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Enhancing scientific discovery learning through metacognitive support

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ABSTRACT

Using a virtual physics lab, we analyzed the impact of metacognitive support on simulation-based scientific discovery learning (SDL). The dependent variables for learning outcome were the immediate conceptual knowledge gain and the retained conceptual knowledge three weeks later. Additional dependent variables were the actual use of a domain-specific cognitive strategy, motivation, emotions, and cognitive load. To contrast the effects of metacognitive support with possible effects of goal specificity, the experimental study followed a 2 × 2 design with a sample of $N = 129$ ninth grade students and with metacognitive support (yes vs. no) and learning goals (specific vs. nonspecific) as factors. The results showed positive effects of metacognitive support on learning outcome, on actual cognitive strategy use, and on learning emotions. No interaction effect of metacognitive support and goal specificity on learning outcome was observed.

1. Introduction

This study examines the impact of metacognitive support on knowledge gain, strategy use, motivation, and emotions as important criteria for scientific discovery learning. As a main essence of various definitions, Alfieri, Brooks, Aldrich, and Tenenbaum (2011) suggest that *discovery learning* (Bruner, 1961) occurs when learners have to discover the knowledge of a target concept in a self-regulated way with only the provided materials. *Scientific discovery learning* (SDL; de Jong & van Joolingen, 1998; Klahr & Dunbar, 1988) focuses specifically on learning science (e.g., in physics) and is close to inquiry learning (Lazonder, Wilhelm, & Hagemans, 2008). SDL involves stating and testing hypotheses in a self-regulated cycle of planning, conducting, and evaluating scientific experiments (Friedler, Nachmias, & Linn, 1990; Künsting, Wirth, & Paas, 2011; Rivers & Vockell, 1987). Many studies on SDL used virtual, simulation-based environments (de Jong & van Joolingen, 1998; Künsting et al., 2011; van der Meij & de Jong, 2006), which can be an effective method (Zacharia & Olympiou, 2011).

However, SDL requires self-regulation, which is problematic for many learners (de Jong & van Joolingen, 1998; Lazonder et al., 2008). During the experimentation in a process of SDL students have to regulate their use of cognitive strategies, their motivational and emotional states, and their effort. The process of learning is to be planned, monitored, and evaluated on a metacognitive level (de Jong et al., 2005; Veenman, Elshout, & Busato, 1994; Wirth & Leutner, 2008). Thus, students' success during SDL depends on their metacognitive skills used to cope with these demands (de Jong et al., 2005). Adequate instruction can avoid excessive cognitive demands with detrimental effects on learning (Kirschner, Sweller, & Clark, 2006; Mayer, 2004). Because many students do not have enough metacognitive skills, they need metacognitive instruction, which also applies to SDL (de Jong & van Joolingen, 1998; Zion, Michalsky, & Mevarech, 2005).

Successful SDL requires the metacognitive regulation of general cognitive strategies (e.g., selecting and memorizing) and domain-specific cognitive strategies (de Jong et al., 2005). One domain-specific cognitive strategy that particularly promotes SDL is to design unconfounded experiments by varying only one variable at a time while holding constant all others (e.g., Chen & Klahr, 1999; de Jong et al., 2005; Künsting et al., 2011). This *control of variables strategy (CVS)* is crucial for scientific reasoning because it is a prerequisite for valid causal inferences. However, many learners do not use CVS, which can even apply to university students (Vollmeyer, Burns, & Holyoak, 1996). Metacognitive support including instructions to think about a systematic plan and to control the appropriateness of learning activities during SDL should stimulate a systematic learning behavior on the cognitive level, such as the use of CVS. So far research offers very little empirical evidence for effects of metacognitive support on the actual use of CVS during simulation-based SDL.

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Beyond, detrimental effects that occur when students feel unable to cope with learning demands also pertain to low motivation and negative emotions, which in turn can affect the learning outcome (Boekaerts, 1997, 2002). However, if at all, so far there are very few studies on SDL that have examined whether metacognitive support as an aid to cope with learning demands can promote learning outcome *and* both motivation and emotions. In previous studies on SDL, students were supported, for instance, by metacognitive instructions (Veenman et al., 1994), by the help to structure the scientific process (Linn & Songer, 1991) and to design systematic experiments (Rivers & Vockell, 1987), by model progression and assignments (Swaak, van Joolingen, & de Jong, 1998), and by given learning goals that are similar to assignments (Künsting et al., 2011).

However, providing learners with specific learning goals in addition to metacognitive support has been shown to promote transfer task performance but not declarative knowledge gain and recall (Bannert, 2003). One explanation for this finding could be that processing both specific learning goals *and* metacognitive support have engaged a great proportion of the students' cognitive resources. Thus, the cognitive capacities available for a declarative knowledge gain at the same time might have been restricted. With regard to simulation-based SDL this explanation is supported by the study of Künsting et al. (2011) that revealed specific learning goals to impose a higher cognitive load than nonspecific learning goals. It is thus possible that combining metacognitive support with nonspecific learning goals instead of specific learning goals could be a better method to foster knowledge gain during SDL. To our knowledge, no study has addressed this question so far.

