Detecting, Tracking, and Modeling Self-Regulatory Processes during Complex Learning with Hypermedia

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Abstract

Self-regulated learning (SRL) involves a complex set of interactions between cognitive, metacognitive, motivational and affective processes. The key to understanding the influence of these self-regulatory processes on learning with open-ended, non-linear learning computer-based environments involves detecting, capturing, identifying, and classifying these processes as they temporally unfold during learning. Understanding the complex nature of the processes is key to building intelligent learning environments that adapt to learners' fluctuations in their SRL processes and emerging understanding of the topic of domain. The foci of this paper are to: (1) introduce the complexity of SRL with hypermedia, (2) briefly present an information processing theory (IPT) of SRL and using it to analyze the temporally, unfolding sequences of processes during learning, (3) present and describe sample data to illustrate the nature and complexity of these processes, and (4) present challenges for future research that combine several techniques and methods to design intelligent learning environments that trace, model, and foster SRL.

Self-Regulated Learning

Learning about conceptually-rich domains with open-ended computer-based learning environments (CBLEs) such as hypermedia involves a complex set of interactions between cognitive, metacognitive, motivational, and affective processes (Azevedo, 2005, 2007, in press; Graesser, McNamara, & VanLehn, 2005; Jacobson, 2008; Moos & Azevedo, in press a; Vollmeyer & Rheinberg, 2006; Zimmerman, 2008). Current research from several fields including cognitive and learning sciences provides evidence that learners of all ages struggle when learning about these conceptually-rich domains with hypermedia. This research indicates that learning about conceptually-rich domains with hypermedia is particularly difficult because it requires students to regulate their learning. 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, students need to deploy several metacognitive processes to determine whether they understand what they are learning, and perhaps modify their plans, goals, strategies, and effort in relation to dynamically changing contextual conditions. In addition, students must also monitor, modify, and adapt to fluctuations in their motivational and affective states, and determine how much social support (if any) may be needed to perform the task. Also, depending on the learning context, instructional goals, perceived task performance, and progress made towards achieving the learning goal(s), they may need to adaptively modify certain aspects of their cognition, metacognition, motivation, and affect.

Despite the ubiquity of hypermedia environments for learning, the majority of the research has been criticized as atheoretical and lacking rigorous empirical evidence (see Azevedo & Jacobson, 2008; Dillon & Jobst, 2005; Dillon & Gabbard, 1998; Jacobson, 2008; Jacobson & Azevedo, 2008; Neiderhauser, 2008; Tergan, 1997a, 1997b). In order to advance the field and our understanding of the complex nature of learning with hypermedia environments, we need theoretically-guided, empirical evidence regarding how students regulate their learning with these environments.

Despite the recent rise of quality research on learning with hypermedia, we also raise several critical issues related to learning with hypermedia environments which have not yet been addressed by cognitive and educational researchers. For example, there is the question of *how* (i.e., with what processes) a learner regulates his/her learning with a hypermedia environment. Most of the research have used the *product(s)* of learning (i.e., pretest-posttest learning gains) to infer the connection between *individual differences* (e.g., prior knowledge, reading ability), *learner characteristics* (e.g., developmental level), *cognitive processes* (e.g., learning strategies used during learning), and *structure of the hypermedia environment* or the inclusion (or exclusion) of certain *system features*. In our research, we have adopted self-regulated learning (SRL) because it allows us to directly investigate how task demands, learner characteristics, cognitive and metacognitive processes, and system structure interact during the cyclical and iterative phases of planning, monitoring, and control while learning with hypermedia environments.

In this paper, we provide a synthesis of existing research on learning with hypermedia, illustrate the complexity of self-regulatory processes during hypermedia learning, and present a theoretical account of SRL based on Winne and colleagues' (1995, 1998, 2001, 2008) information processing theory (IPT) of SRL. We also provide a synthesis of recent research on using SRL as a framework with which to capture and study self-regulatory processes, and provide theoretically-driven and empirically-based guidelines for supporting learners' self-regulated learning with hypermedia.

