

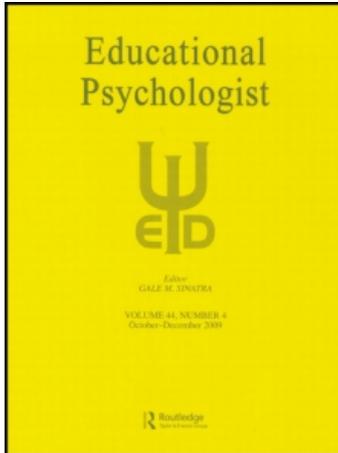
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Measuring Cognitive and Metacognitive Regulatory Processes During Hypermedia Learning: Issues and Challenges

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Measuring Cognitive and Metacognitive Regulatory Processes During Hypermedia Learning: Issues and Challenges

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Self-regulated learning (SRL) with hypermedia environments involves a complex cycle of temporally unfolding cognitive and metacognitive processes that impact students' learning. We present several methodological issues related to treating SRL as an event and strengths and challenges of using online trace methodologies to detect, trace, model, and foster students' SRL processes. We first describe a scenario illustrating the complex nature of SRL processes during learning with hypermedia. We provide our theoretically driven assumptions regarding the use of several cognitive methodologies, including concurrent think aloud protocols, and provide several examples of empirical evidence regarding the advantages of treating SRL as an event. Last, we discuss challenges for measuring cognitive and metacognitive processes in the context of MetaTutor, an intelligent adaptive hypermedia learning environment. This discussion includes the roles of pedagogical agents in goal-generation, multiple representations, agent-learner dialogue, and a system's ability to detect, track, and model SRL processes during learning.

Learning with open-ended learning environments such as hypermedia typically involves the use of numerous self-regulatory processes such as planning, knowledge activation, metacognitive monitoring and regulation, and reflection (Azevedo, 2005, 2007, 2008, 2009; Graesser, Mc-Namara, & VanLehn, 2005; Greene & Azevedo, 2009; Moos & Azevedo, 2008; Schraw, 2007; Veenman, 2007; Winne & Nesbit, 2009; Zimmerman, 2008). According to Pintrich (2000), self-regulated learning (SRL) is an active, constructive process whereby students set goals for their learning and then attempt to monitor, regulate, and control their cognition,

motivation, and behavior, guided and constrained by their goals and the contextual features in the environment. Most models of SRL propose a general time-ordered sequence that students follow as they perform a task, but there is no strong assumption that the phases (such as planning, monitoring, control, and reflection) are hierarchically or linearly structured such that earlier phases must occur before later phases (see, e.g., Azevedo, 2009; Azevedo & Witherspoon, 2009; Boekaerts, Pintrich, & Zeidner, 2000; Greene & Azevedo, 2007; Pintrich, 2000; Schraw, 2006; Schraw & Moshman, 1995; Schunk, 2001, 2005; Winne, 2001; Winne & Hadwin, 1998, 2008; Zimmerman, 1986, 2001, 2006, 2008; Zimmerman & Schunk, 2001). Whereas most theories, models, and frameworks of SRL tend to agree on some common basic assumptions (e.g., students strive to achieve goals, students are actively constructing knowledge, and contextual factors

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mediate students' ability to regulate aspects of learning), they also differ in some fundamental issues regarding the nature of SRL (e.g., event vs. aptitude, the role of contextual agents to model, scaffold, and foster self-regulatory processes, number and types of processes, specificity and complexity of the underlying internal and external mechanisms, and explanatory adequacy; see Schunk & Zimmerman, 2001; Zimmerman & Schunk, in press). These theoretical discrepancies pose challenges for those interested in understanding and measuring regulatory processes during learning with hypermedia (see Azevedo, 2005, 2007, 2009; Greene & Azevedo, 2007, 2009; Moos & Azevedo, 2008, 2009). The purpose of this article is not to resolve any of these major issues, which are disputed among the various theoretical positions. Instead, we focus on the methodological issues related to the online measurement of cognitive and metacognitive regulatory processes during learning with hypermedia-based environments. One principal goal of the article is to propose future methodological directions necessary to enhance the current theories of SRL, with particular attention to treating SRL as an event that dynamically unfolds during a learning session (Winne & Perry, 2000).

We have divided this article into four sections. First, we illustrate the complex nature of SRL as an event through an example of how a student might use a hypermedia system to learn about a complex science topic. Second, we present theoretically based assumptions regarding the measurement of cognitive and metacognitive processes as an event (based on Winne & Hadwin, 2008; Winne & Perry, 2000), which has been used extensively in our research on SRL with hypermedia. This section provides several hypothetical examples as well as examples from our research. The next section discusses the strengths and weaknesses of using online¹ trace methodologies to capture SRL. Last, we present and discuss several issues and challenges that need to be addressed in terms of measuring cognitive and metacognitive processes during learning. This discussion is contextualized in MetaTutor, an adaptive hypermedia learning system used to detect, trace, model, and foster SRL.

SRL WITH HYPERMEDIA ENVIRONMENTS: AN ILLUSTRATIVE EXAMPLE OF SRL AS AN EVENT

The complexity involved when reconceptualizing SRL as an event can be illustrated with an example of learning with

hypermedia. Some of these environments range from commercially available products such as Microsoft Encarta™ to researcher-developed multiagent intelligent learning systems such as MetaTutor (Azevedo, Johnson, Chauncey, & Burkett, 2010; Azevedo, Johnson, Chauncey, & Graesser, in press; Azevedo et al., 2008). Imagine that a student is asked to learn about the human nervous system with an open-ended hypermedia learning environment that consists of hundreds of paragraphs containing thousands of words with several hundred corresponding static diagrams and animations, all of which are organized linearly (similar to text chapters where the student can navigate from page to page). Furthermore, hundreds of hyperlinks allow the student to navigate nonlinearly through the environment. Consider the cognitive and metacognitive demands imposed by the abundance of information sources to select from and navigate through to reach the goal of developing a deep conceptual understanding of the biological system.

