Using Hypermedia as a Metacognitive Tool for Enhancing Student Learning? The Role of Self-Regulated Learning

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Research shows that learners of all ages have difficulties deploying key cognitive and metacognitive self-regulatory skills during learning about complex and challenging topics when using open-ended learning environments such as hypermedia. This article provides an overview of the research my students and I have conducted on how the use of self-regulated learning can foster and enhance students’ learning about complex science topics using hypermedia. In this article, the term metacognitive tool is used deliberately to highlight (a) the role of metacognitive and self-regulatory processes used by learners during learning and (b) the role of computer environments in prompting, supporting, and modeling students’ self-regulatory processes during learning in specific learning contexts (see Azevedo, 2005). I provide an overview of research regarding the use of hypermedia to learn about complex science topics and learning more generally, illustrate how self-regulated learning can be used as a guiding theoretical framework to examine learning with hypermedia, and provide a synthesis of the laboratory and classroom research conducted by our group. Last, I propose several methods for using our findings to facilitate students’ self-regulated learning of complex and challenging science topics.

Computer-based learning environments (CBLEs) are effective to the extent that they can adapt to the needs of individual learners, for example, by systematically and dynamically providing scaffolding of key processes during learning (Anderson, Corbett, Koedinger, & Pelletier, 1995; Derry & Lajoie, 1993; Lajoie, 2000; Shute & Psoytka, 1996). The ability of CBLEs to provide adaptive, individualized instruction rests on an understanding of how learner characteristics, system features, and mediating learning processes interact within particular contexts. A critical means of providing individualized instruction is through scaffolding, or instructional support in the form of guides, strategies, and tools that are used during learning to support a level of understanding that would be impossible to attain if students learned on their own (Collins, Brown, & Newman, 1989; Hogan & Pressley, 1997; Wood, Bruner, & Ross, 1976). Despite our ability to provide scaffolding of learning of well-structured tasks within traditional CBLEs such as intelligent tutoring systems (ITSs, e.g., Aleven & Koedinger, 2002), providing adaptive scaffolding for students’ learning about conceptually challenging domains, such as the circulatory system and ecology, remains a challenge for hypermedia instruction. We argue that harnessing the full power of hypermedia learning environments will require empirical research aimed at understanding what kinds of scaffolds are effective in facilitating self-regulated learning (SRL) and when they are best deployed. Our research therefore focuses on examining the effectiveness of different kinds of human scaffolding in facilitating undergraduate, high school, and middle school students’ learning about the circulatory system and ecology using hypermedia learning environments. The empirical results of our research are then used to inform the design of adaptive hypermedia learning environments.

The purpose of this article is to present an analysis of the current research on learning with hypermedia; provide an overview of SRL; propose SRL as a guiding framework within which to examine the complex and dynamic interplay between learner characteristics, system features, and learning context; present our model of SRL with hypermedia; and present the results of our lab and classroom research based on our model of SRL. Last, I discuss how the results of our studies can be applied to inform the design of adaptive
hypermedia learning environments that can detect, trace, model, and foster students' SRL about complex and challenging science topics.

CBEs TO FOSTER STUDENTS’ LEARNING OF SCIENCE TOPICS

The use of computer-based learning environments (CBEs) to foster students’ learning of complex and challenging science topics now has a 30-year history (see Derry & Lajoie, 1993; Goldman, Petrosino, & Cognition and Technology Group at Vanderbilt, 1999; Graesser, McNamara, & VanLehn, 2005; Jacobson & Kozma, 2000; Jonassen & Land, 2000; Jonassen & Reeves, 1996; Lajoie, 2000; Lajoie & Azevedo, in press; Land & Hannafin, 2000; Mandinach & Cline, 2000; Pea, 1985; Mathan & Koedinger, 2005; Shute & Potska, 1996; White & Frederiksen, 2005). However, the recent widespread use of technological tools such as Web-based learning environments, hypermedia, and other open-ended learning environments has raised several theoretical, empirical, and educational issues that, if left unanswered, may undermine the potential of these powerful learning environments to foster students’ learning (Azevedo, 2002; Clark, 2004; Mayer, 2003; Shapiro & Neiderhauser, 2004). Theoretically, understanding the underlying learning mechanisms that mediate students’ learning with such environments lags in comparison to the technological advances that have made these same environments commonplace in homes, schools, and at work. We therefore need to conduct research to fully understand the complex nature of the learning mechanisms that may facilitate students’ learning with these environments. Empirically, we need more research that uses multiple methods and levels of converging data to better understand the complex nature of learning with computer-based learning environments. Educationally, we need theory and evidence to drive instructional decisions for the effective use of computers as metacognitive tools. Given the strong interest in and widespread use of these new technologies for teaching and learning, there is a need to extend our current theoretical frameworks, establish a solid research base of replicated findings based on rigorous and appropriate research methods, and apply the findings to inform the design of CBEs (Mayer, 2003).