Self-Regulated Learning with Hypermedia

Learning about complex and challenging science topics, such as the human circulatory system and natural ecological processes with multi-representational, non-linear computer-based learning environments (CBLEs), requires learners to deploy key self-regulatory processes (Azevedo et al., 2004a, 2004b, 2005, 2007, 2008; Biswas et al., 2005; Graesser et al., 2005; Jacobson, 2008; McNamara & Shapiro, 2005; Neiderhauser, 2008). Recent cognitive research with middle-school, high-school, and college students has identified several key self-regulatory processes which are associated with learning, understanding, and problem solving with hypermedia-based CBLEs. First, there are *planning* processes such as activating prior knowledge, setting and coordinating sub-goals that pertain to accessing new information, and defining which problem solution steps to perform for accomplishing a complex task. In addition, there are also several *monitoring* processes that are deployed during task enactment including monitoring one's understanding of the topic, managing the learning environment and other instructional resources necessary to accomplish the learning goals, and engaging in periodic self-assessment (i.e., checking for the correctness of solution steps while solving problems and using this information to direct one's future learning activities). During task performance a learner must also use several effective *learning strategies* for accomplishing the task such as coordinating several informational sources (e.g., text, diagram, animations), generating hypotheses, extracting relevant information from the resources, re-reading, making inferences, summarizing, and re-representing the topic based on one's emerging understanding by taking notes and drawing. Lastly, the learner must continuously adjust during learning by *handling task difficulties and demands* such as monitoring one's progress towards goals, and modifying the amount of time and effort necessary to complete the learning task. As such, we (Witherspoon, Azevedo, & D'Mello, 2008) and other colleagues (e.g., Biswas et al., 2005; Hadwin, Nesbit, Jamieson-Noel, Code, & Winne, 2007) emphasize that understanding the real-time deployment of these processes in the context of learning and problem solving tasks is key to understanding the nature of adaptivity in self-regulated learning (SRL) among learners of all ages and their influence on learning. Therefore, we propose that an IPT theory of SRL will best accommodate the complex nature of learning with hypermedia environments.

Theoretical Framework: Information-Processing Theory of SRL

Self-regulated learning (SRL) involves actively constructing an understanding of a topic/domain by using strategies and goals, regulating and monitoring certain aspects of cognition, behavior, and motivation, and modifying behavior to achieve a desired goal (see Boekaerts et al., 2000; Pintrich, 2000; Zimmerman & Schunk, 2001). Though this definition of SRL is commonly used, the field of SRL consists of various theoretical perspectives that make different assumptions and focus on different constructs, processes, and phases (Dunlosky & Lipko, 2007; Metcalfe & Dunlosky, 2008; Pintrich et al., 2000; Schunk, 2008; Winne & Hadwin, 2008; Zimmerman, 2008). We further specify SRL as a concept superordinate to metacognition that incorporates both metacognitive monitoring (i.e., knowledge of cognition or metacognitive knowledge) and metacognitive control (involving the skills associated with the regulation of metacognition), as well as processes related to planning for future activities within a learning episode and manipulating contextual conditions as necessary. SRL is based on the assumption that learners exercise agency by consciously monitoring and intervening in their learning. While most of our research has focused on the cognitive and metacognitive aspects of SRL with hypermedia, we are currently considering the incorporation of other key processes such motivation and affect (Moos & Azevedo, 2008, in press a, in press b).

Recent studies on SRL with open-ended learning environments such as hypermedia (e.g., see Azevedo, 2005, in press, for recent reviews) have drawn on Winne and colleagues' (Butler & Winne, 1995; Winne, 2001; Winne & Hadwin, 1998, 2008) Information Processing Theory (IPT) of SRL. This IPT theory suggests a four-phase model of self-regulated learning. The goal of this section is to explicate the basics of the model so as to emphasize the linear, recursive, and adaptive nature of self-regulated learning and make the link to its implication for the use in studying SRL with hypermedia (see Greene & Azevedo, 2007 for a recent review).

Winne and Hadwin (1998, 2008) propose that learning occurs in four basic phases: (1) task definition, (2) goal-setting and planning, (3) studying tactics, and (4) adaptations to metacognition. Winne and Hadwin's SRL model differs from the majority of other SRL models, in that they hypothesize that information processing occurs within each phase. Using the acronym COPES[1], they describe each of the four phases in terms of the interactions between a learner's conditions, operations, products, evaluations, and standards. All of the terms except operations are kinds of information used or generated during learning. It is within this cognitive architecture, comprised of COPES, that the work of each phase is completed. Thus, their model complements other SRL models by introducing a more complex description of the processes underlying each phase. It should be noted that