One could imagine that this self-regulated learner would analyze the learning situation, set meaningful subgoals, and determine which strategies to use based on the task conditions. In addition, the student may generate motivational beliefs based on prior experience with the topic and learning environment, success with similar tasks, contextual constraints (e.g., provision of adaptive scaffolding and feedback by the hypermedia environment or an artificial pedagogical agent), and contextual demands (e.g., a time limit for completion of the task). During the course of learning, the student may select strategies and assess whether these particular strategies are effective in meeting previously set learning subgoals. The student may also evaluate the emerging understanding of the topic and make the necessary adjustments regarding knowledge, behavior, effort, and other aspects of the learning context (e.g., whether the types of scaffolding being provided by a pedagogical agent are useful). The adaptive adjustments, based on continuous metacognitive monitoring and control related to the standards for the particular learning task, facilitate decisions regarding when, how, and what to regulate (Winne, 2001, 2005; Winne & Hadwin, 2008; Zimmerman, 2006). Following the learning session, the student may make several cognitive, motivational, and behavioral attributions that affect subsequent learning (Pintrich, 2000; Zimmerman, 2008).

This scenario illustrates the series of events that characterize SRL, particularly within the context of hypermedia. This hypothetical learner developed motivational beliefs, created subgoals, evaluated emerging understanding, and engaged in adaptation through the learning task. The inherent nature of hypermedia is such that the learner controls the sequencing of information embedded in multiple representations. This learning environment thus requires the approach of the hypothetical learner described previously; there is a need to monitor the content and emerging understanding, use a variety of strategies, and make adaptations. This engagement and adaptation illustrates one of many possible ways that

¹Online trace methodologies capture any activity that occurs during processing, whereas offline methods capture any activity that happens either before or after processing. For example, a concurrent think aloud protocol is an online method because cognitive and metacognitive processes are collected while a learner is using a hypermedia environment. In contrast, a retrospective protocol is considered an offline method that can be used by a researcher following a hypermedia learning session to probe a learner into describing why certain cognitive and metacognitive processes were used during the learning session.

learners can take to self-regulate their learning with hypermedia (Azevedo, 2009).

UNDERSTANDING THE COMPLEX NATURE OF SRL: FUNDAMENTAL ASSUMPTIONS

It has become increasingly important for researchers to understand the complex nature of the underlying self-regulatory processes that facilitate learning from multirepresentational open-ended hypermedia learning environments (see Azevedo, 2009; Azevedo et al., in press; Greene & Azevedo, 2009; Moos & Azevedo, 2009; Schraw, 2007; Schwartz et al., 2009; Veenman, 2007; Winne & Nesbit, 2009; Zimmerman, 2008). The example just described is used to illustrate the intricate nature of the metacognitive monitoring and control processes used during learning. Whereas we acknowledge the fundamental roles of other motivational, affective, and social self-regulatory processes, we focus exclusively on cognitive and metacognitive processes during learning with hypermedia environments in this article due to the scope of the current special issue. Careful consideration of these processes first requires a close examination of our fundamental assumptions regarding the measurement of cognitive and metacognitive processes.

Our assumptions are in line with Winne and Hadwin's (2008) information-processing theory of SRL. Briefly, their model posits that learning occurs in four basic phases: task definition, goal-setting and planning, studying tactics, and adaptations to metacognition. This model differs from others (see Dunlosky & Bjork, 2008; Dunlosky & Metcalfe, 2009; Hacker, Dunlosky, & Graesser, 2009; Zimmerman & Schunk, 2001) in that it hypothesizes that a set of processes, all of which are influenced by processed information, occurs within each phase. Winne and Hadwin described each phase in terms of the interaction of a person's Conditions, Operations, Products, Evaluations, and Standards (COPEs). 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.

Although 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 enactment 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 (or learning performance) is the result of recursive processes that cascade back and forth, altering conditions, standards, operations, and products as needed. This complex model leads to several assumptions that are in line with our assumptions regarding the use of online trace methodologies to measure SRL during learning with hypermedia. In the next section, we expand on these assumptions before we exemplify them by highlighting empirical data from our previous studies.

We start by assuming that *it is possible to detect, trace, model, and foster SRL processes during learning*. This approach is in line with the consideration of SRL as an event, which assumes that processes related to self-regulation unfold dynamically within particular contexts. Although some research has viewed SRL as an aptitude (i.e., a relatively enduring trait that can be used to predict future behavior), decades of research in cognitive and learning sciences using online trace methodologies, such as eye tracking, concurrent think aloud protocols, keystroke analysis, and cognitive modeling in capturing cognitive and metacognitive processes provide empirical support for viewing SRL as an event. Each of these techniques is based on information-processing assumptions regarding the role of cognitive, metacognitive, behavioral, and neural processes during learning and problem solving (see Anderson & Lebiere, 1998; Ericsson & Simon, 1993, 2006; Newell, 1990; Newell & Simon, 1972).

