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Metacognitive support promotes an effective use of instructional resources in intelligent tutoring

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A B S T R A C T

We tested whether the provision of metacognitive knowledge on how to cope with the complexity of a learning environment improved learning. In an experimental setting, high-school students ($N = 60$) worked through a computer-based geometry lesson either with or without metacognitive support in the form of a cue card. This cue card encouraged students to use instructional resources in the learning environment (i.e., textual and graphic representations and different help facilities) more strategically. During learning, the learners' gaze and log-file data were recorded. The metacognitive support made learning more efficient (i.e., less learning time without impairing outcomes). In addition, low-prior knowledge students developed deeper conceptual understanding. The effects on learning outcomes were mediated by reducing the non-strategic use of help facilities. Our findings suggest that a lack of metacognitive conditional knowledge (i.e., in which situation to use which help facility) can account for learning difficulty in computer-based learning environments.

1. Introduction

There is a growing tendency to confront learners with rich learning tasks to prepare them for a highly dynamic and increasingly complex world (Field, 2006). This trend is reflected in complex computer-based learning environments (CBLEs) (Azevedo, 2005; Van Merriënboer & Sluijsmans, 2009). These environments offer learners multiple sources of information (Ainsworth, 2006) and a variety of help facilities (tools) serving different instructional purposes (Hannafin, Hall, Land, & Hill, 1994). On one hand, the availability of different instructional resources has the potential to stimulate beneficial learning activities (Sawyer, 2006). For example, the successful coordination and integration of information distributed over different resources offers learners opportunities to acquire a deeper level of understanding and to improve their skills in dealing with complexity (Spiro & Jehng, 1990). Therefore, CBLEs should not free learners from all instructional decisions (e.g., by adding further intelligence to an environment). On the other hand, we must acknowledge that these complex and demanding learning environments "meet" relatively limited cognitive equipment on the learners' side. This contrast contributes to the difficulty learners have in effectively regulating their learning in CBLEs, which becomes especially apparent in complex domains such as science and mathematics (e.g., Aleven & Koedinger, 2000; Azevedo, 2005; Moos & Azevedo, 2008).

1.1. What makes a computer-based learning environment complex?

A CBLE typically includes different information resources (e.g., texts, illustrations, and help facilities) intended to support understanding and learning. These resources can be functionally differentiated into resources *representing* the subject matter (e.g., principles of geometry) and resources *supporting* the acquisition of the subject matter (i.e., *help facilities* or *tools* such as a glossary). Both types of resources are often constructed of multiple external representations: A geometry word problem might be accompanied by a diagram showing known and unknown angles as described in a word problem; a definition of a geometry principle in a glossary might be illustrated by a diagram.

To make effective use of these external information resources, learners need to adequately allocate and regulate their cognitive and attentional resources during learning. However, with each additional external resource, tactical decisions as to where and when to use one or the other resource become harder to make

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(Lajoie, 1993). Multiple information sources can, therefore, easily overwhelm learners' self-regulatory capacities (Ainsworth, Bibby, & Wood, 2002). As a consequence, information resources are often used in less than optimal ways, being underused (Clarebout & Elen, 2007), or overused (e.g., Schofield, 1995), and occasionally even "misused" (see Baker, Corbett, & Koedinger, 2004).

Research on multiple external representations (e.g., Ainsworth, 2006; van Someren, Reimann, Boshuizen, & de Jong & van Joolingen, 1998) and on tool use (e.g., Aleven, Stahl, Schworm, Fischer, & Wallace, 2003; Clarebout & Elen, 2008) has contributed to our understanding of (a) typical difficulties that learners experience in complex environments, (b) typically more and less successful 'coping' strategies in complex learning environments, and (c) promising approaches to support learners to better cope with such complexity.

1.2. Multiple external representations

Information in CBLEs is typically presented as different types of external representations (e.g., text, diagrams). Research on learning from such multiple external representations is mainly interested in how learners make sense of different symbol systems (e.g., text, numbers, and realistic pictures) and how they can be combined to foster understanding and learning. Multiple external representations can fulfil (at least) three different cognitive functions. First, they can complement each other and thus provide a more complete picture of a difficult concept. For example, a verbal description of a mathematical function (e.g., $y = x^2 - 2$) is accompanied by a line drawing depicting that function. Second, multiple representations can help to constrain the interpretation of each other. For example, a scatter plot is accompanied by a table with data from which the scatter plot was drawn. Finally, and probably most importantly, they can be integrated (by the learner) to construct a more abstract internal representation of the externally presented material (Ainsworth, 2006). For example, from a scatter plot and a table presented together, learners infer a general rule about functional relationships among the data depicted.