A Theoretical Framework: Self-Regulated Learning with Hypermedia

As previously mentioned, we have chosen Winne and Hadwin's (1998, 2001, 2008) model of SRL as a comprehensive theoretical framework to conceptualize students' SRL about complex topics with hypermedia. Using their model as a guiding framework has allowed us to examine the complex interplay between learner characteristics (e.g., developmental level, prior knowledge, individual differences), elements of the hypermedia environment (e.g., non-linear structure, non-adaptivity, amount of content, content presentation), and mediating self-regulatory processes used by students (e.g., planning, monitoring processes, learning strategies, methods for handling task difficulties and demands, and interest). Based on an adaptation of Winne and colleagues' model for the particular context in our study, 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 task conditions (e.g., cognitive, motivational) that are contextualized in a particular learning situation (e.g., learning about the circulatory system with a hypermedia environment). Depending on the learning task, students may need to reflect on the learning episode in order to modify their existing understanding of the topic. Because of these many sometimes overwhelming demands, hypermedia environments may be ineffective if learners do not regulate their learning (e.g., Azevedo & Cromley, 2004; Azevedo et al., 2004a, 2005; Hartley & Bendixen, 2003; Greene & Land, 2000; Land & Greene, 2000).

Lastly, Winne (2005) states that certain hypotheses can be postulated when adopting a model of SRL. First, before committing to a goal, a learner must recognize the features of the learning environment that affect the odds of success. Second, if such features are recognized, then they need to be interpreted, a choice must be made (e.g., set a goal), and the learner needs to select among a set of learning strategies that may lead to successful learning. If these first conditions are satisfied, the learner must have the capability to apply these learning strategies. If these three conditions are met, then the learner must be motivated to put forth the effort entailed in applying learning strategies. In sum, this model provides a macro-level framework and elegantly accounts for the linear, recursive, and adaptive nature of self-regulated learning with hypermedia. As such, we have over the last few years adapted this model to account for learning about complex and challenging science topics with hypermedia (see Azevedo, 2002, 2005, in press).

Previous Research on SRLwith Hypermedia: The Role of Monitoring Processes

In our research we have begun to address the theoretical, methodological, conceptual, and educational issues raised by several SRL researchers (e.g., Ainley & Patrick, 2006; Alexander, 1995; Boekaerts & Cascallar, 2006; Efklides, 2006; Pintrich, 2000; Schunk, 2007; Veenman, 2007; Winne & Perry, 2000; Zeidner, Boekaerts, & Pintrich, 2001; Zimmerman, 2008;). First, we chose a mixed methodology, using true- and quasi-experimental designs combined with concurrent think-alouds protocols (based on Ericsson, 2006; Ericsson & Simon, 1993) to produce both outcome measures (i.e., shifts in mental models from pretest to posttest) and process data (i.e., concurrent think-aloud protocols detailing the dynamics of SRL processes during learning). Our primary purpose for using concurrent think-aloud protocols[2] was to map out how SRL variables influence shifts in mental models during learning with a hypermedia environment. Second, we triangulated different data sources, both product (e.g., essay responses, diagram labeling, and outlines of the path of blood on pretests and posttests; matching concepts to definitions) and process data (e.g., think aloud protocols during learning and video coding to capture non-verbal processes and behaviors), to begin to understand the role of SRL in learning complex scientific topics with hypermedia.

In addition to the theoretical issues presented previously, we also addressed several methodological issues raised by SRL researchers (Hadwin et al., 2001; Pintrich, 2000; Zeidner et al., 2000; Winne, 2001; Winne & Perry; 2000; Zimmerman & Schunk, 2001). Little research has been conducted on the inter-relatedness and dynamics of SRL processes—cognitive, motivational/affective, behavioral, and contextual—during

[1] COPES stands for Conditions, Operations, Products, Evaluations, and Standards. Within Operations there are five operations: searching, monitoring, assembling, rehearsing, and translating (SMART) (see Winne & Hadwin, 2008, p. 3003-303 for a detailed review.

[2] Concurrent think-aloud protocols have been used extensively by researchers in several areas including expertise, and reading and text comprehension, to examine the cognitive and metacognitive processes used during learning and performance (see Ericsson, 2006 for a recent review).

the cyclical and iterative phases of planning, monitoring, control, and reflection during learning with hypermedia environments. However, as Hadwin and colleagues (2001) point out, “[if the] hallmark of SRL is adaptation, then data that consist only of self-report questionnaire data and scales that aggregate responses independently of time and context may weakly reflect, and may even distort, what SRL is" (p. 486). One of the main methodological issues related to SRL that we address in our studies is *how* learners regulate their learning during a knowledge construction activity. Most of the research focuses on SRL as an *aptitude*—based on learners’ self-reports of perceived strategy use, resource use, and goal selection that depends on the instructional context (e.g., reading for learning, preparing for a midterm exam). These are mostly correlational studies which assess two or three different goal orientations at the same time, or experimental studies which focus almost exclusively on declarative measures of learning. They assume that differences between pretest and posttest measures reflect learners’ use of cognitive, motivational and contextual SRL variables (Pintrich, 2000). We therefore extended our methodologies and thereby contributed to an emerging set of trace methodologies, which are needed to capture the dynamic and adaptive nature of SRL during learning of complex science topics and with complex, dynamic hypermedia learning environments.