Using online trace methodologies allows researchers to capture the temporally unfolding cognitive and metacognitive processes during SRL. In our research, we have adopted several of these key methodologies to capture the deployment of SRL processes during learning. Therefore, we make a fundamental assumption that cognitive and metacognitive regulatory processes can be detected, traced, modeled, and fostered during learning. This is accomplished by converging several data sources including concurrent think alouds, video and audio time-stamp data, and log-file data all captured during learning with hypermedia. It should be noted that the analytical tool limits the scope with which SRL processes can be detected. Other online trace methodologies (e.g., eye tracking, error detection) are capable of providing additional data on SRL. Further, such alternative methodologies might be capable of revealing the deployment of other cognitive and metacognitive SRL processes, such as the assimilation of specific aspects of the text and diagram that are being integrated into a coherent mental model (e.g., Mayer, 2010; van Gog & Scheiter, 2010). It is also important to highlight that no single methodology can capture all of the processes and that, under some conditions, it is unwise to use some of these methods (e.g., using concurrent think aloud protocols for purely perceptual tasks or examining SRL in experts solving typical problems). The key

is to converge evidence from various analytical methods to measure the deployment of cognitive and metacognitive processes. These methodologies are further explored in the next section.

Second, understanding the complex, dynamic nature of the unfolding regulatory processes during learning with hypermedia is critical in *determining why certain processes are used* (i.e., what decisions did a student make that led to the deployment of a particular process, set of processes, absence of processes, or repeating patterns of processes that may fluctuate during the learning). These questions deal with the role of agency (Bandura, 2001), self-efficacy (Moos & Azevedo, 2008), adaptivity (Winne, 2001), developmental differences in the regulation of learning and task perceptions, and several other issues found in the literature. In addition, attempts at understanding the complex nature of SRL lead researchers to address several issues, which impact how and what is measured during hypermedia learning. For example, it is important to determine whether students used or did not use certain processes because they had the metacognitive knowledge but could not translate that knowledge into regulatory control (Veenman, in press). This scenario may be explained by the perception that particular cognitive and metacognitive processes were too difficult for the learner to understand or because there was a lack of conditional knowledge to determine when to use the SRL process.

Students may also lack experience with certain cognitive and metacognitive strategies, especially the more sophisticated ones (e.g., making inferences and self-questioning). In addition, they may have low self-efficacy in using such processes. This is especially true in the case of learners choosing not to deploy particular learning strategies because of a personal history of not having used them effectively during learning. Also, students may fail to encode some critical aspect(s) of the task environment or fail to continuously and dynamically change models of their task environments leading to poor task understanding. These issues unify perception, encoding, and action and rely on working memory capacity and executive processes. There may also be a lack of appropriate internal standards (or no standards at all for a new task with new demands; Winne, 2001). Furthermore, these issues have become extremely relevant as researchers attempt to find ways to model and externalize learners' internal cognitive standards. Learners may also fail to properly identify and register conditions. There are many cognitive, metacognitive, affective, and motivational explanations for learners' limited capacities to execute necessary regulatory processes such as low task value or lack of metacognitive control required to regulate affective processes (Chauncey & Azevedo, 2010). Last, the hypermedia environment may not afford the learner the ability to deploy the necessary regulatory processes (see Azevedo & Witherspoon, 2009; Winne, 2005; Winne & Nesbit, 2009). Using online methodology that addresses this set of complex issues is critical in determining the explanatory adequacy of SRL models and will

advance the field's understanding of *why certain processes are used*.

Our third assumption is that the use of SRL processes can *dynamically change over time* and that the unfolding of SRL is *cyclical in nature* (Azevedo & Witherspoon, 2009; Schunk, 2001; Winne, 2001; Winne & Perry, 2000; Zimmerman, 2008). This assumption is based on the notion that SRL processes not only are deployed in real time but also fluctuate in terms of frequency over the course of a learning task (e.g., more planning processes at the beginning of a learning task, constant use of metacognition monitoring processes throughout a task) and a host of other critical variables (e.g., making accurate metacognitive judgments, rate of knowledge acquisition, etc.). The learner's level of domain expertise is also a critical factor in the fluctuation of SRL processes, particularly in the observed relative frequencies of specific strategies across a learning session. Increased domain expertise may lead to a sharp decrease in learning strategies, such as note taking and drawing, throughout the learning task. Some metacognitive monitoring processes such as judgment of learning (JOL: an evaluation of one's own level of understanding of the current content) and feeling of knowing (FOK: an assessment of the level of familiarity with the current content from previous exposure) tend to be deployed at a constant rate over the course of a learning session (Azevedo et al., 2008). Other processes tend to occur very infrequently because the learning environment has been designed in such a manner that it prohibits or facilitates the deployment of particular strategies. For example, there are fewer occurrences of content evaluation (a metacognitive judgment made when one compares the content of the hypermedia learning environment to one's current goal) in a hypermedia environment that has been designed so that relevant diagrams have been preselected to appear with corresponding text (e.g., Azevedo et al., in press). In contrast, one can design a hypermedia environment whereby the onus is on the learner to search and select a relevant diagram to go with a particular text passage. These two examples would impact students' regulatory behavior in different ways.

Over the course of learning, learners leave a trace of SRL processes that may reflect their emerging understanding of the content, development or changes in internal standards, motivational beliefs and attributions, understanding of the dynamic changes of the learning context, and particular phases of learning (e.g., Aleven, Roll, McLaren, & Koedinger, 2010/this issue; Graesser & McNamara, 2010/this issue; Greene & Azevedo, 2009; Greene, Muis, & Pieschl, 2010/this issue; Moos & Azevedo, 2009). These traces can be analyzed in several ways and are informative in determining the qualitative and quantitative changes in SRL processes. For example, an utterance of, "I want to use the search engine to look for the next topic," as captured by a concurrent think aloud during the hypermedia learning task, provides a trace of the learner engaging in a goal-directed search. Quantitative changes are the raw frequency

with which learners use in specific SRL processes (i.e., How often did a learner engage in goal-directed search during the hypermedia learning task?). Qualitative changes, on the other hand, can be explored by examining how the learner makes a conscious decision to deploy a different SRL process than the one currently being enacted. An example would include determining whether the learner monitors the environment after engaging a goal-directed search.

