

Chapter 11

Self-regulated Learning with MetaTutor: Advancing the Science of Learning with MetaCognitive Tools

Roger Azevedo, Amy Johnson, Amber Chauncey, and Candice Burkett

Cognition and Technology Research Lab, Department of Psychology, Institute for Intelligent Systems, University of Memphis, Memphis, TN, USA

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 (Chi, 2005). 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 self-regulated learning (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 toward achieving the learning goal(s), they may need to adaptively modify certain aspects of their cognition, metacognition, motivation, and affect (Azevedo & Witherspoon, 2009; Winne, 2005).

R. Azevedo (✉)

Cognition and Technology Research Lab, Department of Psychology, Institute for Intelligent Systems, University of Memphis, Memphis, TN, USA
e-mail: razevedo@memphis.edu

To appear in: In M. S. Khine & I.M. Saleh (Eds.), *New Science of Learning: Computers, Cognition, and Collaboration in Education*.

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. Lastly, we provide theoretically driven and empirically based guidelines for supporting learners' self-regulated learning with MetaTutor.

Metaphor: MetaCognitive Tools for Enhancing Learning

The history of CBLEs spans decades (see Koedinger & Corbett, 2006; Lajoie, 2000; Lajoie & Azevedo, 2006; Shute & Psotka, 1996; Shute & Zapata-Rivera, 2008; Woolf, 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 have 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 twenty-first century. This example illustrates the need for a framework that allows researchers, designers, and educators to understand the role of CBLEs and the multidimensional aspects associated 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, 2005b, 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 metalevel 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 metalevel (i.e., going beyond cognitive) aspects including 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. Figure 11.1 provides a macroview of the critical aspects of the learning context, types of regulatory processes, task 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, a microworld, or a collaborative learning environment. The characteristics explicitly stated by Lajoie (1993, p. 261) and several others (see Derry & Lajoie, 1993; Jonassen & Land, 2000; Jonassen & Reeves,

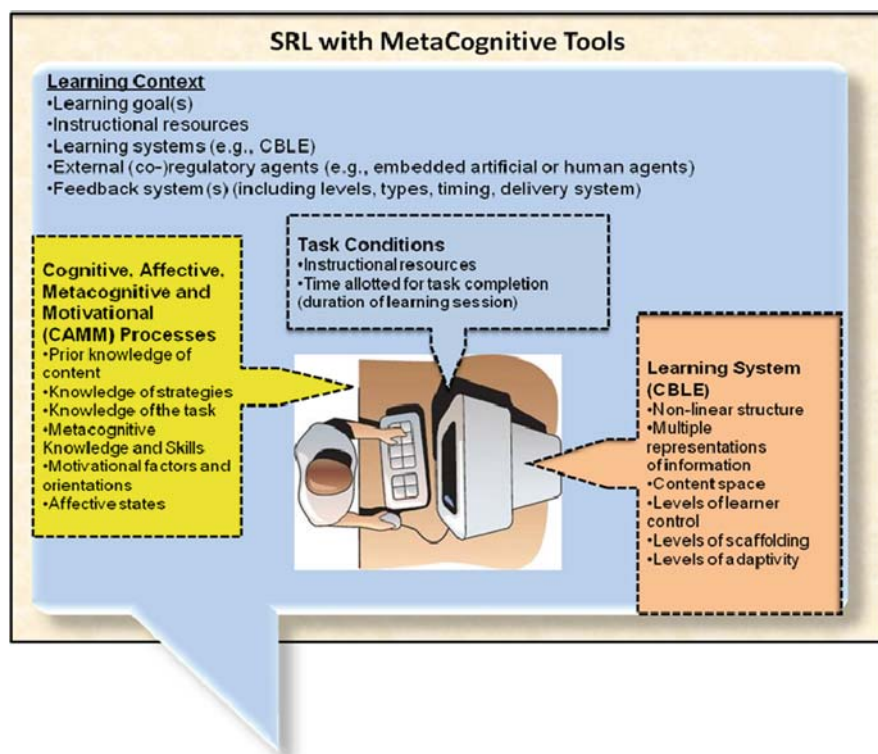


Fig. 11.1 A macroview of the variables associated with using computers as MetaCognitive tools for learning

1996; Lajoie, 1993, 2000; Lajoie & Azevedo, 2006; Pea, 1985; Perkins, 1985) 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 in accomplishing 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 (1993) definition of cognitive tool, also has the following additional characteristics:

- (a) *it requires students to make instructional decisions regarding instructional goals* (e.g., 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 that 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 learners' self-regulatory processes (to some degree)* which may include cognitive (e.g., activating prior knowledge, planning, creating subgoals, learning strategies), metacognitive (e.g., feeling of knowing [FOK], judgment of learning [JOL], evaluate emerging understanding), motivational (e.g., self-efficacy, task value, interest, effort), affective (e.g., frustration, confusion, boredom), or behavior (e.g., engaging in help-seeking behavioral, 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 deploys key metacognitive and self-regulatory processes prior to, during, and following 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 and be accomplished by the learner, environment, or some other external agent(s) (human, artificial). The capturing of these processes can occur at some level of specificity and 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 to make instructional decisions (at some level of specificity) on 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 is 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).

Theoretical Framework: Self-regulated Learning

SRL has become an influential theoretical framework in psychological and educational research (Azevedo, 2007, 2008, 2009; Boekaerts, Pintrich, & Zeidner, 2000; Dunlosky & Metcalfe, 2009; Dunlosky & Bjork, 2008; Hacker, Dunlosky, & Graesser, 1998, 2009; Metcalfe, 2009; Paris & Paris, 2001; Schunk, 2008; Schunk & Zimmerman, 2008; Winne & Hadwin, 2008; Zimmerman, 2006, 2008; Zimmerman & Schunk, 2001, in press). *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 (see Pintrich & Zusho, 2002; Schunk & Zimmerman, 2006; Wigfield, Eccles, Schiefele, Roeser, & Davis-Kean, 2006). 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.

Addressing our national science learning challenges requires a theoretically driven and empirically based approach (Pashler et al., 2007). Winne and Hadwin's (1998, 2008) model is currently the only contemporary model that provides phases, processes, and emphasis on metacognitive monitoring and control as the "hubs" of SRL. The model has been empirically tested in several complex educational situations (e.g., Azevedo et al., 2008) and makes assumptions regarding the (linear and iterative) nature and temporal deployment of SRL processes that fit perfectly

with our current research (e.g., Azevedo, 2007, 2008; Witherspoon, Azevedo, & D'Mello, 2008). The model allows researchers to derive testable hypotheses regarding the complex nature of metacognitive monitoring and control, as well as the complex cycles that a learner and system undergo.

