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Level of interactivity and executive functions as predictors of learning in computer-based chemistry simulations

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ABSTRACT

High school students' learning outcomes was examined comparing exploratory vs. worked simulations. The effects of added icons and students' executive functions were also examined. In Study 1, urban high school students ($N = 84$) were randomly assigned to one of four versions of a web-based simulation of kinetic molecular theory that varied in instructional format (exploratory vs. worked simulation) and representation (added icons vs. no added icons). Learning was assessed at two levels: comprehension and transfer. For transfer, a main effect was found for instructional format: the exploratory condition yielded greater levels of transfer than the worked simulation. Study 2 used the same conditions and a more complex simulation, the ideal gas law, with a similar sample of students ($N = 67$). For transfer, an interaction between instructional format and executive functions was found: Whereas students with higher levels of executive functions had better transfer with the exploratory condition, students with lower levels of executive functions had better transfer with the guided simulations. Results are discussed in relation to current theories of instructional design and learning.

1. Introduction

In recent years there has been considerable interest in the educational effectiveness of more open-ended discovery approaches compared with more direct approaches to learning and instruction. The recent interest in this issue was set off in part by an article by Kirschner, Sweller, and Clark (2006) who criticized "minimally guided" instructional approaches, which they argue result in increased cognitive load and therefore reduced learning. In subsequent commentaries to their article, a number of authors point out that many instructional approaches that have a constructivist orientation, such as problem based learning, are not at all "minimally guided" and have been shown to be very effective (e.g., Hmelo-Silver, Duncan, & Clark, 2007; Schmidt, Loyens, Van Gog, & Paas, 2007). This debate has direct implications for the design of computer-based approaches to learning, such as educational games and simulation. Although many researchers have argued that the interactive, exploratory nature of many computer-based multimedia learning environments has great educational potential (e.g., Bransford, Brown, & Cocking, 1999; Duffy & Jonassen, 1992; Hannafin & Peck, 1988), others have suggested that these very exploratory features can interfere with learning.

There are a number of reasons for this disagreement, including differing views on the nature of learning and the meaning of "interactivity" (Domagk, Schwartz, & Plass, 2010). Additionally, we propose that the effects of interactive exploration actually may be different for different learners, with certain students being better able to take advantage of the potential benefits of increased interactive exploration and others becoming overwhelmed by the cognitive load they experience as a result of the increased interactivity. This reasoning is analogous to the well-established phenomenon of expertise reversal, in which a specific educational intervention is beneficial to learners with low levels of prior knowledge, but can actually interfere with learning for individuals with higher levels of prior knowledge (Homer & Plass, 2010; Kalyuga, Ayres, Chandler, & Sweller, 2003). In a similar fashion, interactivity and exploration may have positive effects for certain learners, particularly for those who are better able to manage their cognitive resources, but have negative consequences for other learners, specifically those who have greater difficulties managing their cognitive resources. This possibility is investigated in the current paper, which examines the educational effectiveness of exploration and interactivity in computer-based multimedia learning, and how the ability to manage cognitive resources, as identified

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by the individual differences factor of executive functions, interacts with exploration and interactivity to affect learning outcomes.

2. Interactivity and cognitive load in multimedia learning

The considerable criticism of highly interactive exploratory educational approaches has to a large extent originated from researchers with a cognitive load theory (Sweller, 1999) orientation (e.g., Handelsman et al., 2004; Kirschner et al., 2006; Klahr & Nigam, 2004). In their review, Kirschner et al. (2006) are particularly critical of exploratory educational approaches that, they claim, offer only "minimal guidance" to learners. Kirschner and his colleagues argue that more direct instructional approaches, such as worked-examples, result in better learning for students. A number of studies have indeed found that appropriately structured worked-out examples can result in greater learning outcomes than a purely problem-based instruction approach (e.g., Paas, 1992; Sweller & Cooper, 1985; Zhu & Simon, 1987). For example, Tuovinen and Sweller (1999) examined learning outcomes in an interactive, exploratory vs. a worked example approach to teaching students how to use a database program with a graphical user interface. The authors hypothesized that the increased cognitive load induced by the exploratory approach would result in reduced learning outcomes for the students. In support of their hypothesis, Tuovinen and Sweller did find a negative effect for interactivity, however, only for student with no prior database experience; for students who had prior database experience, no difference was found between the two instructional approaches.

Moreno and Valdez (2005) similarly examined the effects of interactivity in multimedia learning environments with students. They hypothesized that although interactivity could result in cognitive overload that would interfere with learning, interactivity could also support more active processing by the students and result in more meaningful learning. Moreno and Valdez found that students in interactive conditions had lower learning outcomes than students in non-interactive condition (Experiment 1), but that interactivity could be effective if students were provide with feedback that promoted "intentional and purposeful" processing of the information being presented (Experiment 3).