Considering both quantitative and qualitative changes is critical to address fundamental questions. In particular, are some SRL processes associated with knowledge acquisition rather than knowledge integration? If so, what would models of SRL predict? For example, Zimmerman and Schunk's (2001) sociocognitive model would predict that there would be more planning at the beginning of the task, but does this hold if the task is dynamical and cyclical (Schunk, 2005; Winne, 2001)? If so, then when does one cycle end and another begin? What determines the onset of an SRL cycle? Is it knowledge acquisition phases, SRL phases (planning, monitoring, control, and reflection), internal cognitive changes (e.g., changes in goal setting, knowledge acquisition, standards), changes in contextual conditions (e.g., running out of time to complete the task), or fluctuations in motivational (e.g., increasing effort after realizing that one is completing goals in a timely manner) and affective (e.g., feeling confused after reading a complex paragraph) processes?

These traces provide quantitative data that should be mined with various statistical techniques to determine the relative probabilities of learners' SRL behavior. For example, work on state-transition analysis is currently being performed with machine learning techniques (e.g., Baker & Yacef, 2009; Biswas, Leelawong, Schwartz, Vye, & the Teachable Agents Group at Vanderbilt, 2005; Rus, Lintean, & Azevedo, 2009; Witherspoon, Azevedo, & D'Mello, 2008). State-transitions are calculated by creating a matrix of all the possible SRL processes and then entering the number of times a learner went from one state to the next (e.g., from planning to monitoring) based on coded online trace data (e.g., mostly from concurrent think alouds and log-file data). The end result is a state-transition table or diagram that is used to calculate the probability estimates of transitioning from one state to another during SRL with hypermedia. For example, our results show that there is a higher likelihood probability of using a metacognitive control process following metacognitive monitoring. In contrast, there is a low likelihood probability of using a planning to monitoring (Witherspoon et al., 2008). Last, as Veenman (in press) and Winne and Nesbit (2009) stated, these fluctuations can be modeled as production rules, which can then be embedded in intelligent learning environments to model and foster learners' SRL with hypermedia (e.g., Azevedo et al., 2008). These types of analyses are further explored in the following section.

Most of these issues related to the fluctuations of SRL during hypermedia learning can be best illustrated in Figure

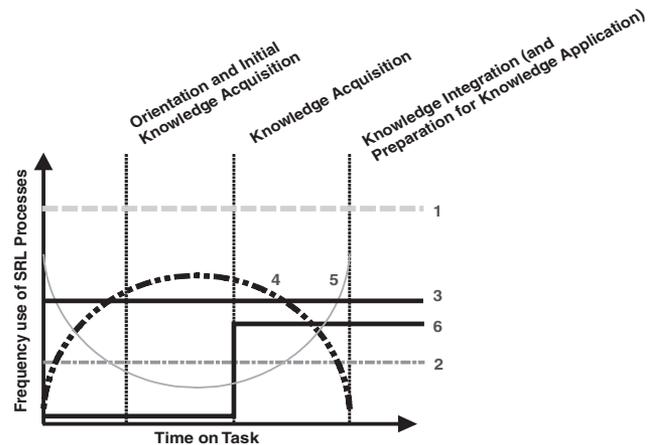


FIGURE 1 Hypothetical traces of self-regulated learning (SRL) processes used during learning with hypermedia.

1. The figure shows a hypothetical situation where we plot the relative frequency of SRL processes used by learners on the y -axis and the time spent on a learning task with a hypermedia environment on the x -axis. In addition, we include three hypothetical phases of learning (modeled loosely after several models of SRL including Winne & Hadwin, 2008; Zimmerman, 2006). In our example, we created three phases. In the *orientation and initial knowledge acquisition phase*, learners spend quite some time searching, analyzing, selecting, and orienting themselves to the structural elements of the hypermedia environment (e.g., types of navigation, location of potentially relevant and irrelevant informational sources, embedded system features that may facilitate knowledge acquisition such as annotation and note-taking tools). We would argue that during this phase, learners do commit to the processing of the hypermedia information, and we therefore consider this an initial phase of knowledge acquisition. After orientation, learners may begin to self-regulate by deploying SRL processes related to an initial knowledge acquisition phase, including time spent reading content and inspecting diagrams. The second (hypothetical) phase involves more time spent on *knowledge acquisition*, during which the learner moves away from the orientation and begins the process of acquiring information provided by the environment. This phase is then followed by the more advanced *knowledge integration phase*, which may include preparing oneself for knowledge application (such as getting ready to take a posttest). Each of these hypothetical phases is delineated by a vertical dotted line.

Figure 1 also depicts six potential trends illustrating the trace patterns of any number of SRL processes. Line 1 represents a constant high frequency use of some SRL process(es) throughout the task. Line 2 illustrates the opposite of Line 1; it represents constant but less frequent use of some SRL process(es) throughout the task. This pattern is typically found in the rare use of some sophisticated learning

strategies (e.g., making correct inferences) and metacognitive judgments (e.g., monitoring use of strategies). Line 3 is the “average” of Lines 1 and 2 and is more typical of what one would find with more frequently used SRL processes such as JOLs and FOK during hypermedia learning. Lines 4 and 5 are rarely observed and represent changes in the frequency of the deployment of certain SRL processes over the course of a learning task. Either of these patterns may be indicative of a learner’s initial awareness of SRL processes as either adequate or inadequate, followed by increased or decreased use of these processes, and last a return to using the SRL processes with the same frequency used during the initial part of the task. Line 6 is also rarely observed but demonstrates the case where significant time passes in a learning task before a student effectively uses a particular SRL process. This action is then followed by an abrupt and drastic change in the use of this strategy in the latter part of the task. In sum, these are representative traces and do not encompass all of the possible patterns that might occur during learning with hypermedia.