Winne and Hadwin (1998, 2008) posit that learning occurs in four basic phases: task definition, goal-setting and planning, studying tactics, and adaptations to metacognition. Winne and Hadwin's SRL model also differs from others in that it hypothesizes that an information-processing (IP)-influenced set of processes occurs within each phase. Using the acronym COPEs, Winne and Hadwin describe each phase in terms of the interaction of a person's conditions, operations, products, evaluations, and standards. All of the terms except operations are kinds of information that a person uses or generates during learning. It is within this COPEs architecture that the work of each phase is completed. Thus, the model complements other SRL models by introducing a more complex description of the processes underlying each phase.

Through monitoring, a person compares products with standards to determine if phase objectives have been met or if further work remains to be done. These comparisons are called cognitive evaluations; a poor fit between products and standards may lead a person to enact control over the learning operations to refine the product, revise the conditions and standards, or both. This is the object-level focus of monitoring. However, this monitoring also has a metalevel or metacognitive focus. A student may believe that a particular learning task is easy, and thus translate this belief into a standard in Phase 2. However, when iterating in Phase 3, the learning product might be consistently evaluated as unacceptable in terms of object-level standards. This would initiate metacognitive monitoring that determines that this metalevel information (in this case task difficulty) does not match the previously set standard that the task is easy. At this point, a metacognitive control strategy might be initiated where that particular standard is changed ("this task is hard"), which might in turn affect other standards created during the goal setting of Phase 2. These changes to goals from Phase 2 may include a review of past material or the learning of a new study strategy. Thus, the model is a "recursive, weakly sequenced system" (Winne & Hadwin, 1998, p. 281) where the monitoring of products and standards within one phase can lead to updates of products from previous phases. The inclusion of monitoring and control in the cognitive architecture allows these processes to influence each phase of self-regulated learning.

While there is no typical cycle, most learning involves re-cycling through the cognitive architecture until a clear definition of the task has been created. The next phase produces learning goals and the best plan to achieve them, which leads to the enacting of strategies to begin learning. The products of learning (e.g., understanding of the circulatory system) are compared against standards that include the overall accuracy of the product, the learner's beliefs about what needs to be learned, and other factors such as efficacy and time restraints. If the product does not fit the standard adequately, then further learning operations are initiated, perhaps with changes to conditions such as setting aside more time for studying. Finally, after the

main learning process, students may make more long-term alterations to the strategies that make up SRL, such as the addition or deletion of conditions or operations, as well as changes to the ways conditions cue operations (Winne, 2001). The output (performance) is the result of recursive processes that cascade back and forth, altering conditions, standards, operations, and products as needed. In sum, this complex model leads to several assumptions that have guided the design and development of MetaTutor.

Theoretical Assumptions about SRL and 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 CBLEs (Azevedo, 2008, 2009; Jacobson, 2008; 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; Siegler, 2005); lack of metacognitive knowledge or inefficient regulatory control of metacognitive processes (Dunlosky & Bjork, 2008; Dunlosky & Metcalfe, 2009; Dunlosky, Rawson, & McDonald, 2002, 2005; Hacker et al., 2009; Schraw, 2006; Schraw & Moshman, 1995; Veenman, Van Hout-Wolters, & Afflerbach, 2006); 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, 2009; Pintrich & Zusho, 2002).

Third, the integration of multiple representations during complex learning with hypermedia environments involves the deployment of a multitude of self-regulatory processes. *Macrolevel 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 (Ainsworth, 1999, 2006; Mayer, 2001, 2005; Schnotz, 2005). These same mid-level control processes are also necessary to exert control over other contextual components that are critical during learning (Aleven, Stahl, Schworm, Fischer, & Wallace, 2003; Newman, 2002; Roll, Aleven, McLaren, & Koedinger, 2007). Researchers have identified several dozen additional learning strategies including coordinating informational sources, summarizing, note-taking, hypothesizing, drawing, etc. (Azevedo, 2008; Van Meter & Garner, 2005).

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 (Cox, 1999; Goldman, 2003; Kozma, 2003; Mayer, 2005; Schnotz & Bannert, 2003; Seufert et al., 2007; Witherspoon et al., 2008). Lastly, a critical issue centers on the development and effective use of cognitive and metacognitive processes in middle school and high school students (Baker & Cerero, 2000; Borkowski, Chan, & Muthukrishna, 2000; Lockl & Schneider, 2002; Pintrich, Wolters, & Baxter, 2000; Pressley, 2000; Schneider & Lockl, 2002, 2008; Veenman et al., 2006).

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.

Synthesis of SRL Data on Learning with Hypermedia

In this section, we present a synthesis of the research on SRL and hypermedia conducted by our team over the last 10 years, focusing explicitly on deployment of self-regulatory processes, and the effectiveness of different types of scaffolding in facilitating students' learning of complicated science topics. More specifically, we have focused on laboratory and classroom research to address the following questions: (1) Do different scaffolding conditions influence students' ability to shift to more sophisticated mental models of complex science topics? (2) Do different scaffolding conditions lead students to gain significantly more declarative knowledge of science topics? (3) How do different scaffolding conditions influence students' ability to regulate their learning of science topics with hypermedia? (4) What is the role of external regulating agents (i.e., human tutors, classroom teachers, and peers) in students' SRL of science topics with hypermedia? (5) Are there developmental differences in college and high school students' ability to self-regulate their learning of science with hypermedia?

In general, our empirical results show that learning challenging science topics with hypermedia can be facilitated if students are provided with adaptive human scaffolding that addresses both the content of the domain and the processes of SRL (see Azevedo, 2008 for effect sizes by type of scaffolding, developmental group, and learning outcome). This type of sophisticated scaffolding is effective in facilitating learning, as indicated by medium to large effect sizes (range of $d = 0.5\text{--}1.1$) on several measures of declarative, procedural, and inferential knowledge and mental models. In contrast, providing students with either no scaffolding or fixed scaffolds (i.e., a list of domain-specific subgoals) tends to lead to negligible shifts in their mental models and only small gains in declarative knowledge in older students.

Verbal protocols provide evidence that students in different scaffolding conditions deploy different key SRL processes, providing a clear association between these scaffolding conditions, mental model shifts, and declarative knowledge gains. To date, we have investigated 38 different regulatory processes related to

planning, monitoring, learning strategies, methods of handling task difficulties and demands, and interest (see Azevedo et al., 2008 for a sample of the SRL processes and for details). These studies have shown some interesting developmental differences. Compared to college students, high school students tend to use fewer and less-sophisticated self-regulatory processes to regulate their learning with hypermedia. Specifically, they fail to create subgoals, monitor aspects of the learning environment (e.g., content evaluation, CE), or evaluate their own cognitive processes (e.g., feeling of knowing, FOK) or emerging understanding (e.g., JOL). Furthermore, they use less effective learning strategies such as copying information verbatim from the learning environment to their notes. The data also indicate that certain key self-regulatory processes related to planning, metacognitive monitoring, and learning strategies are not used during the integration process with multiple representations during hypermedia learning. This leads to declarative knowledge gains but failure to show qualitative mental model shifts related to understanding these complex topics.

