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Multiple levels of metacognition and their elicitation through complex problem-solving tasks

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ABSTRACT

Building on prior efforts, we re-conceptualize metacognition on multiple levels, looking at the sources that trigger metacognition at the individual level, the social level, and the environmental level. This helps resolve the *paradox of metacognition*: metacognition is personal, but it cannot be explained exclusively by individualistic conceptions. We develop a theoretical model of metacognition in collaborative problem solving based on models and modeling perspectives. The theoretical model addresses several challenges previously found in the research of metacognition. This paper illustrates how metacognition was elicited, at the environmental level, through problems requiring different problem-solving processes (definition building and operationalizing definitions), and how metacognition operated at both the individual level and the social level during complex problem solving. The re-conceptualization of metacognition has the potential to guide the development of metacognitive activities and effective instructional methods to integrate them into existing curricula that are necessary to engage students in active, higher-order learning.

1. Introduction

In the first overview of the new science of learning, Bransford, Brown, and Cocking (2000) emphasized the critical role of metacognition in successful learning. Metacognition is the process in which students monitor, assess, and modify their own learning progress. It can help students develop their knowledge for teaching themselves and improve positive learning transfer to new settings and events. This has been demonstrated in numerous studies across multiple disciplines (e.g., Bielaczyc, Pirolli, & Brown, 1995; Borkowski, Carr, & Pressely, 1987; Muir, Beswick, & Williamson, 2008; Rasekh & Ranjbary, 2003; Schraw, 1998; White & Frederickson, 1998). These studies demonstrate the need for instructional approaches to help students become more metacognitive about their learning. However, more needs to be understood about the mechanisms of metacognition, how to effectively encourage students' metacognition in problem solving, and how to promote the development of students' metacognitive abilities – a mechanism that enables one efficiently to organize, monitor, and regulate what one knows to reach a goal successfully.

Metacognition has traditionally been defined at the *individual level*, as thinking about one's own thinking (Flavell, 1976). In the research presented here, we re-conceptualize the construct of metacognition on multiple levels, considering thinking about thinking at the individual level, the *social level*, and the *environmental level*. At the individual level, a student has access

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to internal sources to monitor or regulate her/his cognitive processes. However, this raises what we term *the paradox of metacognition*: metacognition is personal, but it cannot be explained exclusively by individualistic conceptions (e.g., Iiskala, Vauras, & Lehtinen, 2004; Iiskala, Vauras, Lehtinen, & Salonen, 2011; Vauras, Iiskala, Kajamies, Kinnunen, & Lehtinen, 2003). For example, individuals may experience a time when they are "stuck." If individuals only have access to their own internal thinking to help them resolve their obstacle – thinking which caused them to get stuck in the first place – how can they make progress?[1] Another example might be individuals lacking good self-regulation abilities. How can they detect their own (false) cognition when it goes awry, and adapt their thinking? One way to resolve this paradox is to observe that in addition to their internal psychological resources, individuals also have access to external sources that trigger metacognitive thinking. These external sources include both social triggers that come from other people interacting with the individual, and environmental triggers that come from interacting with the environment in which one is learning. This access to external sources of metacognition informs how metacognitive failures, such as an absence of checking behavior (Stacey, 1992), metacognitive blindness, metacognitive vandalism, and metacognitive mirage (Goos, 2002), can be prevented or resolved. The research reported here shows how metacognition, operating at multiple levels (individual, social, and environmental), functions during complex collaborative problem solving to overcome the paradox of metacognition, and ultimately informs instructional practice.

We consider metacognition in the context of solving complex problems of the kind found in mathematics and science classrooms. In particular, we focus on two processes required by complex problem solving, *definition building* and *operationalizing definitions*. These processes are strongly dependent upon (1) whether or not problems involve directed information, including clear definitions and unique solution paths, to accomplish well-defined goals; and (2) the degree to which problems are directed in the conceptualization and planning of the problem-solvers' final argument. Non-triviality and complexity in definition building and operationalizing definitions are the representative sources that trigger metacognition at the environmental level. They hold potential for revealing metacognition at the individual, and especially the social levels (e.g., Efklides, 2006; Iiskala et al., 2011; Prins, Veenman, & Elshout, 2006). The central research questions of this study are:

(1) How is metacognition elicited through the definition building and operationalizing definitions processes during complex collaborative problem solving?
(2) How does metacognition operate during complex collaborative problem solving at the individual, social, and environmental levels?

The type of complex problems we consider here are Model-Eliciting Activities (MEAs). MEAs are team-oriented, interdisciplinary, and realistic problem-solving tasks that reveal participants' thinking (Chamberlin & Moon, 2005; Diefes, Moore, Zawojewski, Imbrie, & Follman, 2004; Lesh & Doerr, 2003; Lesh, Hoover, Hole, Kelly, & Post, 2000; Moore & Diefes-Dux, 2004; Moore & Hjalmarson, 2010; Moore, Diefes-Dux, & Imbrie, 2006). They were initially created by mathematics educators as a research tool for exploring students' conceptual understanding and problem-solving strategies (Lesh et al., 2000; Lesh & Lamon, 1992). Thus, they work well as an authentic method for verbal protocol analysis, since students are required to verbalize their thoughts while working on MEAs in teams in natural classroom settings. Here, the Paper Airplane Contest MEA (described in Section 3.3) was used to explore how metacognition on multiple levels can be fostered by complex collaborative problem solving.

2. Multiple levels of metacognition

In this section, we review a subset of the expansive literature on metacognition, focusing on the distinction among the individual, social, and environmental levels. We also review the literature suggesting the utility of MEAs for studying the development of metacognition on multiple levels as authentic methodological tools and sources of metacognition at the environmental level.

This research study has adopted the Models and Modeling Perspectives (MMP) in order to study metacognition. MMP has been expanded and applied to the teaching and learning of various subjects, in particular in STEM (Science, Technology, Engineering, and Mathematics) education. The focus of MMP is on how students develop conceptual systems of interpretation that include the complexity of their daily lives and their knowledge and experiences of various content domains in collaborative modeling problem-solving settings (Lesh & Doerr, 2003). These perspectives provide new insights into metacognition compared with traditional viewpoints of metacognition (Lesh & Zawojewski, 2007; Lesh, Lester, & Hjalmarson, 2003). One focus of MMP research is on individuals' conceptual systems, including both cognitive (e.g., understanding, skills) and metacognitive (e.g., beliefs, awareness) components. The MMP assumes that both cognitive and metacognitive components within the holistic conceptual systems interactively and bi-directionally influence each other. For example, as students increase

[1] There are anecdotal examples of mathematicians and natural scientists being "stuck" on hard problems and then becoming "unstuck" on their own, following an "incubation" period lasting many days, weeks, or months (Hadamard, 1954). Indeed, the Gestalt tradition made much of the role of "incubation" in problem solving (Duncker, 1945). However, modern psychological studies have found little evidence that "incubation" plays a fundamental role in problem solving (Kaplan & Simon, 1990). Thus, the proposal that there are problems that people can solve on their own (i.e., given internal knowledge sources) and additional problems they can solve in collaboration with others (i.e., given external knowledge sources) merits investigation.