Computers & Education 81 (2015) 69–81

Contents lists available at ScienceDirect

Computers & Education

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

Constrained interactivity for relating multiple representations in science: When virtual is better than real

Trevor J. Barrett*, Andrew T. Stull, Ted M. Hsu, Mary Hegarty

Department of Psychological & Brain Sciences, University of California, Santa Barbara, CA 93106, United States

ARTICLE INFO

Article history:
Received 20 June 2014
Received in revised form
18 September 2014
Accepted 18 September 2014
Available online 2 October 2014

Keywords:
Chemistry
Diagrams
Models
Virtual
Constrained interactivity

ABSTRACT

Virtual models are increasingly used in science education, especially in spatially demanding domains. However, few studies have directly compared the effectiveness of virtual and concrete models, or systematically characterized differences between them. Here, we compared students' accuracy and efficiency using virtual and concrete models to align and produce different representations in the domain of organic chemistry. Naïve undergraduate students learned the conventions of different molecular representations (diagrams and models) and then performed tasks that involved matching models to diagrams and using models to complete diagrams. The results indicated similar levels of accuracy for virtual and concrete models and greater efficiency for virtual models. Students preferred virtual models, but rated the usability of the two model types about equally. The efficiency benefit associated with using virtual models can be explained by their constrained interactivity, which prevented students from making task-irrelevant manipulations and increased the salience of the task-relevant information in the models.

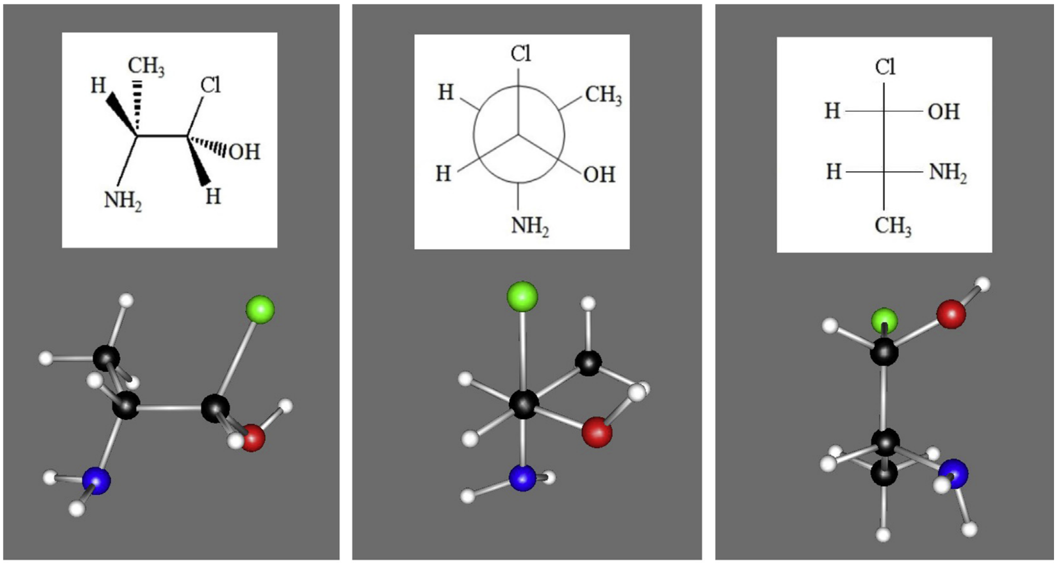
1. Introduction

Many science, technology, engineering, and mathematics (STEM) disciplines employ concrete models in both teaching and research. Concrete models (that is, tangible physical manipulatives) are used to represent both physical phenomena and abstract concepts in mathematics (McNeil & Uttal, 2009), physics (Zacharia & Olympiou, 2011), engineering (Klahr, Triona, & Williams, 2007), geology (Steer, Knight, Owens, & McConnell, 2005), and chemistry (Goodwin, 2008). As computers and mobile devices become more powerful and available in modern classrooms, virtual models (i.e., interactive 3D computer visualizations) are increasingly used in place of traditional concrete models (Dede, 2009), especially in domains that are rich in spatial information, such as chemistry and medicine (e.g., Limniou, Roberts, & Papadopoulos, 2008; Trelease, 2008). Despite the rapid adoption of virtual model technology, there have been relatively few studies that directly compare the relative effectiveness of concrete and virtual models in STEM domains, while systematically controlling and charactering differences between them. In the present study we describe a virtual model system that allows us to systematically control aspects of virtual models and use this to compare the effectiveness of virtual and concrete models for teaching about representations in the domain of organic chemistry.

When considering the potential effectiveness of virtual and concrete models, it is important to consider what type of information is being taught. For example, in previous studies in domains such as mathematics (Sarama & Clements, 2009) and experimental and engineering design (Klahr et al., 2007; Triona & Klahr, 2003), students learned to manipulate and control variables or run experimental simulations using real or virtual models. In general, no significant differences in learning outcomes were found between using virtual and concrete learning aids in these studies. One explanation of this apparent equivalence of concrete and virtual models is that the content to be learned in these situations is abstract, so that learning in these cases resulted from interacting with the content of the lesson, rather than from the act of physically manipulating the models.