Students in the fixed scaffolding conditions tend to regulate learning by monitoring activities that deal with the hypermedia learning environment (other than their own cognition), and use more ineffective learning strategies. By contrast, external regulation by a human tutor leads students to regulate their learning by activating prior knowledge and creating subgoals; monitoring their cognitive system by using FOK and JOL; using effective strategies such as summarizing, making inferences, drawing, and engaging in knowledge elaboration; and, not surprisingly, engaging in an inordinate amount of help-seeking from the human tutor (Azevedo et al., 2005a, 2006; Greene & Azevedo, 2009).

In a recent study, Azevedo and colleagues (2008) examined the effectiveness of SRL and externally regulated learning (ERL) on college students' learning about a science topic with hypermedia during a 40 min session. A total of 82 college students with little knowledge of the topic were randomly assigned either to the SRL or ERL condition. Students in the SRL condition regulated their own learning, while students in the ERL condition had access to a human tutor who facilitated their SRL. We converged product (pretest–posttest declarative knowledge and qualitative shifts in participants' mental models) with process (think-aloud) data to examine the effectiveness of SRL versus ERL. Analysis of the declarative knowledge measures showed that the ERL condition group mean was statistically significantly higher than the group mean for the SRL condition on the labeling and flow diagram tasks. There were no statistically significant differences between groups on the matching task, but both groups showed statistically significant increases in performance. Further analyses showed that the odds of being in a higher mental model posttest group were decreased by 65% for the SRL group as compared to the ERL group. In terms of SRL behavior, participants in the SRL condition engaged in more selecting of new information sources, rereading, summarizing, free searching, and enacting of control over the context of their learning. In comparison, the ERL participants engaged in more activation of prior knowledge, utilization of FOK and JOL, monitoring of their progress toward goals, drawing, hypothesizing, coordination of information sources, and expressing task difficulty.

In sum, our existing data stresses that learning about complex science topics involves deploying key self-regulatory processes during learning with hypermedia. These include several planning processes (creating subgoals, activating prior knowledge), metacognitive judgments (about emerging understanding, relating new content with existing knowledge), and learning strategies (coordinating informational sources, drawing, summarizing). In addition, the use of these processes can be facilitated by adaptive scaffolding by an external agent. In the next section, we describe the MetaTutor environment.

MetaTutor: A Hypermedia Learning Environment for Biology

MetaTutor is a hypermedia learning environment that is designed to detect, model, trace, and foster students' SRL about human body systems such as the circulatory, digestive, and nervous systems (Azevedo et al., 2008). Theoretically, it is based on cognitive models of SRL (Pintrich, 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 SRL enhances students' learning about challenging science topics with hypermedia (e.g., see Azevedo, 2008; Azevedo & Witherspoon, 2009 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. Figure 11.2 has four screen shots that illustrate the various phases including (1) modeling of key SRL processes (see top-left corner), (2) a discrimination task where learners choose between good and poor use of these processes (see top-right corner), (3) a detection task where learners watch video clips of human agents engaging in similar learning tasks and are asked to stop the video whenever they see the use of an SRL process (and then indicate the process from a list) (see bottom-right corner), and (4) the actual learning environment used to learn about the biological system (see bottom-left corner).

The interface of the actual learning environment contains a learning goal set by either 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*). The learning goal is associated with the subgoals box where the learner can generate several subgoals for the learning session. A list of topics and subtopics is presented on the left side of the interface, while the actual science content (including the text,

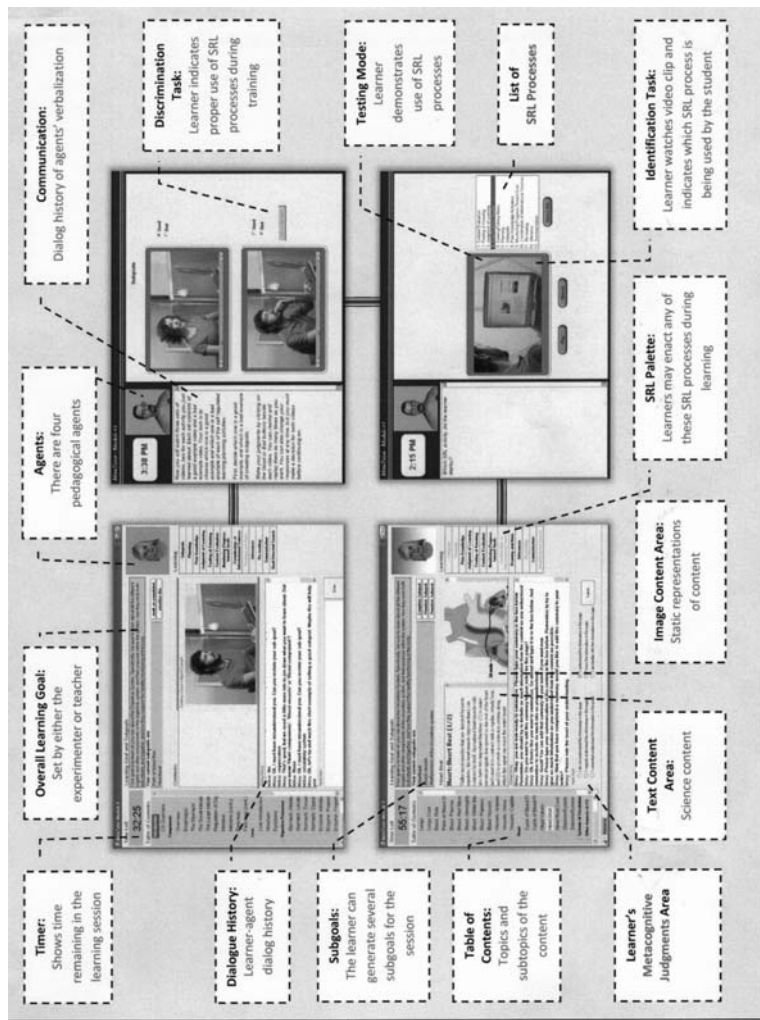


Fig. 11.2 Screenshots of MetaTutor

static, and dynamic representations of information) is 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 in the top right-hand corner of the interface. In this case, Mary the Monitor is available to assist learners through the process of evaluating their understanding of the content. Below the agent box is a list of SRL processes that learners can use throughout the learning session. Specifically, learners can select the SRL process they are 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, and thus the algorithms to guide feedback to the student have not yet been developed or tested. The challenge will be to provide feedback on both 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 microadaptive tutoring methods based on detailed system traces of learners' navigational paths through the MetaTutor system (Witherspoon et al., 2009). In the next section, we present data collected from an initial study using MetaTutor.

Preliminary Data on SRL with MetaTutor

During the past year we collected data using the current nonadaptive 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 2 h 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 ($d = 0.47$ – 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 *concurrent think-aloud protocols* with the nonadaptive 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 60) participants are 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, during a 60 min learning session learners used approximately two learning strategies every minute and made a metacognitive judgment approximately once every 4 min while using the nonadaptive version of MetaTutor.

