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Full Length Article

The effects of static versus dynamic 3D representations on 10th grade students' atomic orbital mental model construction: Evidence from eye movement behaviors

Sheng-Chang Chen, Mi-Shan Hsiao, Hsiao-Ching She *

Institute of Education, National Chiao-Tung University, Hsinchu City, Taiwan, ROC

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A B S T R A C T

This study examined the effectiveness of the different spatial abilities of high school students who constructed their understanding of the atomic orbital concepts and mental models after learning with multimedia learning materials presented in static and dynamic modes of 3D representation. A total of 60 high school students participated in this study and were randomly assigned into static and dynamic 3D representation groups. The dependent variables included a pre-test and post-test on atomic orbital concepts, an atomic orbital mental model construction test, and students' eye-movement behaviors. Results showed that students who learned with dynamic 3D representation allocated a significantly greater amount of attention, exhibited better performance on the mental model test, and constructed more sophisticated 3D hybridizations of the orbital mental model than the students in the static 3D group. The logistic regression result indicated that the dynamic 3D representation group students' number of saccades and number of re-readings were positive predictors, while the number of fixations was the negative predictor, for developing the students' 3D mental models of an atomic orbital. High-spatial-ability students outperformed the low-spatial-ability students on the atomic orbital conceptual test and mental model construction, while both types of students allocated similar amounts of attention to the 3D representations. Our results demonstrated that low-spatial-ability students' eye movement behaviors positively correlate with their performance on the atomic orbital concept test and the mental model construction.

1. Introduction

Learning the concepts of atoms or molecules in chemistry is difficult because atoms and molecules are invisible and abstract for students. This is especially true for the atomic orbital concept that involves quantum mechanics because it is often remote from students' prior knowledge. As a result, students often create a lot of alternative concepts or inappropriate mental models (Nakiboglu, 2003; Taber, 2001; Tsaparlis, 1997). To alleviate these difficulties, the use of symbolic and microscopic representations can facilitate students' understanding of the structure of atoms and molecules (Barak & Dori, 2005; Chandrasegaran, Treagust, & Mocerino, 2008; Griffiths & Preston, 1992; Johnstone, 1993). Moreover, students can construct their own mental models to correspond with these symbolic and microscopic representations, which will further enable them to manipulate their mental models to solve the problems (Adbo & Taber, 2009; Gkitzia, Salta, & Tzougraki, 2011; Taber, 2005). To foster students' chemical concepts and their mental models of atoms or molecules, many studies have developed various multimedia tools in recent years.

1.1. Static 3D representations vs. dynamic 3D representations

Many studies have suggested that multimedia tools or software enable students to overcome the difficulty of learning chemical concepts successfully and thus help students to achieve better learning outcomes (Copolo & Hounshell, 1995; Kozma & Russell, 1997; Schank & Kozma, 2002; Xie & Tinker, 2006). Molecular Workbench, written in Java and created by Concord Consortium, provides interactive molecular dynamics simulations to facilitate

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Abbreviations: NOF, number of fixation; TIT, total inspection time; MFD, mean fixation duration; NOS, number of saccade; TSD, total saccade distance; NOR, number of re-reading.

* Corresponding author at: Institute of Education, National Chiao-Tung University, No. 1001 Ta-Hsueh Rd, Hsinchu City 300, Taiwan, ROC.

E-mail address: hcshe@mail.nctu.edu.tw (H.-C. She).