However, learners often have difficulty learning from multiple external representations (e.g., Ainsworth et al., 2002). They frequently use different external representations in isolation, or they use only a subsample of available representations, even when a learning task strongly suggests attending to the different representations. Constructing referential connections between the concepts depicted by different external representations seems to be particular difficult for learners (Ainsworth, 2006). Some of these difficulties can be attributed to the learners' limited knowledge of the roles or functions of external representations. For example, Schwonke, Berthold, and Renkl (2009) found that even advanced learners who studied worked examples with multi-representational solutions (i.e., word problems accompanied by tree diagrams and equations) in the domain of 'probability' were largely unaware of the cognitive functions of these external representations (e.g., complementing or constraining interpretation of one another). In a subsequent intervention study, simply informing about the cognitive functions (especially of tree diagrams in the worked-out examples) led to deeper conceptual understanding of probability problems and better procedural skills in solving probability problems. The effect of providing the information on learning outcomes was mediated (i.e., was attributable to) a reduction in non-strategic inspection time of the diagrams and equations (as determined by eye-tracking analyses).

In summary, students have difficulty (a) in relating the contents of different external representations to one another and (b) in understanding how different external representations can contribute to understanding and learning.

1.3. Tools to support cognitive and metacognitive processes in CBLEs

CBLE tools are artefacts designed to support cognitive and metacognitive processes related to the actual learning task (e.g., a pocket calculator embedded in a CBLE for algebra or geometry). *Tool use* can, thus, be defined as student–system interactions (with help facilities in CBLEs) that aim to overcome or prevent problems during learning (Aleven & Koedinger, 2000). Research into tool use has described typical ways in which learners use available help facilities and how such use affects learning outcomes. Learners often ignore available tools, even when the tools have proven to be useful (Clarebout & Elen, 2007). In addition, they often use tools inadequately or at least not as intended by the instructional designers (e.g., Aleven et al., 2003; Clarebout & Elen, 2006). In a log-file analysis on how school children in a geometry course used an intelligent tutoring system (a Cognitive Tutor Geometry), Aleven and Koedinger (2002) found that students did not use errors as a signal to ask for a hint. They thus tended to wait too long before asking for help (e.g., a solution-specific hint message). When students requested help, they tended to proceed to the most solution-specific hints, "clicking" more general hints away. This "bottom-out hint strategy" indicated that at least some learners tended to use available help facilities in a non-learning-oriented way (Aleven & Koedinger, 2002). Such "gaming the system" behaviour related negatively to learning outcomes (Baker et al., 2004). However, when learners take the time to study bottom-out hints, then learning outcomes can be improved (Shih, Koedinger, & Scheines, 2008).

In summary, learners use help facilities either not enough, not at the right occasion, too much, or for the "wrong" purpose. Learners have difficulty in mapping help facilities to impasses during learning, especially in deciding when to refer to which type of support.

1.4. How to explain suboptimal use of information resources in CBLE?

In most CBLEs, learners decide much on their own whether, when, and how to make use of available information resources. Within the context of this self-regulated nature of using external resources (Karabenick, 2011), theories of self-regulated learning (SRL; e.g., Boekaerts, 1999; Schiefele & Pekrun, 1996; Winne, 1996; Winne & Perry, 2000) can serve as a framework for the role of external resource use. Self-regulated learning is described as the behaviourally, metacognitively, and motivationally active participation in one's own learning (Zimmerman, 1986). Self-regulated learners employ cognitive strategies (e.g., elaboration) to achieve learning goals. Choice of strategies, their application, and the quality of the outcomes of strategy application are embedded into and controlled by metacognitive activities such as planning, monitoring, and self-evaluation (Zimmerman, 1990). Metacognitive knowledge as the knowledge about factors affecting cognitive activities (Flavell, 1979) refers to three broad categories: the person, task, and strategies. In Flavell's classic definition, the 'task' category includes information about a proposed task that is available to a person, including knowledge about tangible resources necessary for task completion. As such, knowledge about information resources belongs to this category.

Contemporary models of SRL such as the *four-stage model of SRL* (e.g., Winne & Perry, 2000) differentiate between two broad knowledge categories: (a) knowledge about cognitive conditions (e.g., knowledge of study tactics and strategies; domain knowledge) and (b) knowledge about task conditions (e.g., knowledge about instructional cues, time, and social context). Here, knowledge about external resources belongs to the 'task conditions' category.