Figure 11.3 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 min learning session in our initial MetaTutor experiment. To examine trends and changes in SRL over time, the 60 min sessions were divided into six 10 min 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 min 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 fewer 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.

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 s while drawing lasts an average of 30 s. Learners are

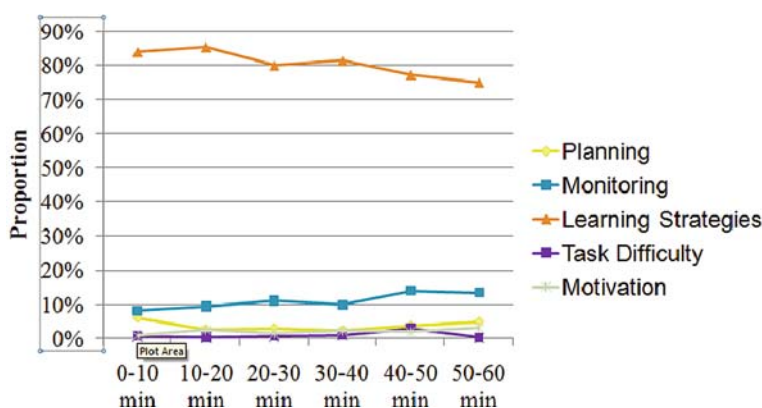


Fig. 11.3 Proportion of SRL processes (by class) during a 60 min learning task with MetaTutor

making FOK, JOL, and content evaluation more often than any other metacognitive judgment. These judgments tend to last an average of 3–9 s. Such data demonstrate the need for an adaptive MetaTutor, and will be useful in developing new modules.

The *log-file data* have also been mined to investigate the navigational paths and explore the behavioral signatures of cognitive and metacognitive processing while students use MetaTutor (Witherspoon, Azevedo, & Cai, 2009). It should be noted that MetaTutor traces learners' behavior within the environment and logs every learner interaction into a log file. These trace data are critical in identifying the role and deployment of SRL processes during learners' navigation through the science content. We conducted a cluster analysis using five navigational variables: (1) percentage of 'linear forward' transitions (e.g., p. 1 to p. 2); (2) percentage of 'linear backward' transitions (e.g., p. 2 to p. 1); (3) percentage of 'nonlinear' transitions (e.g., p. 3 to p. 7); (4) percentage of category shifts (from one subheading to another); and (5) percentage of image openings.

From this quantitative analysis, we found four major profiles of learners. One group tended to remain on a linear path within the learning environment, progressing from one page to the next throughout the session (average of 90% linear navigations). Another group demonstrated a large amount of nonlinear navigation (average of 36% of the time), while a third group opened the image a majority of the time (78% on average). The fourth group of learners was more balanced in their navigation, navigating nonlinearly on average 18% of the time, and opening the image accompanying the page of content 39% of the time. Further analysis revealed that learners in this fourth, "balanced" group scored significantly higher on composite learning outcome measures. An adaptive MetaTutor system should scaffold balanced navigational behavior.

A qualitative analysis of MetaTutor's traces of learners' navigational paths during each learning session was also performed (see Witherspoon et al., 2009 for a complete analysis). The work here is emphasizing the need to examine how various types of navigational paths are indicative (or not) of strategic behavior expected from self-regulating learners (Winne, 2005). Figures 11.4a and b illustrate the navigational paths of two learners from our dataset while they use MetaTutor to learn about the circulatory system. In Fig. 11.4a and b, the x -axis represents move x and the y -axis represents $x+1$. Figure 11.4a shows the path of a low performer (i.e., small pretest–posttest learning gains) while Fig. 11.4b illustrates the path of a high performer. These figures highlight the qualitative differences between a low and high performer in terms of the linear vs. complex navigational paths and reading times. For example, the low performer tended to progress linearly through the content until he got to a key page (e.g., p. 16 on blood vessels) and decided to return to a previous page. In contrast, the high performer's path is more complicated and is more consistent with a strategic, self-regulated learner by the complexity shown in Fig. 11.4b. This learner progresses linearly, at times makes strategic choices about returning to previously visited pages, and deploys twice as many SRL processes as the low-performing learner (i.e., 212 moves vs. 102 moves, respectively). This is symbolically illustrated in the figures by the difference between the "space" between the dots—i.e., more space between dots = longer reading times.

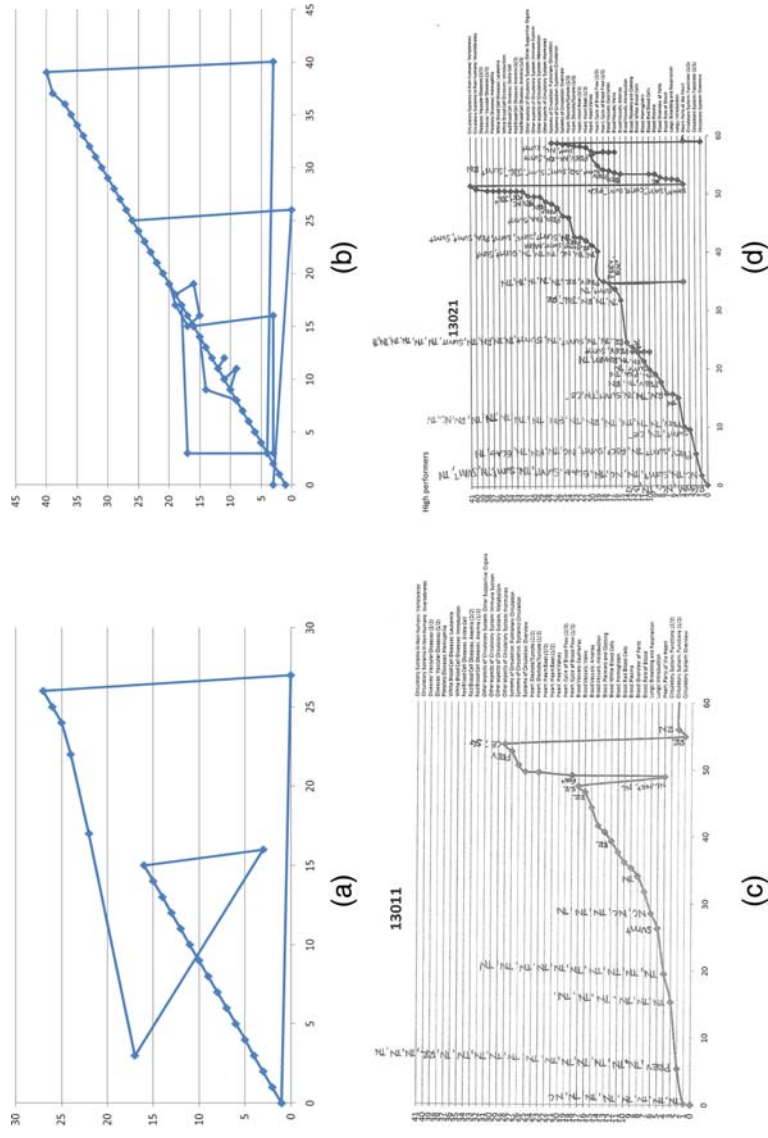


Fig. 11.4 Trace of a low-high mental model jumper during learning with hypermedia. (a) Navigational path of a low performer (#3011). (b) Navigational path of a high performer (#3021). (c) Navigational path of a low performer (#3011) with SRL processes annotated by hand. (d) Navigational path of a high performer (#3021) with SRL processes annotated by hand

