MetaTutor: A MetaCognitive Tool for Enhancing Self-Regulated Learning

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Abstract
Learning about complex and challenging science topics with advanced learning technologies requires students to regulate their learning. The deployment of key cognitive and metacognitive regulatory processes is key to enhancing learning in open-ended learning environments such as hypermedia. In this paper, we propose a metaphor—Computers as MetaCognitive tools—to characterize the complex nature of the learning context, self-regulatory processes, task conditions, and features of advanced learning technologies. We briefly outline the theoretical and conceptual assumptions of self-regulated learning (SRL) underlying MetaTutor, a hypermedia environment designed to train and foster students’ SRL processes in biology. Lastly, we provide preliminary learning outcome and SRL process data on the deployment of SRL processes during learning with MetaTutor.

1. Introduction
Learning about conceptually-rich domains with advanced learning technologies requires students to regulate their learning (Jacobson, 2008). Current research from cognitive and learning sciences provides ample evidence that learners have difficulty learning about these domains. This research indicates that the complex nature of the learning content, internal and external conditions, and contextual environment requirements are particularly difficult because they require students to regulate their learning (Azevedo, 2008). Regulating one’s learning involves analyzing the learning context, setting and managing meaningful learning goals, determining which learning strategies to use, assessing whether the strategies are effective in meeting the learning goals, evaluating emerging understanding of the topic, and determining whether there are aspects of the learning context which could be used to facilitate learning. During SRL, students need to deploy several metacognitive processes and make judgments necessary to determine whether they understand what they are learning, and perhaps modify their plans, goals, strategies, and effort in relation to dynamically changing contextual conditions. In addition, students must also monitor, modify, and adapt to fluctuations in their motivational and affective states, and determine how much social support (if any) may be needed to perform the task. Also, depending on the learning context, instructional goals, perceived task performance, and progress made towards achieving the learning goal(s), they may need to adaptively modify certain aspects of their cognition, metacognition, motivation, and affect (Azevedo & Witherspoon, in press; Winne, 2005).

Despite the ubiquity of such environments for learning, the majority of the research has been criticized as atheoretical and lacking rigorous empirical evidence (see Azevedo, 2008; Azevedo & Jacobson, 2008; Jacobson, 2008). In order to advance the field and our understanding of the complex nature of learning with advanced learning technologies such as hypermedia-based environments, we need theoretically-guided, empirical research regarding how students regulate their learning with these environments.

In this paper, we provide an overarching metaphor—“computers as MetaCognitive tools”—to highlight the complex nature of the use of computer-based learning environments (CBLEs) (Azevedo, 2005a). We also present an overview and basic assumptions of SRL models followed by a global description of SRL with hypermedia. This is followed by a synthesis of extensive product and process data from our lab regarding the role of key SRL processes and the role of adaptive scaffolding in designing an adaptive MetaTutor. We also provide an overview of MetaTutor, a hypermedia learning environment designed to train and foster high school and college students’ learning about several biological systems. We present the results of an initial study aimed at examining the effectiveness of MetaTutor on the deployment of key SRL processes during learning.

The history of CBLEs spans decades (see Wolff, 2009) and is replete with examples of multimedia, hypermedia, intelligent tutoring systems and simulations used to enhance students’ learning. However, their widespread use and rapid proliferation has surpassed our fundamental understanding of the scientific and educational potential of these tools to enhance learning. For example, researchers and designers are developing advanced learning technologies that integrate several technologies (e.g., adaptive hypermedia-based mixed-initiative tutoring systems with pedagogical agents) to train, model, and
foster critical learning skills needed for students to remain competitive in the 21st century. This example illustrates the need to for a framework which allows researchers, designers, and educators to understand the role of CBLEs and the multidimensional aspects associate with learning with CBLEs.

One approach to understanding the landscape and the various uses of CBLEs is to impose a metaphor—computers as MetaCognitive tools (Azevedo, 2005a,b, 2008). The use of this term has at least two meanings. First, it is meant that current applications of CBLEs go beyond the development or training of cognitive skills (e.g., acquisition of declarative knowledge or the development of procedural knowledge), and that meta-level aspects of learning are critical for acquiring life-long skills. The use of the term highlights the complex nature of the multitude of contextually-bound learning processes. In addition, we also use “meta” to include meta-level (i.e., going beyond cognitive) aspects include metacognition as well as other internal (e.g., motivational and affective states) and external (e.g., assistance from external regulatory agents such as adaptive scaffolding) aspects of learning. A macro-view would include the critical aspects of the learning context, types of regulatory processes, tasks conditions, and features of the CBLE that comprise the foundation for the metaphor of computers as MetaCognitive tools.