Our last assumption states that capturing, identifying, and classifying SRL processes used during learning with hypermedia are rather *challenging* tasks. Concurrent think aloud protocols are the premier tool used to capture, analyze, and classify SRL processes. This method should be augmented with other methods such as time-stamped video data and log-file data to get the precision needed to classify SRL processes at several levels of granularity. Researchers using these techniques have created coding schemes that differ in complexity, level of granularity, and task- or topic-dependency. The application of a particular methodology reflects the researcher’s theoretical orientation (e.g., Azevedo et al., 2008; Bannert & Mengelkamp, 2008; Manlove, Lazonder, & de Jong, 2007). For example, some coding schemes have several categories to capture broad categories of metacognition and SRL. These categories, termed “macrolevel,” can include planning, monitoring, and learning strategies. Other coding schemes include specific processes related to these broader categories of SRL. These “microlevel” processes can include JOL and FOK, which both fall under the macrolevel category of monitoring. As an example, students who deploy a microlevel process such as judgments of learning (i.e., “I did not understand what I just read”) are engaging in the macrolevel SRL process of monitoring. This operationalization of macrolevel SRL processes into component microlevel processes allows for a much more detailed examination of the many ways learners self-regulate but also presents challenges in terms of measurement (Greene & Azevedo, 2009; Greene et al., 2010/this issue).

We have recently added valence to our microlevel processes associated with monitoring and learning strategies to examine how issues of valence are related to specific SRL behaviors. In the context of this coding scheme, valence is defined as a negative or positive value assigned to the individual microlevel SRL processes. For example, a negative

content evaluation (CE–) would be reflected in the comment that “this picture does not help me learn about the structure of the mitral valve.” As such, the valence for monitoring processes indicates a positive or negative evaluation. According to Azevedo and colleagues’ work (Azevedo, 2008; Azevedo & Witherspoon, 2009) these classifications allow for different granularities in the analysis. In other words, the level of detail can vary depending on the scope of the analysis. For example, classification can be accomplished at the (a) macrolevel (e.g., monitoring process), and/or (b) microlevel (e.g., JOL) with associated valence (either + or –). The same can be done for learning strategies (e.g., correct summarization vs. incorrect summarization).

The addition of valence allows us to examine the feedback mechanisms and the nature of the linear and recursive feedback loops during SRL and test predictions based on current models. For example, according to several models of SRL, metacognitive monitoring precedes metacognitive control if learners are engaged in goal-driven learning. So, this assumption allows for the hypothesis that when learners make the metacognitive judgment that they do not understand what was just read (i.e., a negative judgment of learning [JOL–]), this judgment should be adaptively followed by a learning strategy such as re-reading. After re-reading, learners may evaluate that they now understand the paragraph (i.e., JOL+), and so on. What if they still do not understand the paragraph after re-reading it? What should they do next? Would they re-read again? If so, this could lead into a maladaptive SRL cycle that causes frustration or continued confusion. We argue that tracing the temporal unfolding of these SRL processes is key to understanding the nature of SRL processes, their interrelationships, adaptive versus maladaptive processes, the nature of the cycles, and testing predictions based on current models of SRL.

Examples From Empirical Evidence

In this section, we provide examples from our data to exemplify how we have treated SRL as an event during hypermedia learning. This presentation includes a brief summary of each data representation. First, Table 1 represents a snippet of a coded and segmented concurrent think aloud transcription from Moos and Azevedo (2008). The segments are in the first column (see Azevedo et al., 2008, for the details regarding the segmentation and coding), the second column contains the utterances from the participant, and the third column includes both the macrolevel (classes of SRL) codes related to *planning*, *monitoring*, and *strategy use* as well as microlevel codes related to SRL (i.e., summarizing, feeling of knowing, identifying the adequacy of information). This snippet revealed that this participant monitored both her² understanding of the topic (circulatory system) and the

²Personal pronouns are used in this section because they refer to the gender of the actual participant who provided these data.

TABLE 1
Example of a Segmented and Coded Concurrent Think Aloud Transcription With Micro and Macro SRL codes

Segment	Utterance Transcribed From Participant During Learning With Hypermedia	[Micro SRL] and Macro SRL Codes
1	I am going to start with the circulatory system just because I am already there . . .	[No Code]
2	. . . and I'm just reading the introduction..circulatory system..it also known as the cardiovascular system and it deals with the heart..it transports oxygen and nutrients and it takes away waste. . .	[Summarizing] <i>Strategy Use</i>
3	... um, it does stuff with blood and I'm kind of remembering some of this from bio in high school, but not a lot of it, um ...	[Feeling of Knowing] <i>Monitoring</i>
4	Reads: <i>The heart and the blood and the blood vessels are the three structural elements and the heart is the engine of the circulatory system, it is divided into four chambers.</i>	[No Code]
5	I knew this one, two right and two left .. the atrium, the ventricle and the left atrium, and the left ventricle . . .	[Feeling of Knowing] <i>Monitoring</i>
6	... okay start the introduction [of the heart], just kind of scout it out real quick..and there's a section called function of the heart . . . and it looks like it will give me what I need to know..	[Identifying Adequacy of Information] <i>Monitoring</i>
7	... um .. introduction, oh that's just basic stuff that we've been doing	[Feeling of Knowing] <i>Monitoring</i>
8	Reads: <i>Structure of the heart has four chambers</i>	[No Code]
9	We did that..	[Feeling of Knowing] <i>Monitoring</i>
10	Reads: <i>The atria are also known as auricles. They collect blood that pours in from veins.</i>	[No Code]
11	So, it looks like the first step is atria in the system and then the veins	[Summarizing] <i>Strategy Use</i>

Note. SRL = self-regulated learning.

relevancy of the environment's content. For example, she decided to hyperlink to the heart article after identifying that she had previously learned information in the circulatory system article (Segment 5). She continued to monitor her understanding (Segments 7 and 9) and then eventually used the strategy of summarization (Segment 11).