The majority of the research in the area of learning with hypermedia has been criticized as being atheoretical and lacking rigorous empirical evidence (see Dillon & Gabbard, 1998; Tergan, 1997a, 1997b; Shapiro & Neiderhauser, 2004, for extensive reviews). To advance the field and our understanding of the complex nature of learning with such hypermedia environments, we need theoretically guided, empirical evidence regarding how students regulate their learning in these environments. In this article, I make the argument that SRL should be used as a guiding framework within which to examine learning with hypermedia environments.

SRL is a theoretical framework that can encompass the complexity of learning with hypermedia, and can account for learner characteristics (e.g., prior knowledge, age), hypermedia system features (e.g., access to multiple representations of information, nonlinear structure of information), and mediating contextual learning processes (e.g., metacognitive skills, strategy use), while also considering how these various aspects interact during students’ learning about complex systems. Before proposing SRL as a guiding framework with which to examine complex learning with hypermedia, I will provide a brief overview of the existing research on learning about complex science topics with hypermedia.

STUDENTS’ LEARNING OF COMPLEX SCIENCE TOPICS

Understanding complex and challenging science topics is a critical part of learning and is crucial for solving real-world problems (National Research Council, 2005). However, such topics have many characteristics that make them difficult to understand (Hmelo, Holdan, & Kolodner, 2000; Jacobson & Archodidou, 2000). For example, to have a coherent understanding of the circulatory system, a learner must comprehend a multitude of intricate multilevel systems of relations and feedback loops that exist at the physiological, cellular, organ, and system level (Azevedo & Cronley, 2004; Chi, 2000; Chi, 2005; Chi, de Leeuw, Chiu, & LaVancher, 1994; Chi, Siler, & Jeong, 2004; Chi, Silet, Jeong, Yamauchi, & Hausmann, 2001). Similarly, in ecological systems, the complex relationships between variables related to water quality indicators (e.g., toxins) and land use (e.g., agriculture) make it extremely difficult for students to understand how mathematical, biological, chemical, physical, and geographical concepts and principles need to be integrated to understand the complex nature of the whole system (Azevedo, Winters, & Moos, 2004). Complex science topics are inherently multitiered, with nonlinear, recursive relations that can be difficult for novice learners to quantify and grasp.

Understanding the complexity of these topics is also challenging for most students because the properties and behavior of the components that comprise the topics and the interrelationships of the components are not always available for direct inspection. In addition, students’ must integrate multiple representations of information (e.g., text, diagrams, formulas, structural models, animations, digitized video clips) to attain fundamental conceptual understanding, and then must use these representations to reason, solve problems, and make inferences (Goldman, 2003; Kozma, Chin, Russell, & Marx, 2000). Some educators and researchers have turned to CBEs such as hypermedia as a means of enhancing students’ understanding of complex topics.
standings of complex and challenging science topics. There is, however, a continuing debate about the effectiveness of such technologies for learning (see Azevedo, 2002; Dillon & Gabbard, 1998; Shapiro & Neiderhauser, 2004).