We broadly define a computer environment as a MetaCognitive tool as one that is designed for instructional purposes and uses technology to support the learner in achieving the goals of instruction. This may include any type of technology-based tool, such as an intelligent tutoring system, an interactive learning environment, hypermedia, multimedia, a simulation, microworld, collaborative learning environment, etc. The characteristics explicitly stated by Lajoie (2000) and several others (e.g., Lajoie & Azevedo, 2006), serve as the foundational basis for the metaphor of computers as metacognitive tools. The definition subsumes the characteristics of a computer as a cognitive tool, in that the tool can (a) assist learners to accomplish cognitive tasks by supporting cognitive processes, (b) share the cognitive load by supporting lower-level cognitive skills so that learners may focus on higher-level thinking skills, (c) allow learners to engage in cognitive activities that would be out of their reach otherwise because there may be no opportunities for participating in such tasks (e.g., electronic troubleshooting, medical diagnosis; see Lajoie & Azevedo, 2006), and (d) allow learners to generate and test hypotheses in the context of problem solving.

As such, a metacognitive tool is any computer environment, which in addition to adhering to Lajoie’s definition of cognitive tool, also has the following additional characteristics:

- **a)** it requires students to make instructional decisions regarding instructional goals (e.g., such as setting learning goals, sequencing instruction, seeking, collecting, organizing, and coordinating instructional resources, deciding which embedded and contextual tools to use and when to use them in order to support their learning goals, deciding which representations of information to use, attend to, and perhaps modify in order to meet instructional goals);
- **b)** it is embedded in a particular learning context which may require students to make decisions regarding the context in ways which support and may lead to successful learning (e.g., how much support is needed from contextual resources, what types of contextual resources may facilitate learning, locating contextual resources, when to seek contextual resources, determining the utility and value of contextual resources);
- **c)** it models, prompts, and supports a learners’ self-regulatory processes (to some degree) which may include cognitive (e.g., activating prior knowledge, planning, creating sub-goals, learning strategies), metacognitive (e.g., feeling of knowing, judgment of learning, evaluate emerging understanding), motivational (e.g., self-efficacy, task value, interest, effort), affective (e.g., frustration, surprise, delight), or behavior (e.g., engaging in help-seeking behavior, modifying learning conditions; handling task difficulties and demands);
- **d)** it models, prompts, and supports learners (to some degree) to engage or participate (alone, with a peer, or within a group) in using task-, domain-, or activity-specific learning skills (e.g., skills necessary to engage in online inquiry and collaborative inquiry), which also are necessary for successful learning;
- **e)** it resides in a specific learning context where peers, tutors, humans or artificial agents may play some role in supporting students’ learning by serving as external regulating agents;
- **f)** it is any environment where the learner’s use and deployment of key metacognitive and self-regulatory processes prior to, during, and following learning that are critical for successful learning. As such, this involves capturing, modeling, and making inferences based on the temporal deployment of a myriad of self-regulatory processes. The capturing, modeling, and inferences may occur at some level of granularity, be accomplished by the learner, environment, and/or some other external agent(s) (human, artificial) and the capturing of these processes can occur at some level of specificity and can be used for various instructional purposes (i.e., from understanding the development of these skills) to accurately model, track, and foster SRL, and perhaps also used to make instructional decisions (at some level of specificity) as how best to support learning.
- **g)** it should also be noted that not all CBLEs include characteristics a) –f) and that the choice of which
aspects to choose from are based on theoretical assumptions about the nature of learning, educational philosophy, the goal and purpose of the tool, and a fundamental conceptualization regarding the role of external agents (human or artificial).

3. Self-Regulated Learning and MetaTutor

Self-regulated learning (SRL) has become an influential theoretical framework in psychological and educational research (Azevedo, 2009; Boekaerts et al., 2000; Dunlosky & Bjork, 2008; Hacker, Dunlosky, & Graesser, in press; Winne & Hadwin, 2008; Zimmerman, 2008). SRL is an active, constructive process whereby learners set learning goals and then attempt to monitor, regulate, and control their cognitive and metacognitive processes in the service of those goals. We acknowledge that SRL also includes other key processes such as motivation, and affect; however, we limit our research to the underlying cognitive and metacognitive processes during learning about complex science. The focus of SRL research over the last three decades has been on academic learning and achievement, with researchers exploring the means by which students regulate their cognition, metacognition, motivation, and task engagement. With this context in mind, the current scientific and educational challenge is to investigate comprehensively the effectiveness of (pedagogical agents) PAs on SRL processes during learning with hypermedia-based, intelligent tutoring systems like MetaTutor.