The SRL processes deployed were handwritten on their navigational paths and presented in Fig. 11.4c and d. In Fig. 11.4c and d, the *x*-axis represents time (in minutes) within the learning session and the *y*-axis represents pages of content (and their corresponding titles). There are several key observations to highlight in terms of keeping with our goal of extracting information for the design of the adaptive MetaTutor. First, there is more complexity in the navigational paths and deployment of SRL processes as seen in the number of processes handwritten in the figures. Second, 70% of the low performer's SRL moves were coded as taking notes while the high performer only used 39% of his processes for taking notes. Third, one can infer (from the "space" between moves) that the low performer spent more time acquiring knowledge (reading the science content) from the environment while the high performer spent less time reading throughout the session. Fourth, the high performer used a wider variety of SRL processes compared to the low performer. A related issue is the nonstrategic move by the low performer to create a new subgoal near the end of the learning session. However, the high performer is more strategic in his self-regulatory behavior throughout the learning session. For example, he engages in what can best be characterized as "time-dependent SRL cycles." These cycles involve creating subgoals, previewing the content, acquiring knowledge from the multiple representations, taking notes, reading notes, evaluating content, activating prior knowledge, and periodically monitoring understanding of the topic.

Overall, these data show 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.

Implications for the Design of an Adaptive MetaTutor

In the next section, we highlight some general and specific design challenges that need to be addressed in order to build an adaptive MetaTutor system.

General challenges. Our results have implications for the design of the adaptive MetaTutor hypermedia environments intended to foster students' learning of complex and challenging science topics. Given the effectiveness of adaptive scaffolding conditions in fostering students' mental model shifts, it would make sense for a MetaCognitive tool such as MetaTutor to emulate the regulatory behaviors of the human tutors. In order to facilitate students' understanding of challenging science topics, the system would ideally need to dynamically modify its scaffolding methods to foster the students' self-regulatory behavior during learning. However,

these design decisions should also be based on the successes of current adaptive computer-based learning environments for well-structured tasks (e.g., Koedinger & Corbett, 2006; Graesser, Jeon, & Dufty, 2008; VanLehn et al., 2007; Woolf, 2009), technological limitations in assessing learning of challenging and conceptually rich, ill-structured topics (e.g., Brusilovsky, 2001; Jacobson, 2008; Azevedo, 2008), and conceptual issues regarding what, when, and how to model certain key self-regulated learning processes in hypermedia environments (Azevedo, 2002). Current computational methods from AI and educational data mining (e.g., Leelawong & Biswas, 2008; Schwartz et al., 2009) need to be explored and tested to build a system designed to detect, trace, and model learners' deployment of self-regulated processes. Other challenges associated with having the system detect the qualitative shifts in students' mental models of the topic must be circumvented by using a combination of embedded testing, frequent quizzing about sections of the content, and probing for comprehension.

As for SRL processes, our data show that learners are using mainly ineffective strategies and they tend to use up to 45 min of the 60 min session using these processes. In contrast, the same data show learners use key metacognitive processes but they may last a short period of time (up to 9 seconds). The challenge for an adaptive MetaTutor is for it to be sensitive enough to detect the deployment of these processes and to accurately classify them. Aggregate data from state-transition matrices are also key in forming the subsequent instructional decision made by the system. All this information would then have to be fed to the system's students and instructional modules in order to make decisions regarding macro- and microlevel scaffolding and tailor feedback messages to the learner. Associated concerns include keeping a running model of the deployment of SRL processes (including the level of granularity, frequency, and valence; e.g., monitoring, JOL, and JOL-) and evolving understanding of the content and other learning measures. This history would be necessary to make inferences about the quality of students' evolving mental models and the quality of the SRL processes.

To be most effective in fostering SRL, adaptive hypermedia learning environments must have the capacity to both scaffold effective SRL and provide timely and appropriate feedback. In this section we focus on two specific and important modules for an adaptive MetaTutor that provide these critical components.

Scaffolding module. Scaffolding is an important step in facilitating students' conceptual understanding of a topic and the deployment of SRL processes (Azevedo & Hadwin, 2005; Pea, 2004; Puntabmbekar & Hubscher, 2005). Critical aspects include the agents' ability to provide different types of scaffolding depending on the students' current level of conceptual understanding in relation to the amount of time left in a learning session, and also their navigation paths and whether they have skipped relevant pages and diagrams related to either their current subgoal or the overall learning goal for the session. In addition, we need to figure in how much scaffolding students may have already received and whether it was effective in facilitating their mastery of the content. The proposed adaptive MetaTutor may start by providing generic scaffolding that binds specific content to specific SRL processes (e.g., intro to any section of content is prompted by scaffolding to

preview, skimming the content, evaluating the content vis-à-vis the current sub-goal, and then determining whether to pursue or abandon the content) versus a fine-grained scaffolding that is time-sensitive and fosters qualitative changes in conceptual understanding. This approach fits with extensive research on human and computerized tutoring (Azevedo et al., 2007, 2008; Chi et al., 2004; Graesser et al., 2008). One of the challenges for the adaptive MetaTutor will be to design graduated scaffolding methods that fluctuate from ERL (i.e., a student observes as the agent assumes instructional control and models a particular strategy or metacognitive process to demonstrate its effectiveness) to fading all support once the student has demonstrated mastery of the content. Our current data on SRL processes show that learners are making FOK, JOL, and content evaluation (CE) more often than any other metacognitive judgment. However, they are deploying these processes very infrequently. Thus, agents could be designed to prompt students to explicitly engage in these key metacognitive processes more frequently during learning. Another level of scaffolding would involve coupling particular metacognitive processes with optimal learning strategies. For example, if students articulate that they do not understand a certain paragraph (i.e., JOL-), then a prompt to re-read is ideal. In contrast, students who report that they understand a paragraph (i.e., JOL+) should be prompted to continue reading the subsequent paragraph or inspect the corresponding diagram.

Feedback module. Feedback is a critical component in learning (Koedinger & Corbett, 2006; VanLehn et al., 2007). The issues around feedback include the timing and type of feedback. Timing is important because feedback should be provided soon after one makes an incorrect inference or incorrectly summarizes text or a diagram. The type of feedback is related to whether the agents provide knowledge of results after a correct answer, inference, etc., or elaborative feedback, which is difficult to create because it requires knowing the student's learning history and therefore relies heavily on an accurate student model. For example, a key objective of this project is to determine which and how many learner variables must be traced for the system to accurately infer the students' needs for different types of feedback. We emphasize that feedback will also be provided for content understanding and use of SRL processes. The data may show that a student is using ineffective strategies, and therefore the agent may provide feedback by alerting the student to a better learning strategy (e.g., summarizing a complex biological pathway instead of copying it verbatim).

