Learning and Instruction xxx (2017) 1–13

Contents lists available at ScienceDirect

Learning and Instruction

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

Learning by enacting: The role of embodiment in chemistry education

Andrew T. Stull [a], [*], Morgan J. Gainer [b], Mary Hegarty [a]

[a] Department of Psychological and Brain Sciences, University of California, Santa Barbara, CA 93106, USA
[b] Department of Chemistry and Biochemistry, University of California, Santa Barbara, CA 93106, USA

ARTICLE INFO

Article history:
Received 8 May 2017
Received in revised form
9 August 2017
Accepted 23 September 2017
Available online xxx

Keywords:
Enactment
Hand-held models
Representational competence
Cognitive load
STEM learning

ABSTRACT

Can students learn from viewing an instructor's model-supported demonstrations alone or do they benefit from physically enacting the demonstrated concepts? This study investigated the value of enactment when learning chemistry using 3D molecular models in video and classroom lectures. We hypothesized that students who used models to enact demonstrated concepts would learn more than those who only watched a model-supported demonstration. Students watched a video lecture in a small classroom in Study 1 and a live lecture in a large lecture hall in Study 2. In both studies, one group watched and enacted the instructor's model-supported demonstration and the second group watched without enacting. In both contexts, students learned more if they enacted the demonstration than if they just watched the demonstration. Specifically, those who used models to enact an instructor's demonstrations performed better on problems that required drawn answers. Learning from enacted demonstrations was resilient over a delay of five days between instruction and testing and transferred to performance on classroom assessments that differed from the demonstrated tasks. We conclude that enactment with hand-held models promoted learning by off-loading the demand of imaging concepts and processes in the mind on to external objects and actions in the world, and that meaningful learning was promoted by lowering cognitive load while enhancing generative processing.

1. Introduction

In science classes, students often listen and watch as their instructor attempts to explain novel representations and scientific concepts. For example, organic chemistry students watch as their instructors explain how 2D structural diagrams represent 3D space (Fig. 1), how rotation of a molecule's bond will form different spatial configurations (Fig. 2), and how different spatial configurations have different relative energy values (Fig. 3). These concepts are notoriously difficult for many students to understand and visualize (Harle & Towns, 2010). What can be done to help these students? A common method applied by many instructors is to use a model to augment an explanation of a to-be-learned concept. For example, a chemistry instructor might demonstrate how rotation of parts of a molecule around a central bond changes the configuration and relative energy of the molecule. Typically students just observe the instructor's demonstration. However, a growing body of research suggests that enactment of an unfamiliar concept by the student can be beneficial for learning (Fiorella & Mayer, 2015; Kiefer & Trumpp, 2012). Does adding enactment improve learning from lectures that include demonstrations?

1.1. Representational competence

An essential aspect of education and workforce preparation in the Science, Technology, Engineering, and Mathematics (STEM) disciplines is teaching students how to use representations as tools for learning (Ferk, Vrtacnik, Blejec, & Gril, 2003; Trumbo, 2006). The teacher must instruct students in cultural aspects of their discipline, including how to interpret representations, how to use representations to reason, and how to create effective representations when communicating with peers. This combination of skills is referred to as *representational competence* (Kozma & Russell, 1997). Representational skills are often modeled for students using concrete and virtual models, (i.e., three-dimensional visuo-spatial representations), as demonstration aids, especially when teaching difficult spatial concepts. A common assumption among instructors is that demonstrating these concepts is sufficient for learning (Springer, 2014). However, watching demonstrations of elaborate spatial processes is likely to cause high cognitive load, hindering

---

[*] Corresponding author.

E-mail addresses: Andrew.Stull@psych.ucsb.edu (A.T. Stull), Gainer@chem.ucsb.edu (M.J. Gainer), Mary.Hegarty@psych.ucsb.edu (M. Hegarty).

https://doi.org/10.1016/j.learninstruc.2017.09.008
0959-4752/

Please cite this article in press as: Stull, A. T., et al., Learning by enacting: The role of embodiment in chemistry education, *Learning and Instruction* (2017), https://doi.org/10.1016/j.learninstruc.2017.09.008

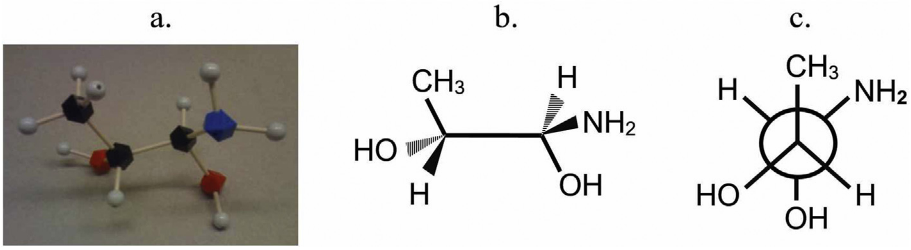

Fig. 1. Three structural representations of the same organic molecule. (a) A concrete (ball-and-stick) model where color is used to denote different atoms. Black is carbon, white is hydrogen, red is oxygen, and blue is nitrogen. (b) A Dash-Wedge diagram, uses solid lines, dashed wedges (i.e., dashes), and solid wedges (i.e., wedges) to represent spatial positions of a molecule's component parts (i.e., substituents). In this representation, solid lines are *in* the plane of the page, dashes are *behind* the plane of the page, and wedges are *in front* of the plane of the page. Carbon is assumed present at any intersection or termination of lines, unless it is explicitly drawn otherwise. (c) A Newman projection is used to represent the molecule from a side-on perspective, obtained by ‘sighting-down’ one of potentially many carbon-carbon bonds. In the carbon-carbon bond of interest, the carbon that is nearest to the viewer is depicted at the intersection of the three lines. The second carbon of the carbon-carbon bond is occluded by the first but represented as the circle in the Newman diagram (Originally published in Stull et al., 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