OVERVIEW OF RESEARCH ON LEARNING WITH HYPERMEDIA

Due to the educational potential of hypermedia, there has recently been an increase in studies examining their effectiveness in facilitating students' learning (e.g., Hartley, 2001; Jacobson & Archodidou, 2000; Narayanan & Hegarty, 1998; Shapiro, 2000). This research has begun to address several cognitive issues related to learning, including the role of basic cognitive structures (e.g., multimodal short-term-memory stores), cognitive functions (e.g., mental animation), multiple representations (text, diagrams, video), navigation profiles, system structure (e.g., linear vs. hierarchical), system features (e.g., advance organizers), and several types of scaffolds (embedded static scaffolds and adaptive human scaffolding from peers and teachers). The research has also explored several different varieties of tool use (e.g., frequency of use of embedded procedural scaffolds), examined several different learning outcomes (e.g., declarative knowledge, conceptual knowledge), and begun to converge multiple sources of data to examine the complex nature of students' learning of challenging and complex science topics with hypermedia. This research has employed a variety of theoretical frameworks and models of instruction (e.g., information processing theory, problem solving, constructivism, cognitive flexibility theory [Spiro, Coulson, & Thota, 2003], the construction–integration model [Kintsch, 1988]), as well as a variety of research methodologies (e.g., informal observations, case studies, experimental designs, quasi-experimental designs). In general, these studies indicate that students who lack key metacognitive and self-regulatory skills learn very little from these open-ended environments and that some kind of scaffolding is usually necessary to support their learning of conceptually challenging topics.

Some research has focused on learners' characteristics. For example, researchers have examined the role of prior knowledge (Shapiro, 1999), use of instructional strategies (Simons, Klein, & Brush, 2004), metacognitive skills (Schwartz, Andersen, Hong, Howard, & McGee, 2004), and individual differences and ability levels (Bera & Liu, in press). Other research has focused on hypermedia system features, such as the role of pedagogical agents (Baylor & Ryu, 2003), reflection prompts (van den Boom, Paas, van Merrienboer, & van Gog, 2004), embedded scaffolds (Jacobson & Archodidou, 2000; Liu, 2004), navigation support (Hegarty, Narayanan, & Freitas, 2002), expert modeling (Pedersen & Liu, 2002), system structure (Hargis, 2001), comprehension aids (Hartley & Bendixen, 2003), fixed scaffolds (Brush & Saye, 2001), and the nature of the problem posed to learners (Shin, Jonassen, & McGee, 2003).

Despite the recent wealth of research on hypermedia, there are several outstanding issues related to learning with hypermedia environments that have yet not been addressed by educational and cognitive researchers. For example, there is the question of whether (i.e., with what processes) a learner regulates his or her learning with a hypermedia environment. Most of the research has used the product(s) of learning (i.e., learning gains based on pretest–posttest comparisons) to infer the interplay between learner characteristics (e.g., low prior knowledge), cognitive processes (e.g., strategy use, metacognition), and structure of the system or the presence or absence of system features. In our research, we have adopted SRL because it allows us to directly theorize how learner characteristics, cognitive processes, and system structure interact during the cyclical and iterative phases of planning, monitoring, control, and reflection while learning with hypermedia environments.

SRL AS AN OVERARCHING THEORETICAL FRAMEWORK

Can SRL be used as a guiding theoretical framework within which to examine learning with hypermedia? By adopting SRL, we make certain theoretically based assumptions about learning (based on Pintrich, 2000; Zimmerman, 2000, 2001). These include the belief that self-regulated learners are active and efficiently manage their own learning in many different ways (Boekaerts, Pintrich, & Zeidner, 2000; Corno & Mandinach, 1983; Paris & Paris, 2001; Winne, 2001; Winne & Perry, 2000; Zimmerman, 2001; Zimmerman & Schunk, 2001). Students are self-regulating to the degree that they are cognitively, motivationally, and behaviorally active participants in their learning process (Zimmerman, 1986). SRL is a constructive process whereby learners set goals for their learning and then attempt to plan, monitor, regulate, and control their cognition, motivation, behavior, and context (Pintrich, 2000; Zimmerman, 2001). Models of SRL describe a recursive cycle of cognitive activities central to learning and knowledge-construction activities (e.g., Butler & Winne, 1995; Pintrich, 2000; Schunk, 2001; Winne, 2001; Zimmerman, 2001). The empirical literature in educational psychology (e.g., Corno & Randi, 1999; Newman, 2002; Perry, 2002; Pintrich & Zusho, 2002), and in the learning sciences (e.g., Azevedo, Cromley, & Seibert, 2004; Chi, 2005; Chi et al., 1994; Graesser et al., 2005; Quintana, Zhang, & Kraijcik, 2005; Shapiro & Neiderhauser, 2004) converge to suggest that students have difficulties learning about complex and challenging topics with CBLEs such as
hyperméedia because they do not deploy key self-regulatory processes during learning.

