional activities support students in *making sense* of how representations depict concepts (for an overview, see Ainsworth, 2006; Rau, 2016). Cognitive learning theories (Koedinger, Corbett, & Perfetti, 2012) suggest that instructional activities should engage *verbally mediated* sense-making processes, for instance self-explanation prompts.

1.1.1. Self-explanation prompts that support verbal sense-making processes

Self-explanation prompts have proven effective in helping students engage in sense-making processes (Roelle, Lehmkuhl, Beyer, & Berthold, 2015; Wylie & Chi, 2014). For instance, self-explanation prompts can ask students to explain how the spatial arrangement of electrons around the nucleus explains an atom's properties and bonding behavior. Research shows that such self-explanation prompts are especially effective when implemented in *educational technologies* that provide adaptive feedback on students' self-explanations (Rittle-Johnson, Loehr, & Durkin, 2017; Wylie & Chi, 2014). Self-explanation prompts with feedback can help students focus on relevant visual features shown in representations and connect features among multiple representations (Berthold & Renkl, 2009; Rau et al., 2015b).

Self-explanation prompts engage students in *verbally mediated* sense-making processes (Koedinger et al., 2012). Such processes involve verbal explanations of principles that describe how representations depict concepts (Chi, Bassok, Lewis, Reimann, & Glaser, 1989). However, a new line of research suggests that verbal explanations may not adequately help students make sense of visual-spatial concepts shown in representations (Bobek & Tversky, 2014; Vosniadou, 1994). Specifically, studies show that self-explanation prompts that support verbal sense-making processes may be less effective than drawing prompts that support *visually mediated* sense-making processes (Leopold & Leutner, 2012; Scheiter et al., 2017).

1.1.2. Drawing prompts that support visual sense-making processes

Recent research shows that prompting students to draw their own representations is an effective means to support visual sense-making processes (Brooks, 2009; Van Meter & Firetto, 2013). Drawing prompts have been shown to enhance students' learning of domain knowledge in STEM (Leutner & Schmeck, 2014; Van Meter & Garner, 2005) by helping students learn how visual representations depict concepts (Prain & Tytler, 2012; Valanides et al., 2013). In addition, drawing has been shown to enhance long-term retention of concepts shown in visual representations (Mason, Lowe, & Tornatora, 2013).

How can drawing help students visually make sense of concepts? According to Van Meter's Cognitive Model of Drawing Construction (CMDC), students' generation of drawings involves three iterative phases (Van Meter & Firetto, 2013). In the first phase, students must understand the drawing task at hand. For instance, a prompt that instructs students to "draw what comes to mind" when they think of an atom will direct students to focus on their mental models, not traditional representations. Prior research suggests that students do not spontaneously draw (Leutner & Schmeck, 2014; Van Meter, Aleksic, Schwartz, & Garner, 2006). Therefore, simply providing paper and pens is insufficient. Students must receive *drawing prompts* to help them engage in visual sense-making processes, discussed in the following two phases.

In the second phase, students generate the drawing. To this end, students must identify, organize, and integrate relevant information about the to-be-learned concepts into a coherent mental model and then translate it into a visual representation. For example, to draw atoms, students first determine what concepts are relevant (e.g., nucleus and electrons), organize information about the atom by determining how different concepts relate to

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