MetaTutor is based on several assumptions regarding the role of SRL during learning about complex and challenging science topics. First, learners need to regulate their SRL processes to effectively integrate multiple representations (i.e., text and diagram) while learning complex science topics in CBLEEs (Azevedo, 2008, 2009; Mayer, 2005; Niederhauser, 2008). Second, students have the potential to regulate their learning but are not always successful for various reasons, such as extraneous cognitive load imposed by the instructional material (Sweller, 2006); lack of or inefficient use of cognitive strategies (Pressley & Hilden, 2006); lack of metacognitive knowledge or inefficient regulatory control of metacognitive processes (Dunlosky & Bjork, 2008; Veenman, 2007); lack of prior knowledge (Shapiro, 2008); or developmental differences or limited experience with instructional practices requiring the integration of multiple representations or nonlinear learning environments (Azevedo & Witherspoon, in press).

Third, the integration of multiple representations during complex learning with hypermedia environments involves the deployment of a multitude of self-regulatory processes. Macro-level processes involve executive and metacognitive processes necessary to coordinate, allocate, and reallocate cognitive resources, and mediate perceptual and cognitive processes between the learner’s cognitive system and external aspects of the task environment. Mid-level processes such as learning strategies are used to select, organize, and integrate multiple representations of the topic (e.g., Ainsworth, 1999; Schnotz, 2005). These same mid-level control processes are also necessary to exert control over other contextual components that are critical during learning (Aleven et al., 2003; Roll et al., 2007). Researchers have identified several dozen additional learning strategies including coordination of informational sources, summarizing, note-taking, hypothesizing, drawing, etc. (Azevedo, 2008).

Fourth, little is understood regarding the nature of SRL processes involved in the integration of multiple external representations that are needed to build internal knowledge representations that support deep conceptual understanding, problem solving, and reasoning (Goldman, 2003). Lastly, a critical issue centers on the development and effective use of cognitive and metacognitive processes in middle school and high school students (Lockl & Schneider, 2002).

In sum, the last two sections have provided an overview of SRL, described the information-processing of Winne and Hadwin, and followed-up with a more detailed description of the SRL processes used when learning with a hypermedia learning environment. This leads to a synthesis of our extensive product and process data that was collected, classified, and analyzed, based on theoretical frameworks and models of SRL models.

4. MetaTutor: A Hypermedia Learning Environment for Biology

MetaTutor is a hypermedia learning environment that is designed to detect, model, trace, and foster students’ self-regulated learning about human body systems such as the circulatory, digestive, and nervous systems (Azevedo et al., 2008, 2009). Theoretically, it is based on cognitive models of self-regulated learning (Pintrich et al., 2000; Schunk, 2005; Winne & Hadwin, 2008; Zimmerman, 2008). The underlying assumption of MetaTutor is that students should regulate key cognitive and metacognitive processes in order to learn about complex and challenging science topics. The design of MetaTutor is based on extensive research by Azevedo and colleagues’ showing that providing adaptive human scaffolding, that addresses both the content of the domain and the processes of self-regulated learning, enhances students’ learning about challenging science topics with hypermedia (e.g., see Azevedo, 2008; Azevedo & Witherspoon, in press for extensive reviews of the research). Overall, our research has identified key self-regulatory processes that are indicative of students’ learning about these complex science topics. More specifically, they include several processes related to planning, metacognitive monitoring,
learning strategies, and methods of handling task difficulties and demands.

Overall, there are several phases to using MetaTutor to train students on SRL processes and to learn about the various human body systems. The various phases include (1) modeling of key SRL processes, (2) discrimination task where learners choose between good and poor use of these processes, (3) a detection task where learners get to see video clips of human agents engage in similar learning tasks and are asked to stop the video whenever they see the use of a SRL processes (and then they have to indicate the process from a list), and (4) the actual learning environment used to learn about the biological system.

The interface of the actual learning environment is comprised of a learning goal (either set by the experimenter or teacher; e.g., *Your task is to learn all you can about the circulatory system. Make sure you know about its components, how they work together, and how they support the healthy functioning of the human body*), and is associated with the sub-goals box where the learner can generate several sub-goals for the learning session. A list of topics and sub-topics are presented on the left-side of the interface, while the actual science content (including the text, static and dynamic representations of information) are presented in the center of the interface. The main communication dialogue box (between the learner and the environment) is found directly below the content box. The pedagogical agents are available and reside on the top right-hand corner of the interface. In this case, Mary the Monitor is available to assist the learner through the process of evaluating his/her understanding of the content. Below the agent box is a list of SRL processes that the learner can use throughout the learning session. Specifically, the learner can select the SRL process he/she is about to use by highlighting it. The goal of having learners select the processes is to enhance metacognitive awareness of the processes used during learning and to facilitate the environment’s ability to trace, model, and foster learning. In addition to learner-initiated SR, the agent can prompt learners to engage in planning, monitoring, or strategy use under appropriate conditions traced by MetaTutor.