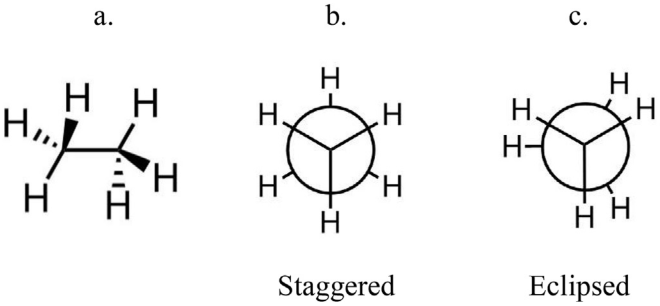

Fig. 2. Staggered and eclipsed configurations of ethane. The carbon-carbon bond rotates allowing ethane to move between staggered and eclipsed configurations. The staggered configuration (a and b) has side-groups staggered between the front and rear carbons. This is not obvious in a dash-wedge diagram (a) but is easily visible in a Newman projection (b) when viewed down the carbon-carbon bond. Rotating the carbon-carbon bond 60° produces the eclipsed configuration (c), which has overlapping side-groups when viewed down the carbon-carbon bond. Staggered configurations have lower relative energy (i.e., higher stability) than eclipsed configurations (i.e., lower stability).

students' learning (Harle & Towns, 2010). Here we examine whether enactment of the demonstration, might promote the development of representational competence. Specifically, we examine whether students learn more from an instructor's demonstration with models if they also have models and copy the instructor's interactions with the model to enact the relevant spatial transformations.

Learning novel representational formalisms in organic chemistry induces high cognitive load (Paas, Renkl, & Sweller, 2004; Sweller, 1999, 2005) for a number of reasons. First, representations of molecules made up of several atoms in specific spatial configurations are quite complex, so that mental representations are likely to overload spatial working memory (Shah & Miyake, 1996). Second, interpreting different diagrams involves recalling and imagining how different diagrammatic conventions depict 3D spatial entities in the two dimensions of the printed page (Tversky, 2005), placing more demands on working memory. Third, translating between different diagrammatic representations involves mentally transforming these representations and is also very memory intensive (Stull & Hegarty, 2016).

1.2. *Enacting versus observing*

Should students actively manipulate models while watching a model demonstration or is it sufficient to view the results of another's manipulations? Research by Springer (2014) indicated that students learn more from chemistry lectures that include model demonstrations than when the same lectures are given without demonstrations. He concluded that models helped students learn topics that required mental imagery because they served to off-load cognition. We build on this research by examining whether it is of further benefit for students to enact the instructor's demonstrations.

The present research is informed by findings that students are more successful in chemistry problem solving if they manipulate models than if they view models without manipulating them (Padalkar & Hegarty, 2014; Stull & Hegarty, 2016; Stull, Hegarty, Dixon, & Stieff, 2012; for a review, see Stull, Gainer, Padalkar, & Hegarty, 2016). For example, Stull et al. (2012) investigated the benefit of actively using versus passively viewing hand-held molecular models when reasoning about spatial diagrams in organic chemistry. They observed that students who used the models to enact translations between different spatial diagrams were significantly more accurate in their translations than those students who received no models or than those who received models but who did not use them. Thus, just observing the 3D spatial configuration of the molecule, which is represented directly by viewing the concrete models, did not offer any benefit. Stull et al. concluded that models served to off-load cognition, enabling students to enact difficult mental processes.

There are several reasons to believe that enacting demonstrations with models will scaffold learning beyond simply watching a modeling demonstration. First, research on enactive learning has shown that memory for verbal information can be enhanced when students enact descriptive material (Cohen, 1989; Engelkamp, Zimmer, Mohr, & Sellen, 1994; Glenberg, Gutierrez, Levin, Japuntich, & Kaschak, 2004; Schwartz & Plass, 2014). Enactive learning theorists suggest that physical action enhances multimodal coding and recall because enactment enables to-be-learned concepts to be mapped onto sensorimotor representations (Barsalou, 2008). Although this research involved learning about everyday actions (e.g., throw a ball, hammer a nail) to support reading comprehension rather than scientific processes, enactment with models might also support memory encoding and recall of scientific concepts (e.g., rotating a model to represent the imagined rotation of a molecule) (Yelland & Masters, 2007).

Second, there is now considerable evidence that mental and manual spatial transformations share common processes (Wohlschläger & Wohlschläger, 1998), and that performing spatial transformations manually can improve the corresponding mental spatial transformation processes. Specifically, practice in manually rotating physical or virtual objects can improve mental rotation skills (Adams, Stull, & Hegarty, 2014; Pani, Chariker, Dawson, &

Please cite this article in press as: Stull, A. T., et al., Learning by enacting: The role of embodiment in chemistry education, *Learning and Instruction* (2017), https://doi.org/10.1016/j.learninstruc.2017.09.008