Summary

Learning with MetaCognitive tools involves the deployment of key SRL processes. We have articulated and explicitly described the metaphor of computers as MetaCognitive tools. We provided an overview of SRL and provided a description of the importance of using SRL as a framework to understand the complex nature of learning with MetaCognitive tools. We provided a synthesis of our previous work and how it was used to design the MetaTutor system. We then provided preliminary

data on the MetaTutor and discussed how this data can be used to design an adaptive version of MetaTutor to detect, trace, model, and foster students' SRL about complex and challenging science topics.

Acknowledgments 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, A. Fike, and R. Anderson for 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 MetaTutor.

References

- Ainsworth, S. (1999). The functions of multiple representations. *Computers & Education*, 33, 131–152.
- Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction*, 16, 183–198.
- Aleven, V., Stahl, E., Schworm, S., Fischer, F., & Wallace, R. M. (2003). Help seeking and help design in interactive learning environments. *Review of Educational Research*, 73(2), 277–320.
- Azevedo, R. (2002). Beyond intelligent tutoring systems: Computers as MetaCognitive tools to enhance learning? *Instructional Science*, 30(1), 31–45.
- Azevedo, R. (2005a). Computers as metacognitive tools for enhancing learning. *Educational Psychologist*, 40(4), 193–197.
- Azevedo, R. (2005b). Using hypermedia as a metacognitive tool for enhancing student learning? The role of self-regulated learning. *Educational Psychologist. Special Issue: Computers as Metacognitive Tools for Enhancing Student Learning*, 40(4), 199–209.
- Azevedo, R. (2007). Understanding the complex nature of self-regulatory processes in learning with computer-based learning environments: An introduction. *Metacognition and Learning*, 2(2/3), 57–66.
- Azevedo, R. (2008). The role of self-regulation in learning about science with hypermedia. In D. Robinson & G. Schraw (Eds.), *Recent innovations in educational technology that facilitate student learning* (pp. 127–156). Charlotte, NC: Information Age Publishing.
- Azevedo, R. (2009). Theoretical, methodological, and analytical challenges in the research on metacognition and self-regulation: A commentary. *Metacognition and Learning*, 4(1), 87–95.
- Azevedo, R., & Hadwin, A. F. (2005). Scaffolding self-regulated learning and metacognition: Implications for the design of computer-based scaffolds. *Instructional Science*, 33, 367–379.
- Azevedo, R., & Jacobson, M. (2008). Advances in scaffolding learning with hypertext and hypermedia: A summary and critical analysis. *Educational Technology Research & Development*, 56(1), 93–100.
- Azevedo, R., & Witherspoon, A. M. (2009). Self-regulated use of hypermedia. In D. J. Hacker, J. Dunlosky, & A. C. Graesser (Eds.), *Handbook of metacognition in education* (pp. 319–339). New York, NY: Routledge.
- Azevedo, R., Greene, J. A., & Moos, D. C. (2007). The effect of a human agent's external regulation upon college students' hypermedia learning. *Metacognition and Learning*, 2(2/3), 67–87.
- Azevedo, R., Cromley, J. G., Winters, F. I., Moos, D. C., & Greene, J. A. (2006). Using computers as metacognitive tools to foster students' self-regulated learning. *Technology, Instruction, Cognition, and Learning Journal*, 3, 97–104.
- Azevedo, R., Witherspoon, A., Chauncey, A., Burkett, C., & Fike, A. (2009). MetaTutor: A MetaCognitive tool for enhancing self-regulated learning. In R. Pirrone, R. Azevedo, & G. Biswas (Eds.), *Proceedings of the AAAI Fall Symposium on Cognitive and Metacognitive Educational Systems* (pp. 14–19). Menlo Park, CA: Association for the Advancement of Artificial Intelligence (AAAI) Press.

- Azevedo, R., Witherspoon, A. M., Graesser, A., McNamara, D., Rus, V., Cai, Z., et al. (2008). *MetaTutor: An adaptive hypermedia system for training and fostering self-regulated learning about complex science topics*. Paper to be presented at a Symposium on ITSs with Agents at the Annual Meeting of the Society for Computers in Psychology, Chicago.
- Baker, L., & Cerro, L. (2000). Assessing metacognition in children and adults. In G. Schraw & J. Impara (Eds.), *Issues in the measurement of metacognition* (pp. 99–145). Lincoln, NE: University of Nebraska-Lincoln.
- Biswas, G., Leelawong, K., Schwartz, D., & the Teachable Agents Group at Vanderbilt. (2005). Learning by teaching: A new agent paradigm for educational software. *Applied Artificial Intelligence*, 19, 363–392.
- Boekaerts, M., Pintrich, P., & Zeidner, M. (2000). *Handbook of self-regulation*. San Diego, CA: Academic Press.
- Borkowski, J., Chan, L., & Muthukrishna, N. (2000). A process-oriented model of metacognition: Links between motivation and executive functioning. In G. Schraw & J. Impara (Eds.), *Issues in the measurement of metacognition* (pp. 1–42). Lincoln, NE: University of Nebraska-Lincoln.
- Brusilovsky, P. (2001). Adaptive hypermedia. *User Modeling and User-Adapted Interaction*, 11, 87–110.
- Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences*, 14(2), 161–199.
- Chi, M. T. H., Siler, S., & Jeong, H. (2004). Can tutors monitor students' understanding accurately? *Cognition and Instruction*, 22, 363–387.
- Cox, R. (1999). Representation construction, externalized cognition and individual differences. *Learning and Instruction*, 9, 343–363.
- Derry, S. J., & Lajoie, S. P. (1993). *Computers as cognitive tools*. Hillsdale, NJ: Erlbaum.
- Dunlosky, J., & Bjork, R. (Eds.) (2008). *Handbook of metamemory and memory*. New York: Taylor & Francis.
- Dunlosky, J., & Metcalfe, J. (2009). *Metacognition*. Thousand Oaks, CA: Sage Publications, Inc.
- Dunlosky, J., Hertzog, C., Kennedy, M., & Thiede, K. (2005). The self-monitoring approach for effective learning. *Cognitive Technology*, 9, 4–11.
- Dunlosky, J., Rawson, K. A., & McDonald, S. L. (2002). Influence of practice tests on the accuracy of predicting memory performance for paired associates, sentences, and text material. In T. J. Perfect & B. L. Schwartz (Eds.), *Applied metacognition* (pp. 68–92). Cambridge: Cambridge University Press.
- Dunlosky, J., Rawson, K. A., & Middleton, E. L. (2005). What constrains the accuracy of metacomprehension judgments? Testing the transfer-appropriate-monitoring and accessibility hypotheses. *Journal of Memory and Language. Special Issue: Metamemory*, 52, 551–565.
- Goldman, S. (2003). Learning in complex domains: When and why do multiple representations help? *Learning and Instruction*, 13, 239–244.
- Graesser, A. C., Jeon, M., & Duffy, D. (2008). Agent technologies designed to facilitate interactive knowledge construction. *Discourse Processes*, 45, 298–322.
- Greene, J. A., & Azevedo, R. (2009). A macro-level analysis of SRL processes and their relations to the acquisition of a sophisticated mental model of a complex system. *Contemporary Educational Psychology*, 34(1), 18–29.
- Hacker, D. J., Dunlosky, J., & Graesser, A. C. (Eds.) (1998). *Metacognition in educational theory and practice*. Mahwah, NJ: Erlbaum.
- Hacker, D., Dunlosky, J., & Graesser, A. (2009) (Eds.), *Handbook of Metacognition in Education*. New York, NY: Routledge.
- Jacobson, M. (2008). A design framework for educational hypermedia systems: Theory, research, and learning emerging scientific conceptual perspectives. *Educational Technology Research & Development*, 56, 5–28.
- Jonassen, D. H., & Land, S. M. (2000). *Theoretical foundations of learning environments*. Mahwah, NJ: Erlbaum.