The purpose of the MetaTutor project is to examine the effectiveness of animated pedagogical agents as external regulatory agents used to detect, trace, model, and foster students’ self-regulatory processes during learning about complex science topics. MetaTutor is in its infancy, thus the algorithms to guide feedback to the student are not yet developed and tested. The challenge will be to provide feedback both on the accuracy of the content, as well as the appropriateness of the strategies being used by the student. Current machine learning methods for detecting students’ evolving mental models of the circulatory system are being tested and implemented (Rus, Lintean, & Azevedo, 2009), as well as specific macro- and micro-adaptive tutoring methods based on detailed system traces of learners’

### 5. Preliminary Data on SRL with MetaTutor

During the past year we collected data using the current non-adaptive version with 66 college students and 18 high school students. The data show that the students have little declarative knowledge of key SRL processes. They also tend to learn relatively little about the circulatory system in two-hour sessions when they need to regulate their own learning (Azevedo et al., 2008, 2009). In particular, both college and high school students show small to medium effect sizes ($d = 0.47$ to 0.66) for pretest-posttest shifts across several researcher-developed measures tapping declarative, inferential, and mental models of the body systems.

Newly analyzed data from the current think-aloud protocols with the non-adaptive version of MetaTutor show some very important results that will be used to design and develop the adaptive version. The coded concurrent think-aloud data from 44 (out of 66) participants is also extremely informative in terms of the frequency of use of each SRL class (e.g., monitoring) and the processes within each class (e.g., FOK and JOL are part of monitoring). Overall, the data indicate that learning strategies were deployed most often (77% of all SRL processes deployed during the learning task) followed by metacognitive judgments (nearly 16% of all SRL processes). On average, learners used approximately two learning strategies every minute and made a metacognitive judgment approximately once every four minutes while using the non-adaptive version of MetaTutor during a 60-minute learning session.

Figure 1 represents another approach to examining the fluctuation of SRL processes over time. This figure illustrates average frequencies of four classes of SRL over a 60-minute learning session in our initial MetaTutor experiment. To examine trends and changes in SRL over time, the 60-minute sessions were divided into six 10-minute segments, as indicated by the x-axis. The y-axis indicates average frequency of the four classes of SRL: planning, monitoring, learning strategies, and handling task difficulty and demands. Learning strategies show the highest trend throughout the learning session, peaking in the first 20 minutes and gradually declining as the session progresses. Monitoring processes have the second highest frequency, although they appear to occur far less frequently than learning strategies (averaging less than five times for each time interval). Despite the low frequency of monitoring processes, it is still a step in the right direction to see learning strategies and monitoring occurring most frequently during the session, because these two classes are assumed to be the central hubs of SRL. Processes related to planning and handling task difficulty and demands occur...
least frequently, and do not occur at all in many time intervals.

Figure 1. Proportion of SRL Processes (by Class) during a 60-minute learning task with MetaTutor.

A closer examination of the same data by SRL processes within each class is even more revealing. On average, these same learners are learning about the biology content by taking notes, previewing the captions, re-reading the content, and correctly summarizing what they have read more often than any other strategy. Unfortunately, they are not using other key learning strategies (e.g., coordinating informational sources, drawing, knowledge elaboration) that are associated with conceptual gains (see Azevedo, 2009; Greene & Azevedo, 2009). Another advantage of converging concurrent think-aloud data with time-stamped video data is that we can calculate the mean time spent on each learning strategy. For example, an instance of taking notes lasts an average of 20 seconds while drawing lasts an average of 30 seconds. Learners are making FOK, JOL, and content evaluation more often than any other metacognitive judgment. These judgments tend to last an average of 3–9 seconds. Such data demonstrate the need for an adaptive MetaTutor, and will be useful in developing new modules.

Overall, this data shows the complex nature of the SRL processes during learning with MetaTutor. We have used quantitative and qualitative methods to converge process and product data to understand the nature of learning outcomes and the deployment of SRL processes. The data will be used to design an adaptive version of MetaTutor that is capable of providing the adaptive scaffolding necessary to foster students’ learning and use of key SRL processes. It is extremely challenging to think about how to build an adaptive MetaTutor system designed to detect, trace, model, and foster SRL about complex and challenging science topics. The next section will address these challenges in turn.

6. Acknowledgements

The research presented in this paper has been supported by funding from the National Science Foundation (Early Career Grant DRL 0133346, DRL 0633918, DRL 0731828, HCC 0841835) awarded to the first author. The authors thank M. Cox, R. Anderson, H. Skinner, and J. Wood for the collection of data, transcribing and data scoring. The authors would also like to thank M. Lintean, Z. Cai, V. Rus, A. Graesser, and D. McNamara for design and development of the MetaTutor.

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