In general, models of SRL share certain basic assumptions about learning and regulation, despite the fact that each model proposes different constructs and mechanisms (see Boekaerts et al., 2000; Zimmerman & Schunk, 2001). Pintrich (2000) and Zimmerman (2001) have recently summarized five assumptions shared by all SRL models. One assumption, derived from the cognitive perspective of learning, is that learners are active, constructive participants in the learning process. Learners construct their own meanings, goals, and strategies from the information available from both their own internal environment (i.e., cognitive system) and the external environment (i.e., task conditions, learning context). A second assumption is based on the idea that learners are capable of monitoring, controlling, and regulating aspects of their own cognition, motivation, behavior, and context (e.g., the learning environment). Third, biological, developmental, contextual, and individual constraints can impede or interfere with a learner’s ability to monitor or control his or her cognition, motivation, behavior, or context. Fourth, all models tend to assume that there is a goal, criterion, or standard against which the learner makes comparisons to assess whether the process should continue or if some type of change (e.g., in strategies or metacognitive monitoring) is necessary. In a learning situation, a learner sets goals or standards to strive for during learning; monitors progress toward these goals; and then adapts and regulates cognition, motivation, behavior, and context to reach the goals. Fifth, self-regulatory activities are mediators between personal and contextual characteristics and actual performance and learning. In other words, it is not just the learner’s cultural background, demographic characteristics, or personality that influence achievement and learning directly; nor are contextual characteristics of the classroom the only things that shape achievement, but it is the learner’s self-regulation of his or her cognition, motivation, and behavior that mediates these relationships.

In addition to these basic assumptions, models of SRL typically propose four phases of SRL (Pintrich, 2000; Zimmerman, 2000). The first phase includes planning and goal setting (Pintrich, 2000; Zimmerman, 2001), activation of perceptions and knowledge of the task (Winne 2001; Winne & Hadwin, 1998), and the self in relationship to the task (Pintrich, 2000; Zimmerman, 2001). The second phase includes various monitoring processes that represent metacognitive awareness of different aspects of the self, task, and context (Schunk, 2001). Phase three involves the student’s efforts to control and regulate different aspects of the self, task, and context. Lastly, phase four represents various kinds of reactions and reflections on the self and the task and/or context (Winne, 2001; Winne & Hadwin, 1998). In short, self-regulated learners are goal-driven, motivated, independent, and metacognitively active participants in their own learning (Zimmerman, 1989, 2001). It should also be noted that the complex interactions between internal and external environmental factors and the nature of the learning task influence whether these phases take place linearly and/or recursively during learning (Butler & Winne, 1995).

Based on a comprehensive analysis of the literature, Pintrich (2000) advanced a taxonomy that is comprised of four columns representing areas of SRL, and four rows representing different phases of SRL previously discussed. A closer inspection of the columns in Pintrich’s (2000, p. 454) taxonomy reveals specific aspects of SRL that could inform the study of learning with CBLEs such as hypermedia. For example, the cognitive column includes different cognitive strategies learners may use to learn and perform a task as well as metacognitive strategies individuals may use to control and regulate their cognition. This includes both content knowledge (about a specific topic) and strategic knowledge (under what circumstances should that specific knowledge be used?). The motivation and affect column concerns various motivational beliefs that individuals may have about the task. For example, one’s self-efficacy beliefs as well as positive and negative affective reactions to the self or task are included in this column. Finally, any strategies that individuals may use to control and regulate their motivation and affect are included in this column. The behavior column includes an individual’s effort, persistence, help-seeking, and choice behaviors. Context is included as the fourth column in the framework; it represents the various aspects of the task environment, general classroom, or cultural context where the learning is taking place. This column deals with the external environment, which is defined as any aspect of the instructional environment which is directly “outside” of the learner’s cognitive system. However, in some models (e.g., McCaslin & Hickey, 2001) attempts to control or regulate the context would not be considered self-regulating because the context is not assumed to be part of the individual. In these models, self-regulation refers only to aspects of the self that are being controlled or regulated.