- Jonassen, D., & Reeves, T. (1996). Learning with technology: Using computers as cognitive tools. In D. Jonassen (Ed.), *Handbook of research for educational communications and technology* (pp. 694–719). New York: Macmillan.
- Koedinger, K., & Corbett, A. (2006). Cognitive tutors: Technology bringing learning sciences to the classroom. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 61–77). New York: Cambridge University Press.
- Kozma, R. (2003). The material features of multiple representations and their cognitive and social affordances for science understanding. *Learning and Instruction*, 13(2), 205–226.
- Lajoie, S. P. (1993). Computer environments as cognitive tools for enhancing learning. In S. Derry & S. P. Lajoie (Eds.), *Computers as cognitive tools* (pp. 261–288). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Lajoie, S. P. (Ed.) (2000). *Computers as cognitive tools II: No more walls: Theory change, paradigm shifts and their influence on the use of computers for instructional purposes*. Mahwah, NJ: Erlbaum.
- Lajoie, S. P., & Azevedo, R. (2006). Teaching and learning in technology-rich environments. In P. Alexander & P. Winne (Eds.), *Handbook of educational psychology* (2nd ed., pp. 803–821). Mahwah, NJ: Erlbaum.
- Leelawong, K., & Biswas, G. (2008). Designing learning by teaching agents: The Betty's Brain system. *International Journal of Artificial Intelligence in Education*, 18(3), 181–208.
- Lockl, K., & Schneider, W. (2002). Developmental trends in children's feeling-of-knowing judgments. *International Journal of Behavioral Development*, 26, 327–333.
- Mayer, R. E. (2001). *Multimedia learning*. New York: Cambridge University Press.
- Mayer, R. E. (2005). Cognitive theory of multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 31–48). New York: Cambridge University Press.
- Metcalfe, J. (2009). Metacognitive judgments and control of study. *Current Directions in Psychological Science*, 18, 159–163.
- Newman, R. S. (2002). What do I need to do to succeed ... When I don't understand what I'm doing!?: Developmental influences on students' adaptive help seeking. In A. Wigfield & J. Eccles (Eds.), *Development of achievement motivation* (pp. 285–306). San Diego, CA: Academic Press.
- Niederhauser, D. (2008). Educational hypertext. In M. Spector, D. Merrill, J. van Merriënboer, & M. Driscoll (Eds.), *Handbook of research on educational communications and technology* (pp. 199–209). New York: Taylor & Francis.
- Paris, S. G., & Paris, A. H. (2001). Classroom applications of research on self-regulated learning. *Educational Psychologist*, 36(2), 89–101.
- Pashler, H., Bain, P., Bottge, B., Graesser, A., Koedinger, K., McDaniel, M., et al. (2007). *Organizing Instruction and Study to Improve Student Learning*. Washington, DC: National Center for Education Research, Institute of Education Sciences, U.S. Department of Education. NCER 2007-2004. Retrieved September 10, 2008, from <http://ncer.ed.gov>.
- Pea, R. D. (1985). Beyond amplification: Using the computer to reorganize mental functioning. *Educational Psychologist*, 20, 167–182.
- Pea, R. D. (2004). The social and technological dimensions of scaffolding and related theoretical concepts for learning, education, and human activity. *Journal of the Learning Sciences*, 13(3), 423–451.
- Perkins, D. N. (1985). Postprimary education has little impact on informal reasoning. *Journal of Educational Psychology*, 77(5), 562–571.
- Pintrich, P. R. (2000). The role of goal orientation in self-regulated learning. In M. Boekaerts, P. Pintrich, & M. Zeidner (Eds.), *Handbook of self-regulation* (pp. 451–502). San Diego, CA: Academic Press.
- Pintrich, P., Wolters, C., & Baxter, G. (2000). Assessing metacognition and self-regulated learning. In G. Schraw & J. Impara (Eds.), *Issues in the measurement of metacognition* (pp. 43–97). Lincoln, NE: University of Nebraska-Lincoln.