Monitoring Processes during Learning with Hypermedia

In this section, we present the monitoring processes we have identified in our studies on SRL with hypermedia. Although many of these processes are likely context-independent, applicable to learning with various types of learning resources, some are most appropriately applied to learning with hypermedia, in situations where learners have control over which content, in which modality, they access at any given moment. However, even though we will present real examples of the use of each of these monitoring processes in the context of the circulatory system, each are applicable to learning in any domain.

As previously mentioned, Winne and colleagues’ model provides a macro-level framework for the cyclical and iterative phases of SRL. The data presented in this section provides the micro-level details that can interface Winne’s model. In this section we present the 8 metacognitive monitoring processes we have identified as essential to promoting students’ self-regulated learning with hypermedia. Some of these monitoring processes are coded along with a valence, positive (+) or negative (-), indicating the learners’ evaluation of the content, their understanding, their progress, or familiarity with the material. For example, a learner might state that the current content is either appropriate (content evaluation +) or inappropriate (content evaluation -), given their learning goals and, according to which valence is associated with the evaluation, make choices about persisting with the current material or seeking other content[3].

The first monitoring process we have identified in our research is *Feeling of Knowing (FOK)*. Feeling of knowing is when the learner is aware of having (+) or having not (-) read or seen something in the past and having (+) or not having (-) some familiarity with the material. An example of a learner using FOK is (excerpt from a participant’s transcript): “I learned about this, when did I learn about this, that looks familiar.”

Closely related to FOK is the monitoring process *Judgment of Learning (JOL)*. Judgment of learning is when a learner becomes aware that he/she does (+) or does not (-) know or understand something he reads. An example of a learner using JOL is: “I don’t really understand how that works”

The next monitoring process is *Monitoring Use of Strategies (MUS).* In MUS, the learner acknowledges that a particular learning strategy he/she has employed was either useful (+) or not useful (-). An example of a learner monitoring use of strategies is: “Yeah, drawing it really helps me understand how blood flows throughout the heart.”

Self-test (ST) is when a learner poses a question to him/herself to assess the understanding of the content and determine whether to proceed to re-adjust. An example of a learner self-testing is: “Ok, well how does it go from the atrium to the ventricle?”

In *Monitoring Progress toward Goals (MPTG)*, learners assess whether previously set goals have been met (+) or not met (-), given time constraints. An example of a learner monitoring progress toward goals is: “Let's see blood, heart, I've done blood and heart and I've done circulatory.”

Time Monitoring (TM) involves the learner becoming aware of remaining time which was allotted for the learning task. An example of a learner monitoring his time is: “I still have plenty of time.”

Content evaluation (CE) is when the learner monitors the appropriateness (+) or inappropriateness (-) of the current learning content, given their pre-existing overall learning goal and subgoals. An example of a learner evaluating the content is: “This section with the diagram of the heart with all the labels is important for me to

[3] The use of concurrent think-alouds allows researchers to capture and classify particular processes and determine when they are deployed during learning. The classification can be accomplished at different levels of granularity—(a) macro-level (e.g., metacognitive monitoring process), and micro-level (e.g., JOL) with associated valence (either + or -; e.g., JOL+ or JOL-). However, it should be noted that other classification systems and associated analytical approaches and statistical analyses yield different indices of metacognitive monitoring such as absolute accuracy, relative accuracy, bias, scatter, and discrimination (e.g., see Benjamin & Diaz, 2008; Greene & Azevedo, in press; Schraw, in press; Van Overschelde, 2008).

understand the different components of the heart." The last monitoring process is *Evaluation of Adequacy of Content (EAC)*. Evaluation of adequacy of content is similar to CE, in that learners are monitoring the learning content, given their learning goals, but in this process, learners evaluate learning content they have not yet navigated toward. An example of a learner evaluating the adequacy of content is: "Do they have a picture of the blood flow through the heart?"