Overall, there is a burgeoning amount of research addressing whether students regulate their learning with hypermedia and whether SRL fosters the learning of complex and challenging science topics (e.g., the circulatory system, ecological systems) from dynamic, nonlinear, random-access instructional hypermedia environments. There is a need for more detail regarding how the phases (planning, monitoring, strategy use, handling of task difficulty and demands, and interest) and areas (cognition, motivation, behavior, and context) of SRL mediate the learning of complex science topics with hypermedia environments. In the next section, I present our emerging model of SRL, which is rooted in the existing SRL models described in the previous section.
SRL WITH HYPERMEDIA

Our emerging model has allowed us to examine the complex interplay between learner characteristics (e.g., prior knowledge, developmental level), elements of the hypermedia environment (e.g., nonlinear structure of hypermedia), and mediating self-regulatory processes (e.g., planning, strategy use, monitoring activities) used by students during learning with hypermedia. Based on our model, we hypothesize that students learning with hypermedia need to analyze the learning situation, set meaningful learning goals, determine which strategies to use, assess whether the strategies are effective in meeting the learning goal, and evaluate their emerging understanding of the topic. Students also need to monitor their understanding and modify their plans, goals, strategies, and effort in relation to contextual conditions (e.g., cognitive, motivational, and task conditions). Further, depending on the learning task, students may need to reflect on the learning episode and modify their existing understanding of the topic. Thus, learning with hypermedia requires the student to adaptively regulate these activities to meet task demands. If learners do not regulate their learning when using hypermedia environments, we may erroneously conclude that the environments are inherently ineffective, when in fact what is needed is to foster students’ self-regulation while using these powerful but complex learning environments. One way to foster student self-regulation is through the use of various kinds of contextual aids, which may include access to static educational resources or a human tutor who provides adaptive scaffolding to foster students’ SRL. In studying these contextual aids, it is critical that researchers not only examine what students do but also determine how students regulate their learning and how external regulating agents, such as human tutors, can facilitate students’ SRL.

To address students’ documented difficulties in regulating their own learning, we have further extended our model by examining the role of a human tutor as an external regulating agent. In doing so, we consider any scaffold (human or non-human, static or dynamic) that is designed to guide or support students’ learning with hypermedia to be a part of the task conditions (and is therefore external to the learner’s cognitive system; Winne, 2001). In our studies, we hypothesize that human tutors can assist students in building their understanding of a topic by providing dynamic scaffolding that helps students deploy specific self-regulatory skills (e.g., activating the students’ prior knowledge). In so doing, a human tutor can be seen as an external regulatory agent who monitors, evaluates, and provides feedback regarding a student’s self-regulatory skills. This feedback may involve scaffolding students’ learning by assisting them in planning their learning episode (e.g., creating subgoals, activating prior knowledge), monitoring several activities during their learning (e.g., monitoring progress towards goals, facilitating recall of previously learned material), prompting effective strategies (e.g., hypothesizing, drawing, constructing their own representations of the topic), and facilitating the handling of task demands and difficulty. Empirically testing the effectiveness of externally regulated learning can elucidate how these different scaffolding methods facilitate students’ SRL and provide evidence that can be used to inform the design of hypermedia learning environments.

RESEARCH ON SRL AND HYPERMEDIA CONDUCTED AT THE COGNITION AND TECHNOLOGY LAB

Researchers have successfully used adaptive scaffolding in non-hypermedia based learning environments designed to teach students about well-structured tasks such as math, geometry, and physics (e.g., Anderson et al., 1995; Aleven & Koedinger, 2002). However, research on scaffolding with hypermedia learning environments is scant. The recent widespread use of hypermedia has outpaced our understanding of how scaffolds can be implemented to adapt to students’ individual learning needs. Though there are a few studies on fixed, embedded scaffolds in hypermedia, very little research has been conducted on the effectiveness of adaptive scaffolding and how it may facilitate students’ learning within hypermedia. It is critical that researchers conduct more empirical research in this area to determine how different adaptive scaffolding methods invoke self-regulatory processes that facilitate students’ learning of challenging topics. In our research, we examine the effectiveness of SRL and externally regulated learning (ERL) in facilitating qualitative shifts in students’ mental models (from pretest to posttest) and the use of self-regulatory processes associated with these shifts in conceptual understanding (e.g., Azevedo & Cromley, 2004; Azevedo, Cromley, & Seibert, 2004; Azevedo, Cromley, Winters, Moos, & Greene, in press; Azevedo, Guthrie, & Seibert, 2004; Azevedo, Moos, Winters, Greene, Olson, & Chaudhuri-Godbole, 2005; Azevedo, Winters, & Moos, 2004; Cromley, Azevedo, & Olson, 2005; Greene & Azevedo, 2005; Moos, 2004; Vick, Azevedo, & Hofman, 2005; Winters & Azevedo, in press).