- Pintrich, P., & Zusho, A. (2002). The development of academic self-regulation: The role of cognitive and motivational factors. In A. Wigfield & J. S. Eccles (Eds.), *Development of achievement motivation* (pp. 249–284). San Diego, CA: Academic Press.
- Pressley, M. (2000). Development of grounded theories of complex cognitive processing: Exhaustive within- and between study analyses of think-aloud data. In G. Schraw & J. Impara (Eds.), *Issues in the measurement of metacognition* (pp. 261–296). Lincoln, NE: University of Nebraska-Lincoln.
- Pressley, M., & Hilden, K. (2006). Cognitive strategies. In D. Kuhn & R. S. Siegler (Eds.), *Handbook of child psychology: Volume 2: Cognition, perception, and language* (6th ed., pp. 511–556). Hoboken, NJ: Wiley.
- Puntambekar, S., & Hübscher, R. (2005). Tools for scaffolding students in a complex learning environment: What have we gained and what have we missed? *Educational Psychologist*, 40 (1), 1–12.
- Roll, I., Aleven, V., McLaren, B., & Koedinger, K. (2007). Designing for metacognition—Applying cognitive tutor principles to metacognitive tutoring. *Metacognition and Learning*, 2(2–3), 125–140.
- Rus, V., Lintean, M., & Azevedo, R. (2009). *Automatic detection of student models during prior knowledge activation with MetaTutor*. Paper submitted for presentation at the Biennial Meeting on Artificial Intelligence and Education, Brighton, UK.
- Schneider, W., & Lockl, K. (2002). The development of metacognitive knowledge in children and adolescents. In T. J. Perfect & L. B. Schwartz (Eds.), *Applied metacognition* (pp. 224–257). Cambridge: Cambridge University Press.
- Schneider, W., & Lockl, K. (2008). Procedural metacognition in children: Evidence for developmental trends. In J. Dunlosky & R. Bjork (Eds.), *Handbook of metamemory and memory* (pp. 391–409). New York: Taylor & Francis.
- Schnotz, W. (2005). An integrated model of text and picture comprehension. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 49–69). New York: Cambridge University Press.
- Schnotz, W., & Bannert, M. (2003). Construction and interference in learning from multiple representation. *Learning and Instruction*, 13, 141–156.
- Schraw, G. (2006). Knowledge: Structures and processes. In P. Alexander & P. Winne (Eds.), *Handbook of educational psychology* (pp. 245–263). Mahwah, NJ: Erlbaum.
- Schraw, G., & Moshman, D. (1995). Metacognitive theories. *Educational Psychology Review*, 7, 351–371.
- Schunk, D. (2005). Self-regulated learning: The educational legacy of Paul R. Pintrich. *Educational Psychologist*, 40(2), 85–94.
- Schunk, D. (2008). Attributions as motivators of self-regulated learning. In D. Schunk & B. Zimmerman (Eds.), *Motivation and self-regulated learning: Theory, research, and applications* (pp. 245–266). Mahwah, NJ: Erlbaum.
- Schunk, D., & Zimmerman, B. (2006). Competence and control beliefs: Distinguishing the means and ends. In P. Alexander & P. Winne (Eds.), *Handbook of educational psychology* (2nd ed.). Mahwah, NJ: Erlbaum.
- Schunk, D., & Zimmerman, B. (2008). *Motivation and self-regulated learning: Theory, research, and applications*. Mahwah, NJ: Erlbaum.
- Schwartz, D. L., Chase, C., Wagster, J., Okita, S., Roscoe, R., Chin, D., & Biswas, G. (2009). Interactive metacognition: Monitoring and regulating a teachable agent. In D. J. Hacker, J. Dunlosky, and A. C. Graesser (Eds.), *Handbook of metacognition in education* (pp. 340–359). New York: Routledge.
- Seufert, T., Janen, I., & Brünken, R. (2007). The impact of intrinsic cognitive load on the effectiveness of graphical help for coherence formation. *Computers in Human Behavior*, 23, 1055–1071.
- Shapiro, A. (2008). Hypermedia design as learner scaffolding. *Educational Technology Research & Development*, 56(1), 29–44.

- Shute, V., & Psotka, J. (1996). Intelligent tutoring systems: Past, present, and future. In D. Jonassen (Ed.), *Handbook of research for educational communications and technology* (pp. 570–600). New York: Macmillan.
- Shute, V. J., & Zapata-Rivera, D. (2008). Adaptive technologies. In J. M. Spector, D. Merrill, J. van Merriënboer, & M. Driscoll (Eds.), *Handbook of research on educational communications and technology* (3rd ed., pp. 277–294). New York: Lawrence Erlbaum Associates, Taylor & Francis Group.
- Siegler, R. S. (2005). Children's learning. *American Psychologist*, 60, 769–778.
- Sweller, J. (2006). The worked example effect and human cognition. *Learning and Instruction*, 16(2), 165–169.
- Van Meter, P., & Garner, J. (2005). The promise and practice of learner-generated drawing: Literature review and synthesis. *Educational Psychology Review*, 17(4), 285–325.
- VanLehn, K., Graesser, A. C., Jackson, G. T., Jordan, P., Olney, A., & Rose, C. P. (2007). When are tutorial dialogues more effective than reading? *Cognitive Science*, 31(1), 3–62.
- Veenman, M., Van Hout-Wolters, B., & Afflerbach, P. (2006). Metacognition and learning: Conceptual and methodological considerations. *Metacognition and Learning*, 1, 3–14.
- Wigfield, A., Eccles, J., Schiefele, U., Roeser, R., & Davis-Kean, P. (2006). Development of achievement motivation. In W. Damon, R. Lerner, & N. Eisenberg (Eds.), *Handbook of child psychology* (vol. 3). New York: Wiley.
- Winne, P. H. (2001). Self-regulated learning viewed from models of information processing. In B. Zimmerman & D. Schunk (Eds.), *Self-regulated learning and academic achievement: Theoretical perspectives* (pp. 153–189). Mahwah, NJ: Erlbaum.
- Winne, P. (2005). Key issues on modeling and applying research on self-regulated learning. *Applied Psychology: An International Review*, 54(2), 232–238.
- Winne, P. H., & Hadwin, A. F. (1998). Studying as self-regulated learning. In D. J. Hacker, J. Dunlosky, & A. Graesser (Eds.), *Metacognition in educational theory and practice* (pp. 277–304). Hillsdale, NJ: Erlbaum.
- Winne, P., & Hadwin, A. (2008). The weave of motivation and self-regulated learning. In D. Schunk & B. Zimmerman (Eds.), *Motivation and self-regulated learning: Theory, research, and applications* (pp. 297–314). Mahwah, NJ: Erlbaum.
- Winne, P. H., & Nesbit, J. C. (2009). Supporting self-regulated learning with cognitive tools. In D. J. Hacker, J. Dunlosky, & A. C. Graesser (Eds.), *Handbook of metacognition in education* (pp. 259–277). New York, NY: Routledge.
- Witherspoon, A., Azevedo, R., & D'Mello, S. (2008). The dynamics of self-regulatory processes within self- and externally-regulated learning episodes. In B. Woolf, E. Aimeur, R. Nkambou, & S. Lajoie (Eds.), *Proceedings of the International conference on intelligent tutoring systems: Lecture Notes in Computer Science* (LNCS 5091, pp. 260–269). Berlin: Springer.
- Witherspoon, A., Azevedo, R., & Cai, Z. (2009). *Learners' exploratory behavior within MetaTutor*. Poster presented at the 14th international conference on Artificial Intelligence in Education, Brighton, UK.
- Woolf, B. (2009). *Building intelligent interactive tutors: Student-centered strategies for revolutionizing e-learning*. Amsterdam: Elsevier.
- Zimmerman, B. (2006). Development and adaptation of expertise: The role of self-regulatory processes and beliefs. In K. Ericsson, N. Charness, P. Feltovich, & R. Hoffman (Eds.), *The Cambridge handbook of expertise and expert performance* (pp. 705–722). New York: Cambridge University Press.
- Zimmerman, B. (2008). Investigating self-regulation and motivation: Historical background, methodological developments, and future prospects. *American Educational Research Journal*, 45(1), 166–183.
- Zimmerman, B., & Schunk, D. (2001). *Self-regulated learning and academic achievement* (2nd ed.). Mahwah, NJ: Erlbaum.
- Zimmerman, B. & Schunk, D. (Eds.) (in press). *Handbook of self-regulation of learning and performance*. New York: Routledge.