Self-Regulation using Monitoring Processes

In this section, we describe the learner's application of these eight monitoring processes within the context of self-regulation with hypermedia. For each monitoring process, we provide the aspects of the learning environment which are evaluated, as well as illustrate then using examples of task and cognitive conditions which may lead to the various monitoring processes, as well as examples of appropriate control mechanisms which might be deployed following the evaluations. Feeling of knowing (FOK) is used when the learner is monitoring the correspondence between his or her own pre-existing domain knowledge and the current content. The learner's domain knowledge and the learning resources are the aspects of the learning situation being monitored when a learner engages in FOK. If a learner recognizes a mismatch between his/her pre-existing domain knowledge and the learning resources, more effort should be expended in order to align the domain knowledge and the learning resources. Following more effortful use of the learning material, a learner is more likely to experience/generate more positive FOKs. However, if a learner experiences familiarity with some piece of material, a good self-regulator will attempt to integrate the new information with existing knowledge by employing knowledge elaboration (KE). Often, a learner will erroneously sense a positive FOK toward material, and quickly move on to other material, with several misconceptions still intact.

In contrast to FOK, JOL is used when the learner is monitoring the correspondence between his/her own emerging understanding of the domain and the learning resources. Similar to feeling of knowing, when engaging in judgment of learning, a learner is monitoring his domain knowledge and the learning resources. If a learner recognizes that the emerging understanding of the material is not congruent with the material (i.e., the learner is confused by the material), more effort should be applied to learn the material. A common strategy employed after a negative JOL is re-reading previously encountered material. In order to capitalize on re-reading, a good self-regulator should pay particular attention to elements in a passage, animation, or illustration that confused the learner. When a learner expresses a positive JOL, he/she might self-test to confirm that the knowledge is as accurate as the evaluation suggests. As with FOK, learners often over-estimate their emerging understanding and progress too quickly to other material.

When monitoring use of strategies (MUS), a learner is monitoring the efficacy of recently used learning strategies, given his/her expectations for learning results. MUS encompasses a learner's monitoring of learning strategies, expectations of results, and domain knowledge. By noting the learning strategies used during a learning task and the resulting change in domain knowledge, learners can compare this emergent knowledge with their expectations and make changes to the strategies employed accordingly. For example, many learners will begin a learning episode by taking copious amounts of notes, then realize that the learning outcomes from this strategy are not as high as they would have expected. Good self-regulators will then make alterations to their strategy of note-taking such as employ more efficient methods (making bullet points, outlines, or drawings), or even abandon this strategy for another, more successful strategy (e.g., summarizing). However, if a learner realizes that a particular strategy has been especially helpful to his/her learning, he/she should continue to employ this strategy during the learning session.

Learners self-test (ST) to monitor their emerging understanding of the content and the aspects of the learning situation being monitored are the learner's domain knowledge and the learner's expectations of the content. While tackling difficult material (e.g. complex science topics) learners should occasionally assess their level of understanding of the material, by 'administering' a ST. If the results of this self-test are positive, the learner can progress to new material, but if the learner recognizes, through this self-test, that his or her emergent understanding of the current material is not congruent with what is stated in the material, he or she should revisit the content to better comprehend.

When monitoring progress toward goals, a learner is monitoring the fit between his/her learning results and previously set learning goals for the session. The aspects of the learning situation which are monitored during MPTG are the learner's domain knowledge, his/her expectations of results, and the learning goals. Closely related to time monitoring, MPTG is an essential monitoring activity that learners should use to stay 'on-track' to the completion of the learning task. A learner may be able to generate several critical sub-goals for his/her learning task, but if he does not monitor the completion or incompletion of these sub-goals, the sub-goal generation was inadequate. When a learner monitors the progress toward goals and realizes that he/she has only accomplished one out of four of their sub-goals in 90% of the time devoted to the learning task, a good self-regulator will revisit the remaining sub-goals and decide which is most important to pursue next.

In time monitoring, the learner is monitoring the task condition of time, with respect to their pre-existing learning goals. These learning goals can be either the global learning goal defined before engaging in the learning task, or sub-goals created by the learner during the learning episode. If the learner recognizes that very little time remains and few of the learning goals have been accomplished, he/she should make adaptations to the manner in which the material is being tackled. For example, if a learner has been reading a very long passage for several minutes and realizes that he/she has not accomplished the learning goals, a good self-regulator will begin scanning remaining material for information related to the goals not yet reached.