More specifically, the goals of our research are to conduct laboratory and classroom research, which addresses the following questions: (a) Do different scaffolding conditions influence students’ ability to shift to more sophisticated mental models of complex and challenging science topics? (b) Do different scaffolding conditions lead students to gain significantly more declarative knowledge of complex and challenging science topics? (c) How do different scaffolding conditions influence students’ ability to regulate their learning of complex and challenging science topics with hypermedia? (d) What is the role of external regulating agents (i.e., human tutors, classroom teachers, and peers) in students’ SRL of complex and challenging topics with hypermedia? (e) Are there developmental differences in college students’ and ado-
lescents’ ability to self-regulate their learning about complex and challenging topics with hypermedia?

We address these questions by using mixed methodology that combines true- and quasi-experimental designs with a think-aloud method (Ericsson & Simon, 1993) to produce both outcome measures (i.e., shifts in the quality of students’ mental models from pretest to posttest, and measures of declarative knowledge) and process data (i.e., think-aloud protocols detailing the dynamics of SRL processes used by students during learning, and classroom discourse analyses detailing the interactions between external regulating agents including human tutors, peers, and classroom teachers). We code these think-alouds for self-regulatory processes (cognitive, metacognitive, strategy use, etc.) used by learners and human tutors during learning. Our primary purpose for using think-aloud protocols is to map out how SRL processes influence qualitative shifts in students’ mental models during learning with a hypermedia. We also triangulate different data sources, both product and process data to begin to understand the role of SRL in learning about complex and challenging science topics with hypermedia.

In general, our results show that students’ learning about a challenging science topic with hypermedia can be facilitated if they are provided with adaptive human scaffolding that addresses both the content of the domain and processes of SRL. This type of sophisticated scaffolding is effective in facilitating students’ learning as indicated by (a) shifts in their mental models, (b) gains in declarative knowledge from pretest to posttest, and (c) process data regarding students’ self-regulatory behavior. In contrast, providing students with either no scaffolding or fixed scaffolds (i.e., a list of domain-specific subgoals) tends to lead to minor shifts in students’ mental models and only small gains in declarative knowledge in older students. Verbal protocols provide evidence that students in different scaffolding conditions differentially deploy key SRL processes, suggesting an association between these scaffolding conditions, mental model shifts, and declarative knowledge gains. To date, we have researched 33 different regulatory processes whose use is related to such process and product data. These processes include those related to planning (including subgoals, activating prior knowledge), monitoring activities (related to one’s cognitive system and emerging understanding, the hypermedia system and its content, and dynamics of the learning task), effective and ineffective learning strategies, and methods of handling task difficulties and demands.

Our results indicate, first, that different scaffolding conditions do have different effects on students’ ability to shift to more sophisticated mental models for both the circulatory system and ecology systems (e.g., Azevedo, Guthrie, & Seibert, 2004). We have demonstrated that students who are not provided with scaffolds tend to show little or no qualitative mental model shifts from pretest to posttest (e.g., Azevedo & Cromley, 2004). In contrast, providing college students with fixed scaffolds tends to interfere with their ability to develop sophisticated mental models of the topic (e.g., Azevedo & Cromley, 2004). However, fixed scaffolding tends to facilitate shifts in mental models for adolescents (middle and high school students; Azevedo et al., in press). In general, adaptive scaffolding by a human tutor who provides timely content and process-related scaffolding during learning tends to lead to significant qualitative mental model shifts for middle school, high school, and college students.

Second, in terms of declarative knowledge, our results indicate that for college students, each type of scaffolding condition tends to lead to significant gains from pretest to posttest. In contrast, younger students in adaptive scaffolding conditions tend to show significant declarative knowledge gains from pretest to posttest, whereas younger students in nonadaptive scaffolding conditions do not (e.g., Azevedo et al., in press).