The second example, in Table 2, includes the raw frequencies, proportions, and means of the SRL processes by SRL class from concurrent think aloud protocols (from Azevedo, Johnson, Chauncey, & Burkett, 2010). Table 2 illustrates how our methodological approach addresses the role of these processes in hypermedia learning. This table represents data from 44 participants in an initial 60-min experiment using MetaTutor, a new multiagent hypermedia learning environment. For each of the five classes of SRL, the *Raw Frequencies* column presents an aggregate count of the number of instances of each particular class for all participants. The *Mean* column presents the average occurrence of each class

per participant during a 60-min learning session. Together, these two columns answer questions regarding which classes are used most frequently and how many times each class is deployed. Overall, learning strategies occurred most often (total raw frequency = 3,602) and occurred approximately once every 1.5 min (*M* usage = 81.93). Monitoring processes occurred less often (total raw frequency = 731) and occurred approximately once every 4 min (*M* usage = 16.61). The third column, labeled *Overall Proportion*, offers more insight into the relational nature of the deployment of each SRL class during the experiment. This column presents the proportion of SRL processes accounted for by each class during the 60-min learning session. For example, this data

TABLE 2
Raw Frequencies, Proportions, and Means of SRL Processes by SRL Class

SRL Class	Total Raw Frequencies Across Participants		Overall Proportion Across Participants %
	M (SD)		
Planning	226	5.14 (7.41)	4.80
Monitoring	731	16.61 (20.02)	15.56
Learning strategies	3,602	81.93 (40.40)	76.67
Task difficulty and demands	27	0.61 (1.20)	0.57
Motivation	112	2.55 (4.30)	2.38
Total	4,698		

Note. SRL = self-regulated learning.

TABLE 3
Raw Frequencies, Mean (Standard Deviation) Use of SRL Process, and Mean Duration of Monitoring Processes

SRL Monitoring Processes	Total Raw Frequencies Across Participants	M (SD)	M Duration of SRL Process (Seconds)
Content evaluation (+)	57	1.30 (2.42)	0:00:03
Content evaluation (-)	73	1.66 (2.52)	0:00:04
Expectation of adequacy of content (+)	15	0.34 (0.75)	0:00:04
Expectation of adequacy of content (-)	4	0.09 (0.36)	0:00:06
Feeling of knowing (+)	232	5.27 (6.61)	0:00:03
Feeling of knowing (-)	81	1.84 (3.34)	0:00:03
Judgment of learning (+)	161	3.66 (6.18)	0:00:03
Judgment of learning (-)	56	1.27 (2.49)	0:00:03
Monitor progress toward goals	13	0.30 (0.79)	0:00:09
Monitor use of strategies	11	0.25 (0.89)	0:00:06
Time monitoring	28	0.63 (1.45)	0:00:03

analysis provides insight into the proportion of monitoring and learning strategies in the context of all the SRL processes deployed by participants. These data indicated that learning strategies accounted for 76.67% of all SRL processes deployed by participants during the session. Monitoring only accounted for 15.56%, and the remaining three classes together accounted for only 7.75% of all SRL processes.

Table 3 presents a more detailed analysis of the monitoring data presented in Table 2. Here we have broken the monitoring SRL class into its seven constituents and their corresponding valence. In addition we also provide the raw frequencies, mean use during task performance, and mean duration (based on the concurrent think aloud protocols and time-stamped video recording of the session). This table illustrates the relative infrequency with which participants use metacognitive monitoring processes during hypermedia learning and that the mean duration of each of these processes is relatively short (ranging from 3 to 9 s).

Figure 2 illustrates the fluctuation in participants' use of some of the learning strategies during a 60-min hypermedia learning session (Azevedo et al., in press). The most commonly used learning strategies were taking notes, previewing, summarizing, and re-reading. The figure illustrates that participants took many notes initially and then decreased note-taking behavior throughout the session. In contrast, re-reading was rather infrequent (compared to other studies, e.g., Azevedo et al., 2008), but this result may reflect the design of the hypermedia learning environment. These data can be integrated with similar data presented in Table 3 to indicate that on average, learning strategy use persisted longer ($M = 10$ s) than metacognitive judgments ($M = 4$ s). For example, participants spent approximately 13 s summarizing, 20 s taking notes, and 10 s previewing per deployment of each process. It should be noted that there is a high amount of variability not only in the frequency of use for the SRL processes but also in the duration of each process across participants. We account for this variability in data analysis by

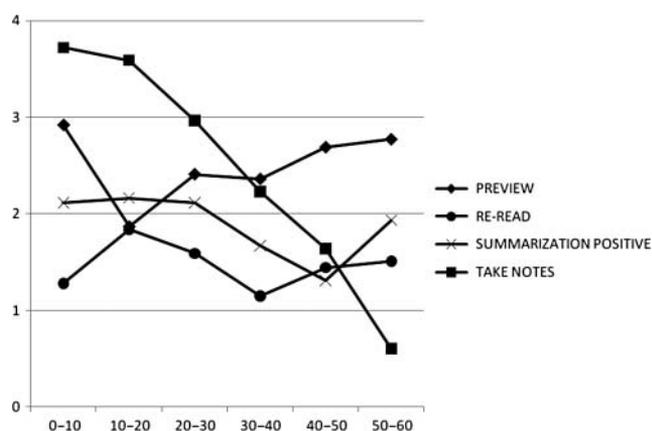


FIGURE 2 Mean frequency of learning strategies used during hypermedia learning by 10-min time intervals.

using proportion as a point for median splits (see Azevedo, 2009, for a discussion). In sum, these are just a few examples of the types of data that are used to represent the measurement of cognitive and metacognitive processes used by students during learning with hypermedia. Other methods not described here, due to space restrictions, include navigational profiles, eye tracking, and log-file analysis.