When learners engage in content evaluation, they are monitoring the appropriateness or inappropriateness of learning material they are currently reading, hearing, or viewing with regards to the overall learning goal or sub-goal they are currently pursuing. In contrast to content evaluation, evaluation of adequacy of content relates to the learner's assessment of the appropriateness of available learning content, rather than content currently being inspected. The aspects of the learning situations monitored in both of these processes are the learning resources and the learning goals. The learner should remain aware of whether learning goals and learning resources are complementary. If a learner evaluates a particular piece of material as particularly appropriate given their learning goal, he or she should direct more cognitive resources toward this material (or navigate toward this material), and persist in reading or inspecting the content in order to achieve this goal. Conversely, if a particular content is evaluated as inappropriate with respect to a learning goal, a good self-regulator will navigate away from (or not at all toward) this content to seek more appropriate material. In sum, these monitoring processes are based on studies examining the role of self-regulatory processes deployed by learners during learning with hypermedia.

The Deployment of Self-Regulatory Processes During Learning with Hypermedia

One of the purposes of treating self-regulated learning as an *event* is that we can capture, trace, and analyze the deployment of these processes during learning. It should be noted that the deployment of such processes unfolds both *linearly* and *recursively* during learning (based on Winne, 2001; Winne & Hadwin, 1998, 2008; Winne & Perry, 2000; Winne et al., 2002). More specifically, the linear unfolding refers to the sequential deployment during learning. For example, a learner may set a goal and then enact a learning strategy such as taking notes and then assess the use of note taking as not particularly helpful in facilitating his learning about the topic. This linear deployment of processes reflects a basic methodological assumption common to all on-line cognitive trace methodologies including think-aloud protocols (i.e., learners' access to the contents of working memory and the sequential, linear, enactment of both cognitive and behavioral self-regulatory processes; see Ericsson, 2006; Ericsson & Simon, 1993). In this section we highlight the theoretical, conceptual, and methodological importance of capturing and analyzing the deployment of self-regulatory processes during learning. We will accomplish this goal by providing evidence regarding the deployment of nearly three dozen self-regulatory processes during hypermedia learning, highlighting the top three self-regulatory processes used by learning across three developmental levels, and then focusing specifically on one participant.

A major issue relates to whether learners, in general, deploy the same amount and same types of self-regulatory processes throughout a learning task. Contemporary SRL models and frameworks (e.g., Pintrich, 2000; Schunk, 2005; Winne, 2001; Zimmerman, 2000, 2001) of SRL postulate that learners initially activate their prior knowledge, set goals, and plan their learning by coordinating their goals throughout the learning session. Despite the accuracy and plausibility of the enactment of such processes, the majority of research using these models has not treated SRL as an event and as such there is no published literature on the accuracy of such models based on SRL as an event, and for learning with CBLEs such as hypermedia. As such, our approach provides evidence regarding SRL as an event. We provide four examples in this section after we briefly describe our methodological approach.

Figure 1 illustrates the proportion[4] of SRL moves of 132 middle-school, high-school, and college students' coded think-aloud protocols (based on a random sample of existing data from students learning with hypermedia). The x-axis is divided into 4, 10-minute episodes of the hypermedia learning task while the y-axis represents the proportion of SRL processes deployment based on aggregate SRL processes—planning, monitoring, learning strategies, handling task difficulties and demands, and interest. As can be seen, there is a difference in the proportion of SRL processes used during the hypermedia learning task. Overall, approximately 50% of the processes used by learners (at any point during the task) are learning strategies. This is then followed by monitoring processes (between 20%-25%), handling task difficulties and demands (approx. 20%), planning (approx. 10%), and interest (approx. 5%). A few observations can be made (based upon this figure) including the fact that there is little fluctuation in the deployment of these processes during a 40 minute hypermedia learning task. The higher proportion of learning strategies and monitoring processes (in Figure 1) during the course of the hypermedia learning task is supported theoretically and conceptually by Winne and Hadwin's (1998, 2001, 2008) model of SRL. This data can also be used to generate certain hypotheses regarding the

[4] The proportion of SRL moves at each time interval illustrated in Figure 1 is based on the relative sum of all participants' self-regulatory processes across are SRL processes within each category, at each time interval.

deployment of SRL. For example, the slight "dip" in the proportion of learning strategies half-way through the task may be indicative of the low-prior knowledge learners switching from a knowledge acquisition mode of learning (all they can about the circulatory system) to a knowledge building mode of learning where monitoring processes (such as FOK) may now be more relevant (as seen in the slight rise in proportion of monitoring processes, see the Figure 2). These hypotheses can be empirically tested.