Third, to trace students’ use of SRL, we have developed and refined a coding scheme that includes the following 33 self-regulatory processes: (a) planning variables including planning, goal setting, activating prior knowledge, and recycling goal in working memory; (b) monitoring activities including feeling of knowing (FOK), judgment of learning (JOL), monitoring progress towards goals, content evaluation, identifying the adequacy of information, evaluating the content as the answer to a goal, and self-questioning; (c) learning strategies including hypothesizing, coordinating informational sources, inferences, mnemonics, drawing, summarizing, goal-directed search, selecting new informational sources, free search, rereading, taking notes, knowledge elaboration, finding location in environment, memorizing, reading notes, and reading new paragraph; (d) handling task difficulties and demands including help-seeking behavior, expect adequacy of information, control of context, time and effort planning, and task difficulty; and (e) interest in the task or the content domain of the task.

Based on our coding scheme, our results indicate that the use of SRL varies by condition. Students assigned to our control conditions (i.e., no scaffolding condition) tend to deploy fewer self-regulatory processes during learning with hypermedia. In addition, these students tend to use fewer learning strategies. Students in the fixed scaffolding conditions tend to regulate their learning by using monitoring activities that deal with aspects of the hypermedia learning environment (other than their own cognition), use several effective and ineffective strategies, and tend to show interest in the topic. By contrast, students in the adaptive scaffolding conditions tend to rely on the tutor for externally regulated learning. This external regulation leads students to regulate their learning by activating prior knowledge and creating subgoals; monitoring their cognitive system by using FOK and JOL and sometimes engaging in self-questioning; and using several 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 (e.g., Azevedo et al., 2005).
In classroom studies, we have found that teachers tend to spend the majority of their instructional time scaffolding students' use of low-level strategies (e.g., copying information), whereas other self-regulatory processes such as metacognitive monitoring and handling task difficulties and demands are rarely used to facilitate students' learning (e.g., Azevedo, Winters, & Moos, 2004). In sum, the think-aloud data and discourse analyses (from our lab and classroom research) tend to indicate that successful students regulate their learning by using significantly more metacognitive monitoring processes and strategies. The data also indicate that certain key self-regulatory processes related to planning (e.g., prior knowledge activation and creating subgoals), metacognitive monitoring activities (e.g., JOL, FOK, self-questioning, monitoring progress toward goals), strategies (e.g., summarizing, drawing, inferences, knowledge elaboration, rereading, coordinating informational sources, goal-directed search, and hypothesizing), and engaging in help-seeking behavior have consistently been shown to facilitate students' learning about complex science topics with hypermedia.

IMPLICATIONS FOR THE DESIGN OF ADAPTIVE HYPERMEDIA LEARNING ENVIRONMENTS

Our results have implications for the design of 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 CBLE to emulate the regulatory behaviors of the human tutors in these conditions. 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., Aleven & Koedinger, 2002; Anderson, Douglass, & Qin, 2005; Graesser, Hu, & McNamara, 2005), technological limitations in assessing learning of challenging and conceptually rich, ill-structured topics (e.g., Brusilovsky, 2001; Jacobson, in press; Lajoie & Azevedo, in press), and conceptual discussions regarding what, when, and how to model certain key SRL processes in hypermedia environments (Azevedo, 2002). The system could be designed to deploy several key SRL mechanisms such as planning (e.g., plan the learning session, create subgoals), monitoring the contents of the hypermedia environment (e.g., identifying the adequacy of information, monitoring progress toward goals), using effective strategies (e.g., coordinating information sources, drawing), and handling task difficulties and demands (e.g., time and effort planning, controlling the context, and acknowledging task difficulty) based on an individual learner's behavior. However, given current technological limitations, it is impossible for a system to fully emulate the scaffolding used by the human tutors—to monitor students' emerging understanding of a challenging science topic and provide adaptive scaffolding by modifying its scaffolding methods based on student requests for assistance (e.g., through help-seeking behavior). For example, embedding scaffolds to accommodate students' judgment of learning (JOL) poses a technical challenge—how can the hypermedia environment "know" that, for example, a student is not aware that he or she is reading too fast? Similar technical challenges exist if designers wanted to have the hypermedia environment "detect" that a student is monitoring the content of the hypermedia environment, which is a nondesirable monitoring activity used predominantly by students in the control conditions. These two examples represent a set of issues that could be resolved with advances in the technical aspects of designing hypermedia environments (e.g., see Brusilovsky, 2001, 2004).