The present study focuses on the effectiveness of a metacognitive support that covers a cyclic process of simulation-based SDL from an orienting phase to an evaluating phase. After testing the general impact of such a metacognitive support on knowledge gain during SDL, this study tries to answer further important research questions the existing research left unaddressed: *First*, there is very little evidence for the impact of metacognitive support on the actual use of CVS. *Second*, although motivational and emotional states are crucial agents for the quality of all learning processes, no studies to our knowledge have examined the impact of metacognitive support on students' motivational and emotional states during simulation-based SDL. *Third*, it remains open whether the impact of metacognitive support on learning outcome depends on the specificity of additionally set learning goals.

1.1. Metacognitive support to foster simulation-based SDL

Previous research has revealed the effectiveness of metacognitive support (e.g., instructions to plan and to monitor a learning process) in computer-based learning, for example, in hypermedia learning (Bannert, 2003; Bannert, Hildebrand, & Mengelkamp, 2009) and simulation-based SDL (Lin & Lehman, 1999; Veenman et al., 1994). Simulation-based SDL offers interactivity, which refers to a learner's choice to change values of input variables and then observe the corresponding change of output variables as a result (cf. Bodemer, Plötzner, Feuerlein, & Spada, 2004). This result is generated by the computer in terms of static or dynamic visualizations that, in turn, can prompt learners to another change of input variables. However, many learners do not use the full potential of interactivity in a structured and goal-oriented way, which can be due to low metacognitive skills or limited intelligence (Veenman et al., 1994).

According to Friedler et al. (1990), successful SDL requires defining a scientific problem; stating a hypothesis; designing experiments; observing, collecting, analyzing, and interpreting the data generated by experiments; applying the results; and predicting on the basis of the results. These *transformative processes* directly generate new knowledge (de Jong & Njoo, 1992) and should include cognitive strategies. With regard to domain-specific cognitive strategies, designing effective experiments requires the use of CVS. Additionally, general cognitive strategies (e.g., organizing, elaborating, and memorizing) should help to observe, collect, analyze, and interpret the experiments' results in a way that promotes understanding and knowledge gain. These processes are to be managed on a metacognitive level, which requires planning, goal setting, and monitoring (*regulative processes* according to de Jong & Njoo, 1992). Thus, metacognitive strategy use includes the planning, the monitoring and the regulation of cognitive strategies (Boekaerts, 1999).

To enhance SDL correspondingly, learners can be assisted by planning support (White, 1984) and monitoring support (Schauble, Raghavan, & Glaser, 1993). For example, Zion et al. (2005) demonstrated that metacognitive instructions significantly contribute to students' achievement in designing experiments and drawing conclusions. In their study on discovery learning with computer simulations, Veenman et al. (1994) found that students' performance can be enhanced by ''metacognitive mediation''. Learners in this condition received assignments similar to goals and were prompted to paraphrase questions, to generate hypotheses, to plan the actions, and to make notes (Veenman et al., 1994, p. 97).

The inefficient use of metacognitive strategies is a problem not only in the context of SDL. For example, studies on hypermedia learning also demonstrated that learners often need support because they are not able to self-regulate their learning (Lawless & Brown, 1997). To address this need, Bannert (2003) developed a model of metacognitive support based on approaches of successful learning (Pressley, Borkowski, & Schneider, 1989). In Bannert's model, learning in hypermedia starts with orientation, specification of goals, and planning. These activities direct the search, appraisal, and processing of information by the use of general cognitive strategies (e.g., organizing, elaborating, and memorizing). This process is permanently to be monitored, evaluated in between, and controlled at its end.

We argue that these metacognitive activities are also relevant for the experimentation during SDL. A metacognitive support of simulation-based SDL should provide learners with explanations of a structured and holistic overview of metacognitive learning activities that cover the process of SDL. It should begin with orienting, which is a metacognitive strategy used to gain an overview of materials, variables, and what can be done in a learning environment. Similar to a scientific problem that is to be defined at first, a given learning goal should be understood before experimentation starts, and it should be tested whether it can be helpful to divide it into subgoals. Planning includes thinking about adequate experimentation steps and other learning activities in order to execute systematic experiments during the pursuit of a goal. Monitoring and controlling involve appraising the comprehension of experimental results and the adequacy of cognitive strategies used during SDL. Evaluating assesses whether the goals set at the start of a process of SDL are achieved.

On the basis of Bannert's (2003) model of metacognitive support we expected that an adapted support with the characteristics of SDL (e.g., to plan the generating of information by experimentation) promotes students' conceptual knowledge gain during simulation-based SDL in physics. *Students provided with metacognitive support are expected to gain more conceptual knowledge than students without metacognitive support (Hypothesis 1).*

SDL involves stating and testing hypotheses about relations between variables. The testing of hypotheses is characterized by planning, conducting, and evaluating scientific experiments (de Jong & van Joolingen, 1998; Klahr & Dunbar, 1988; Kuhn, Black, Keselman, & Kaplan, 2000; cf. Lazonder & Kamp, 2012). To verify hypotheses, systematic experiments can be conducted. The new