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students' ability to learn molecular structures (Molecular Workbench, 2013). The static two-dimensional (2D) representation, static three-dimensional (3D) representation, and dynamic 3D representation are all widely used in multimedia representations. Many studies aimed to investigate how each of these different multimedia representations influenced students' learning outcomes with respect to learning molecular structures (Korakakis, Pavlatou, Palyvos, & Spyrellis, 2009). Compared to 2D representations, some studies reported 3D representations improved students' incomplete mental models and enabled them to construct more complete mental models (Wu & Chiang, 2013). Other studies have proposed that students who learned with 3D representations of molecule structures outperformed those who learned with 2D representations in terms of the accuracy of their concepts involving molecular structures. These results would suggest that 3D representations can reduce the cognitive load in the learning process (Dori & Barak, 2001). Nevertheless, one study reported that both 2D animated and 2D graphic representations can facilitate students' construction of mental models of new concepts (Mayer, 2002). Other studies claimed that students tend to choose 3D representations to aid their learning of more complicated molecular structures, whereas they are more likely to adopt 2D representations to aid their learning of simpler molecular structures (Pavlinic, Buckley, Davies, & Wright, 2002). However, those studies did not reveal any consistent patterns regarding whether 3D representations resulted in better learning outcomes than static 2D representations. Similarly, Williamson and Abraham (1995) reported that animations are better than static graphs at enhancing students' ability to construct mental models involved in dynamic chemical processes. Other studies claimed that learners did not benefit from learning with animated graphics any more than they did from learning with static graphics (Chandler, 2009). Hence, the current literature contradicts itself regarding whether static representations improve students' understanding more than dynamic representations (Tversky, Morrison, & Betrancourt, 2002). Furthermore, most students fail in their efforts to construct accurate mental models of atomic orbitals because understanding the concept of atomic orbitals requires taking a probabilistic perspective rather than a deterministic perspective (Tsaparlis & Papaphotis, 2002). In the middle of the 20th century, scientists found that the electrons of an atom do not have a fixed orbit around the atomic nucleus, in contrast to how, for example, the planets of the solar system follow fixed orbits around the sun. According to the Heisenberg uncertainty principle, the exact trajectory of an electron cannot be predicted, but it is possible to sketch out the space in which the electron can be found. Hence, the atomic orbitals represent the space in which there is a 95% probability of finding the electrons of an atom (Eisberg & Resnick, 1985; Griffiths & Harris, 1995; Orchin, Macomber, Pinhas, & Wilson, 2005). The aim of this study was to foster students' learning performance and help them to accurately construct their mental models of atomic orbitals. Hence, the static 3D representations and dynamic 3D representations were designed specifically with the goal of facilitating their learning of atomic orbital concepts and their construction of atomic orbital mental models. Garg, Norman, Spero, and Taylor (1999) proposed that static 3D representations are similar to dynamic 3D representations with standardized views but static 3D representations had limited views in terms of rotation (Garg et al., 1999). Ferk, Vrtacnik, Blejec, and Gril (2003) further pointed out that static 3D representations provide the function of spatial visualization while dynamic 3D representations provide the function of spatial visualization and spatial rotation. However, other research argued that 3D representations that rotate the visualizations may impose an additional cognitive load and thus hinder students' learning (Keller, Gerjets, Scheiter, & Garsoffky, 2006). It seems there is still no consensus regarding whether dynamic 3D representations are better than static 3D representations. In this study, we intend to explore whether students' performance of atomic orbital conceptions after learning with the dynamic 3D representations are different from those students who learn with static 3D representations. Our design of dynamic 3D representation provides spatial visualization of an atomic orbital with rotation, while the static 3D representation only provides spatial visualization of an atomic orbital.

1.2. Spatial ability and 3D representations

Mayer (2003) reported that high-spatial-ability learners exhibited greater advancement than low-spatial-ability learners when receiving well-designed instruction. Spatial ability has been considered as an important cognitive aptitude with which humans can transform 2D objects to 3D objects, imagine the objects (including their location and direction), and further manipulate the objects by mentally rotating them while they are learning (Baker & Talley, 1972; Carroll, 1993; Coleman & Gotch, 1998; Höffler & Leutner, 2011). Many chemistry concepts are microscopic and abstract, such as the concepts of atoms or molecules, and thus require learners to imagine, manipulate, and mentally rotate atoms or molecules to construct their understanding of these concepts (Carter, LaRussa, & Bodner, 1987; Yang, Andre, Greenbowe, & Tibell, 2003). Moreover, several studies have reported a positive relationship between students' spatial ability and their learning performance in chemistry learning (Pribyl & Bodner, 1987; Urhahne, Nick, & Schanze, 2009). Höffler and Leutner (2007) also reported that spatial ability is related with students' mental model construction during their learning processing. Another study suggested that students who were trained by visual spatial tasks can enhance their spatial ability and effectively foster their learning performance in chemistry (Small & Morton, 1983; Tuckey, Selvaratnam, & Bradley, 1991). With respect to multimedia learning, learners' spatial ability is critical for them to be able to understand 3D representation (Keehner, Montello, Hegarty, & Cohen, 2004). Two hypotheses, known the ability-as-compensator hypothesis and the ability-as-enhancer hypothesis, have been proposed as explanations for learners' spatial ability and their performance in learning 3D representations (Hegarty & Waller, 2005; Huk, 2006). The ability-as-compensator hypothesis assumes that high-spatial-ability learners can use their abilities to compensate for any weaknesses in the learning environment, such that their learning outcomes are similar whether they are in a better learning environment or not (Mayer & Sims, 1994). However, low-spatial-ability learners are impacted by the quality of the learning environment, which results in better learning outcomes when they are taught with materials designed to include multimedia learning effects than when they are taught with materials not designed to impart multimedia learning effect (Lee, 2007). Höffler (2010) again reported similar results in that low-spatial-ability students learned better while learning with dynamic 3D visualizations than while learning with static visualizations. The ability-as-enhancer hypothesis highlights that high-spatial-ability learners can integrate different representations into their working memory, a capability which results in better learning outcomes, while low-spatial-ability learners need more cognitive capacity to hold these representations in working memory and yet have less cognitive resources to devote to those representations (Mayer, 2003). Some empirical studies have supported the ability-as-enhancer hypothesis, suggesting that low-spatial-ability learners would experience an increase in their extraneous cognitive loads while learning with 3D representations because their ability to manipulate their mental images is limited (Huk, 2006; Keller, Gerjets, Scheiter, & Garsoffky, 2006). However, these studies only