STRENGTHS AND WEAKNESSES OF ONLINE TRACE METHODOLOGIES

As can be seen from the previous examples, there are numerous strengths in using online cognitive trace methodologies including the gathering of vast amounts of data that reveal the temporal, dynamic deployment of SRL processes during learning. These data allow researchers to examine SRL processes at different levels of granularity from class-level (e.g., metacognitive monitoring) to various fine-grained levels (e.g., JOL or JOL-). These data provide evidence of the presence or absence, frequency and duration, changes, and sophistication of SRL processes, which are critical in explaining the role of these processes in hypermedia learning. Data can be analyzed at different temporal scales, from milliseconds (with log-file data) to seconds, minutes, and hours. These data are converged to examine the conditions under which these processes are deployed. Among the relevant conditions under study are internal conditions (e.g., a learner's internal standards used to assess the quality of information processing), learner characteristics (e.g., prior knowledge), and contextual conditions (e.g., access to a pedagogical agent that provides feedback, access to additional informational resources needed to complete the task, time constraints). For example, a low-prior knowledge learner may only deploy planning processes associated with prior knowledge acquisition during the later part of a learning session. Unlike self-report measures, which are widely used in SRL research, the data from trace methodologies provide actual evidence of cognitive and metacognitive processes and not learners' perceptions of their use of these processes. Process data can be used to examine not only the microlevel but also the feedback mechanisms associated with SRL processes. It is important to highlight that in some situations, online trace methodologies need to be combined so as to account for missing data captured during learning. For example, when a learner is silent (i.e., not providing a verbal trace) then time-stamped video data may be key in demonstrating that the silence is associated with the learner taking notes or drawing.

Current models of and frameworks of SRL (e.g., Pintrich, 2000; Schunk, 2001; Winne, 2001; Zimmerman, 2006) could be significantly enhanced by including some of the data that we have extracted by treating SRL as an event. Data can be modeled and formally programmed using artificial intelligence (AI) methods to detect, trace, and model the deployment of SRL processes during learning (e.g., Alevi

et al., 2010/this issue; Azevedo, Johnson, Chauncey, & Burkett, 2010; Graesser & McNamara, 2010/this issue). These emerging models can then be used to design specific micro- and macroadaptive tutoring and learning processes to foster students' learning with hypermedia in real time. For example, a microadaptive tutoring strategy may include providing immediate positive feedback regarding a learner's correct summary of the text found in one of the hypermedia pages. In contrast, a macroadaptive strategy may include prompting the learner to consider how well they are doing in terms of meeting their current goal, particularly if the learner has spent a considerable amount of time reading a limited number of pages, inspecting few diagrams, and taking minimal notes. These issues are discussed in the following section on future challenges.

However, though current models have been instrumental in providing global descriptions of various phases of learning (Pintrich, 2000), SRL processes, mechanisms, and feedback mechanisms, there are several challenges and weaknesses associated with these methods used to treat SRL as an event. For example, it takes years of training to properly conduct, code, and analyze data from think aloud protocols. This method is time-consuming and presents a bottleneck for researchers, who have to collect, transcribe (using widely adopted conventions), code, recode, and analyze vast amounts of data. Coding think aloud protocols is also challenging because it involves making theoretically driven inferences about the segmentation of language in terms of where each coded process begins and ends in a transcript. In addition, other specific processes (e.g., reading text) and contextual elements (e.g., clicking a certain interface element) may be added to the transcriptions. Converging other evidence is critical because it provides a context that is absent when just transcribing audio data. For example, we use specialized software that allows us to transcribe while playing a video of what the learner did while using the environments. This approach allows researchers to see exactly what a learner may be doing while there is no audible soundtrack. However, there are times when contextual cues are missing and in their absence certain segments cannot be reliably coded.³ Another challenge involves the temporal alignment of the process data so that inferences about processes are made correctly. Most of the challenges are discussed in the subsequent section on future challenges.

FUTURE CHALLENGES FOR MEASURING SRL WITH HYPERMEDIA ENVIRONMENTS

This section deals with future challenges of measuring cognitive and metacognitive processes with hypermedia environments. We do so by presenting MetaTutor as a useful

platform to raise several issues. MetaTutor is a multiagent, hypermedia-based intelligent tutoring system developed by our interdisciplinary team (Azevedo et al., 2008; Azevedo et al., 2010; Rus et al., in press). MetaTutor scaffolds students in the use of SRL processes in the context of learning about the human circulatory, digestive, and nervous systems. The underlying assumption of MetaTutor is that students should regulate key cognitive and metacognitive SRL processes to learn challenging science topics. Its design is based on extensive research by Azevedo and colleagues (most notably Witherspoon, Johnson, Chauncey, Moos, Greene, Cromley, and Winters) showing that providing adaptive human scaffolding that addresses both the content of the domain and the processes of SRL enhances students' learning of science with hypermedia.