There are some nonadaptive scaffolds that could be provided during learning with hypermedia. First, during learning of a science topic, students could be prompted periodically to plan and activate their prior knowledge. This could be used as an anchor from which to build new understandings and elaborations based on the information presented in the hypermedia environment. A planning net in the form of a static scaffold could also be embedded to allow students access to the general learning goal for the entire learning session with a list of subgoals designed to facilitate their learning.

Scaffolds could be designed to encourage a student to engage in several metacognitive monitoring activities during learning. For example, the system could prompt students to engage in feeling of knowing (FOK) by asking them periodically (e.g., after reading a section of text) to rate the information presented in the hypermedia environment to what they already know about the circulatory system (i.e., knowledge elaboration). A static scaffold could be embedded in the hypermedia environment to facilitate a student's monitoring of his or her progress toward goals by using the planning net and subgoals mentioned earlier and having the student actively verify that he or she has learned about each of the subgoals given the time remaining in the learning session.

A student's use of effective strategies could be scaffolded within a hypermedia environment by providing online prompts. The system might also be able to detect uses of some ineffective strategies (or lack of use of some effective strategies) and provide prompts and feedback designed to discourage students from using those ineffective strategies. Based on the results of our previous research, such a hypermedia environment should foster students' use of hypothesizing, coordinating informational sources, drawing, mnemonics, and inferences. Time and effort planning supports in the system could include a monitoring mechanism that would display a list of goals, marking goals that have not been completed, and indicate the time remaining. Based on
that amount of time remaining, the environment could recom-
mend goals and strategies on which the student should focus in the time remaining. Interest could be fostered by allowing a student to pursue his or her own goals but asking them to periodically verify how their stated goals relate to the planning net and the subgoals set for the learning task. Our research adds to a line evidence suggesting a new way of thinking about using technology to improve education that focuses on the use of computers as metacognitive tools designed to detect, trace, monitor, and foster learners' SRL of conceptually challenging topics (Azevedo, 2002; Lajoie & Azevedo, in press).

CONCLUDING REMARKS

Our research provides a valuable characterization of the complexity of self- and externally regulated learning processes in both laboratory studies and learner-centered science classrooms. We have begun to examine the dynamics of SRL processes—cognitive, motivational/affective, behavioral, and contextual—during the cyclical and iterative phases of planning, monitoring, control, and reflection during learning from hypermedia environments. One of the main methodological issues related to SRL that we address in our research is how students regulate their learning during a knowledge construction activity. We have developed trace methodologies of the type that are needed to capture the dynamic and adaptive nature of SRL during learning of complex and challenging science topics with hypermedia.

We have also begun to address some of the theoretical, methodological, and educational issues raised by several researchers (Mayer, 2003; Pintrich, 2000; Winn, 2003; Winne, Jamieson-Noel, & Muis, 2002; Winne & Perry, 2000; Zeidner, Boekaerts, & Pintrich, 2001; Zimmerman, 2001; Zimmerman & Schunk, 2001). We use mixed methodology by combining experimental designs with a think-aloud method to produce both outcome measures and process data. Using think-aloud protocols has allowed us to map out how SRL processes influence qualitative shifts in students’ mental models during learning with a hypermedia.

Our research has allowed us to examine the effectiveness of scaffolding methods in facilitating students’ learning of complex and challenging science topics. By doing so, we have been able to reconceptualize the existing research on naturalistic human tutoring (e.g., Chi et al., 2004; Graesser, Bowers, Hacker, & Person, 1997) by examining the role of scaffolding on SRL, while concurrently addressing fundamental (see Wood et al., 1976) and contemporary criticisms of the role of scaffolds while learning with CBLEs (see Pea, 2004; Puntambekar & Hubscher, 2005; Quintana et al., 2004). This is a critical issue that is beyond the scope of this article.

Last, our findings provide the empirical basis for the design of technology-based learning environments as metacognitive tools to foster students’ learning of conceptually challenging science topics. However, these design decisions must also be based on the limitations and successes of current adaptive computer-based learning environments for well-structured tasks, current technological limitations in assessing learning of challenging and conceptually rich, ill-structured topics in hypermedia learning environments, and instructional decisions regarding “what, when, and how” to model certain key SRL processes in hypermedia environments.

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