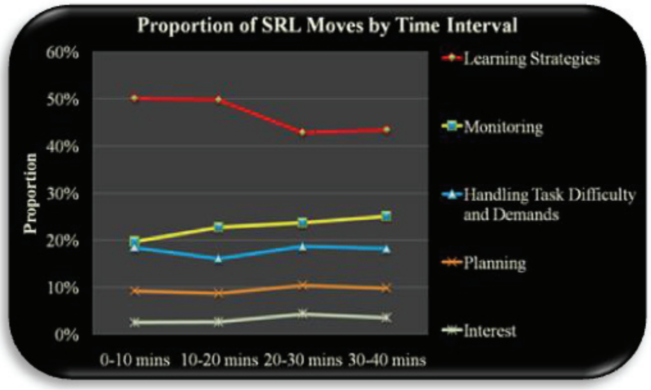

Figure 1. Proportion of SRL Moves by Time Interval during a Hypermedia Learning Task.

While this data is quite important in determining the consistency of SRL processes during learning with hypermedia, there is also a need to examine whether there are particular SRL processes that account for the shape on the lines seen in Figure 1. So, for each of the aggregated data points seen in Figure 1, we illustrate the three most frequently used SRL processes were used by the same sample. The results are presented in Figure 2, which presents the same information presented in Figure 1. The only difference, however, is that we inserted the top three most frequently used SRL processes for each SRL cluster at each of the 4 10-minute intervals. As can be seen, it is quite remarkable that the same three most frequently used SRL processes are taking notes, summarization, and re-reading, at each of these four time intervals. During the middle of the hypermedia learning task (i.e., between the 10-20 and 20-30 minute episodes) there is a switch between summarization, taking notes, and re-reading. This is then followed by another switch in the top three learning strategies—taking notes being the least used of the top three learning strategies. This finding provides some support for the hypothesis that learners will decrease their use of the learning strategy take notes toward the end of the learning session, instead turning to more summarization and re-reading of what has already been learned within the hypermedia environment.

Figure 2 illustrates that the three most frequently used monitoring processes are FOK, JOL, and CE. In addition, this sequence of use remains the same throughout the entire task. It is important to highlight that learners tend to monitor whether or not they are familiar with the content (by using FOK) by attempting to link it with prior knowledge. They also monitor their emerging understanding of the topic during the hypermedia learning task by engaging in JOL. Monitoring the adequacy of the multiple external representations (i.e., text, diagrams, animation) presented in the hypermedia environments is crucial in determining the appropriateness of each of these representations, vis-à-vis one's learning goals. These monitoring processes are used with remarkable consistency throughout the task, which highlights the importance of several monitoring processes related to a learner's prior knowledge, emerging understanding, and hypermedia content. We will not discuss planning, handing task difficulties and demands and interest due to space limitations.

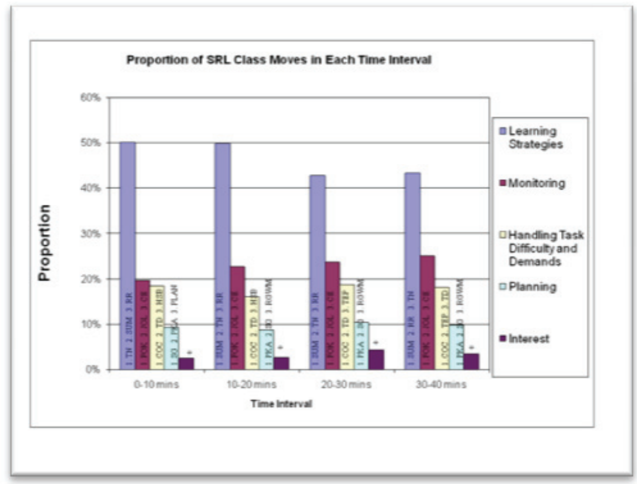

Figure 2. Three Most Frequently Deployed SRL Processes for Each SRL Cluster by Time Interval During a Hypermedia Learning Task.

At a micro-level we can also analyze the deployment of self-regulatory processes. We also contributed to the much needed theoretically-derived and empirically-based research methods that characterize temporally unfolding patterns of engagement with tasks in terms of the phases and areas that constitute SRL (see Figure 3). Figure 3 illustrates the SRL trace data of a "high-jumper" (i.e., a learner who showed a significant mental model shift from pretest to posttest) during a 40-minute hypermedia learning task (from Azevedo et al., 2008). The x-axis represents the number of SRL moves coded based on the think-alouds throughout the learning session while the y-axis represents each of the coded SRL processes. Blue vertical lines are used to delineate each 5-minute episode in the 40-minute learning task.