* Corresponding author.
E-mail address: trevor.barrett@psych.ucsb.edu (T.J. Barrett).

http://dx.doi.org/10.1016/j.compedu.2014.09.009
0360-1315/



a. b. c.

Fig. 1. Three diagrams of the same molecule (above) along with corresponding 3D virtual models (below) showing the orientation and conformation of the molecule depicted by each diagram. In the models, black is carbon, white is hydrogen, red is oxygen, green is chlorine, and blue is nitrogen. (a) Dash-Wedge diagram (side-view): The wedges represents bonds coming towards the viewer, the dashed wedges represents bonds going away from the viewer and straight lines represent bonds in the plane of the page. (b) Newman diagram (end view): shows the molecule from a perspective that is in line with the central carbon–carbon bond. The three joined bonds indicate substituents that are in front in this view. (c) Fischer diagram (upright view) of the same organic molecule depicted in the ball-and-stick model. This diagram represents a specific conformation, known as an eclipsed or "boat" conformation. The horizontal lines represent bonds that are coming towards the viewer, the vertical lines on the top and bottom represent bonds going away from the viewer and the central vertical bond is represented as in the plane of the page. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Potential differences in the effectiveness of virtual and concrete models may be more pronounced in spatial domains, such as anatomy, geology or organic chemistry, in which models are often used to teach about properties such as shape (morphology), configuration, or motion. Basic research on learning the spatial layout of an environment (large-scale spatial knowledge acquisition) from virtual and real environments has found that learning can be impaired when virtual environments do not provide perceptual cues inherent in physical navigation, such as vestibular and proprioceptive cues from self-motion (Chance, Gaunet, Beall, & Loomis, 1998; Richardson, Montello, & Hegarty, 1999). The same may be true of manipulations of virtual models in science education. For example, interacting with a virtual anatomical or molecular model using a keyboard or mouse may not produce the same learning outcomes as manipulating a concrete model, due to interactive and perceptual differences. Tangible concrete models provide richer perceptual information about the spatial configuration through touch and vision, and actions performed on the models (e.g., rotation) are congruent with the resulting transformation of the models.

In comparing virtual and concrete models, it is therefore important to characterize and control differences in perceptual fidelity and interactivity in order to identify causes of observed differences in performance. Many currently available virtual models lack potentially important perceptual information that is present in concrete models, such as stereoscopic depth cues, and haptic information, which can be important in communicating features such as shape and texture of objects. They may also differ in the interactivity afforded to the learner. For example, one can rotate a physical object around any axis, but virtual models often constrain interactivity to rotation around specific axes, such as the horizontal and vertical axes. Such constraints have even been found to be beneficial in medical and mathematics education (Khooshabeh, Hegarty, Keehner, & Cohen, 2008; Sarama & Clements, 2009; Sedig, 2008). For example, Khooshabeh et al. (2008) found that students with low spatial ability were better able to infer cross sections of 3D objects when they were constrained to rotate virtual models of these objects around only horizontal and vertical axes, rather than free rotation around any axis and Sedig (2008) found advantages of virtual models that constrained interactivity to task-relevant actions.

Finally, it is important to consider the virtual model interface, which can vary from a standard mouse and keyboard to 6 degree-of-freedom interaction devices. In this context, Wu, Klatzky, Shelton and Stetten (2005) make a distinction between cognitively mediated and perceptually mediated models. Virtual models that are controlled by keyboard interactions are cognitively mediated. Concrete models and virtual models using direct manipulation interfaces are perceptually mediated. Wu et al. suggest that interfaces that provide more perceptually mediated interaction decrease mental demand by offloading effortful mental operations onto more automatic systems. That is, when directed actions are guided more by perception (e.g., vision, touch, proprioception) than cognition (e.g., visualization, mental rotation), the freed up cognitive resources can be reallocated to improve performance and learning.

In this study we examined the effectiveness of virtual and concrete models in the domain of organic chemistry. We chose organic chemistry education as a test-bed because it is a domain in which spatial information is critical and students have particular difficulty mastering essential spatial concepts and representations. Properties of molecules depend not only on their atomic composition, but also on the spatial arrangement of those atoms in three-dimensional space (stereochemistry) and chemists rely heavily on multiple spatial representations to communicate the spatial arrangement of atoms in molecules (Cheng & Gilbert, 2009; Goodwin, 2008). Chemists commonly employ both three-dimensional (3D) and two-dimensional (2D) representations of molecules. 3D representations include concrete (tangible physical models) and virtual (computer-based) models. 2D representations include diagrams that use different conventions to convey the 3D spatial structure of molecules in the two dimensions of the printed page. Various types of diagrams are specialized for different purposes in chemistry, and often depict molecular structure from different spatial perspectives (Goodwin, 2008). Models and