Rather than emphasize the increased cognitive load associated with exploration and interactivity, others researchers have stressed the importance of exploration and interactivity for enabling students to become engaged with the learning materials and to "take control" of their own learning (e.g., Bransford et al., 1999). This more open, interactive approach to learning has been associated with increased interest and motivation (Steffe & Gale, 1995), and with better knowledge transfer and applicability (Hmelo-Silver et al., 2007).

Schaffer and Hannafin (1986), for example, compared learning outcomes from educational video with different levels of interactivity. The authors systematically varied the degree of user interactivity with the video and found that the group with the most interactivity took the longest to complete the task, but also had the greatest levels of recall on the posttest. Other researchers have similarly found that interactivity in multimedia learning environments can lead to increased or deeper levels of learning. For example, Vollmeyer, Burns, and Holyoak (1994) report that students who could freely explore the effects of environmental parameters in an aquarium simulation acquired a better understanding of the simulation's underlying properties than subjects who were given specific objectives. Similar effects have been reported in number of studies (e.g., Mayer & Chandler, 2001; Schwan & Riempp, 2004; Tung & Deng, 2006).

Considering both of these two apparently disparate bodies of work, it seems as though learning approaches with more student interactivity and exploration can result in increased cognitive load compared to less interactive, more didactic approaches, but that the added cognitive load of increased interactive exploration can also have benefits, particularly for certain learners. A task for researchers then is to determine for which students the benefits of interactivity and exploration outweigh the negative effects of increased cognitive load. The current study sought to address this question by investigating learners' executive functions as one of the factors that predicts the effectiveness of more interactive exploratory approaches to multimedia learning. Of particular interest was the interaction between learners' executive functions and exploratory interactivity in computer-based science simulations.

3. Executive functions and level of interactivity in multimedia learning

Although precise definitions of *executive function* (EF) vary, EF are generally identified as being high-level abilities that influence other more basic functions, such as attention and memory, and enable the planning, monitoring and control of mental activities and behaviors (Meltzer, 2011). EF processes are typically associated with functioning in the prefrontal cortex (Bryan & Luszcz, 2000; Luria, 1966). There is no single task that serves as a direct indicator of EF (Morgan & Lilienfeld, 2000), but a number of recent efforts have attempted to create a battery of measures in order to capture a variety of different aspects of EF (e.g., Carlson, 2005; Zelazo & Bauer, 2013).

When using a battery of measures is not feasible, researchers typically focus on assessing the aspect of EF that is most relevant for their task. One of the most commonly used measures for this purpose is the Stroop Task (Stroop, 1935), which assesses attention and inhibition components of EF (Homack & Riccio, 2004; MacLeod, 1991). The Stroop task is regularly included in neuropsychological assessment as a measure of selective attention, cognitive flexibility, resistance to interference, and inhibitory control (Archibald & Kerns, 1999; Homack & Riccio, 2004; Lezak, 2004; Spreen & Strauss, 1998). In a study with children and preadolescence, Brocki and Bohlin (2004) investigated the dimensionality of several measures of executive functioning, and found that Stroop-like tasks measure not only the ability to inhibit a response, but also the ability to cognitively shift to a new response. In this way, Stroop tasks capture variance in working memory as well as inhibition, two fundamental components of EF (Barkley, 1997).

Because EF enable the intentional allocation of mental resources, such as attention and memory, higher levels of EF should result in a more efficient use of cognitive resources and therefore increased learning in interactive environments. In spite of these obvious implications of executive functions for learning, it is only in the past decade or so that there has been a concentrated effort to examine the implications of EF for education (Best, Miller, & Jones, 2009). Overall, a positive relation between EF and educational outcomes has been found (e.g., Bull, Espy, & Wiebe, 2008; St Clair-Thompson & Gathercole, 2006; Yeniad, Malda, Mesman, van IJzendoorn, & Pieper, 2013). For example, Blair and Razza (2007) found that measures of EF in 3- to 5-year-old children, particularly inhibitory control, predicted early math and reading abilities, independent of general intelligence. Similarly, Best, Miller & Naglieri (2011) examined data from a large sample of 5- to 17-year-olds and found that complex measures of ER were significantly correlated to specific aspects of academic achievement measures. These findings suggest that students' EF may be of particular importance in multimedia learning environments, which can tax learners' cognitive resources (Brünken, Plass, & Leutner, 2003; Brünken, Steinbacher, Plass, & Leutner, 2002; Mayer, 2001; Plass, Moreno, & Brünken, 2010).