In addition, the same SRL process data can be used to calculate state change probability estimates for clusters of SRL processes. Table 1 illustrates the state change table depicting probabilities of learners' subsequent self-regulatory moves based on a recent study with 82 college students (Azevedo et al., 2007). The table is read from the top to the side—for example, if the learner's first move is planning, then there is a .43 chance probability that his/her next move (reading off the right-hand side of the table) will be a strategy. Similarly, if the first move is a strategy then there is a .62 chance probability that the next move will also be a strategy. This table shows an interesting trend—regardless of what the first move is, the next most probable moves in descending order of magnitude are strategies, monitoring processes, planning activities, methods of handling task difficulties and demands, and then interest. These probability tables are useful in determining the granularity of assessing SRL processes and have tremendous utility in building adaptive hypermedia learning environments.

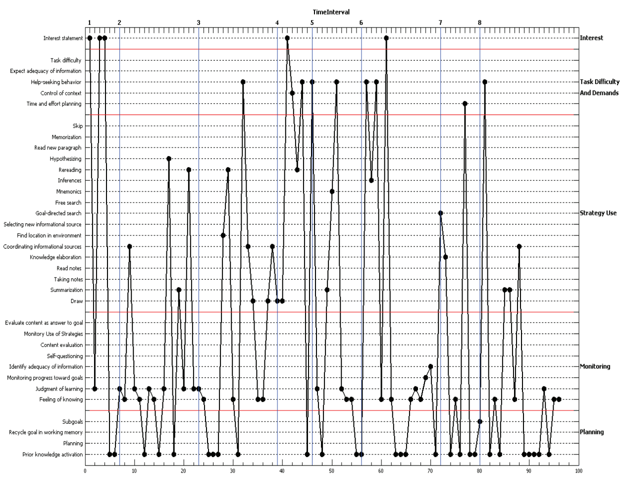

Figure 3. SRL Trace Data from a Participant Shifting from Low Mental Model Pretest to High Mental Model Posttest.

		1st Self-Regulatory Move				
		Planning	Monitoring	Strategy Use	TD&D[5]	Interest
2nd Self-Regulatory Move	Planning	.09	.10	.08	.10	.13
	Monit-oring	.29	.32	.17	.21	.26
	Strategy Use	.43	.38	.62	.48	.41
	TD&D	.17	.16	.11	.19	.09
	Interest	.02	.03	.02	.02	.11

Table 1. State change depicting probabilities of learners' subsequent self-regulatory moves.

Research that compares learning patterns over time and reflects regulation *per se* in a well-defined instructional context (a single learner learning about a complex science topic with a hypermedia environment) is needed. There is a need to use multiple measurements and to triangulate these different data sources. This can lead to a better understanding of SRL and lead to theory-building in the area which can then serve as an empirical basis for the design of computer-based learning environments. Recently, several researchers (Biswas et al., 2005; Witherspoon et al., 2007) have designed CBLEs that are both authentic environments for studying, as well as for gathering trace data about self-regulated learning events during learning. We have adopted a similar approach, and are presently constructing a hypermedia environment designed to study the components of SRL.

Conclusion

In this paper, we have provided a synthesis of existing research on learning with hypermedia by focusing on key cognitive and metacognitive processes related to self-regulation. There are several key theoretical, conceptual, methodological, and analytical issues that need to be addressed in order to advance our understanding of metacognitive monitoring and control processes related to hypermedia learning. Theoretically, there is a need to build a unified model of metacognition and self-regulated learning that incorporates key aspects of existing models, assumptions, processes, mechanisms, and phases. Such a process-oriented model would be ideal becuase it could be used to generate testable hypotheses regarding the facilitative and inhibitory nature of certain processes and underlying mechanisms and their impact on learning and performance. Conceptually, the field needs clarification on the multitude of divergent and overlapping constructs and processes across models to build a unified framework and model of metacognitive monitoring and control. Methodologically, the field needs to use multi-method studies and use current and emerging technological tools and sensors to capture and identify the dynamics of self-regulatory processes as they unfold linearly, recursively, and adaptively during learning. Furthermore, new statistical and analytical procedures need to be advanced in order to align and analyze temporal data from multiple sources such as eye-tracking, think-alouds, and facial expressions (denoting motivational and affective states) with existing measures (e.g., self-report measures) and methods. Lastly, the proposed issues would lead to theoretically-based and empirically-derive principles for designing advanced learning technologies aimed detecting, monitoring, and fostering learners' cognitive and metacognitive self-regulatory processes.

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[5] TD&D = Task Difficulties and Demands

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