A screenshot of the current version of the MetaTutor learning environment is provided in Figure 3. The interface is composed of a learning goal (set by the experimenter or teacher) that is associated with a subgoals box where the learner can generate several subgoals for the session. Topics and subtopics are presented on the left side of the interface (*Table of Contents*), and the actual science content (including the text and static diagrammatic representations of information) is presented in the center. Learners navigate the system by clicking the *next* or *previous* buttons, and the topic and subtopics in the table of contents. The screenshot also shows one of the four agents, Mary (top-right corner), who is responsible for metacognitive monitoring processes. Also illustrated is the timer that can be set for the duration of a learning session to allow the learner to remain aware of time constraints. There is a box for learners to indicate their metacognitive judgments (equivalent to the scales used in metacognitive judgment literature; see Schraw, 2009). There is also a dialogue box that provides an accurate record and history of the various agents' spoken dialogue and the learner's typed input. We have also included an SRL palette that (depending on the experimental condition) can be used by learners to indicate the SRL processes they are using during learning. Figure 3 is ideal for the purposes of presenting, addressing, and raising challenges regarding the detection, tracing, and modeling of cognitive and metacognitive SRL processes. Due to space limitations, we do not deal with issues related to the fostering of SRL processes.

Role of Pedagogical Agents and Goal Generation

One challenge for researchers is to accurately capture and measure students' self-generated goals during learning with hypermedia. Most of the goals generated by learners and captured by online trace methodologies are incomplete and rarely verbalized. As such, this creates a problem for measuring goal generation, assessing the quality of generated goals, and making inferences about how subsequent behaviors (e.g., navigation through the hypermedia, time spent

³These segments are not coded and they are removed from subsequent analyses.

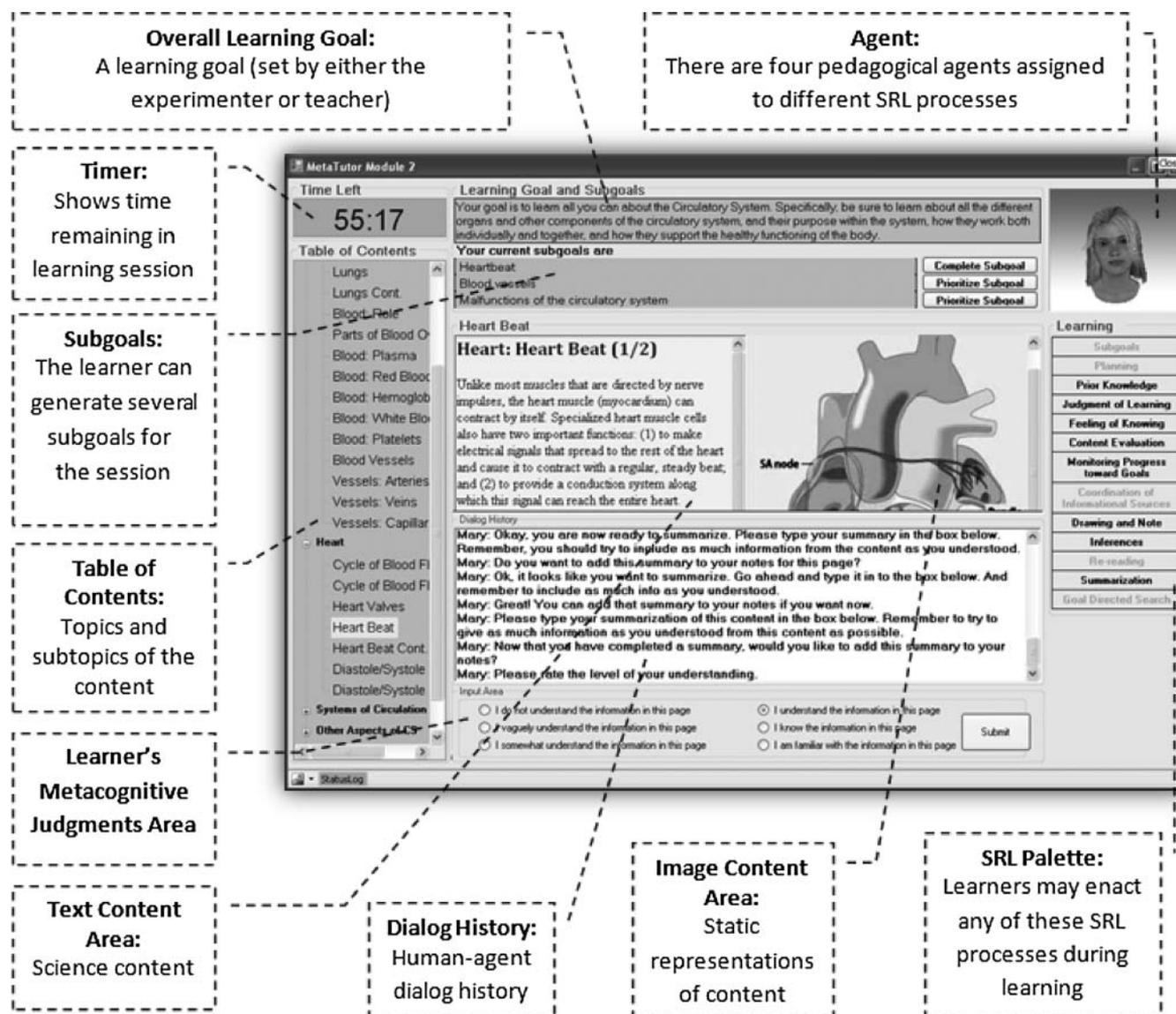


FIGURE 3 Screenshot and interface elements of MetaTutor.

on specific pages, time spent on relevant diagrams) and the deployment of specific SRL processes deployed is related to satisfying a particular goal. These issues can exacerbate and lead researchers to make erroneous assumptions and incorrect inferences regarding the role of goals and SRL. As such, it is extremely challenging to accurately capture and measure the generation, quality, and relevance of student's self-generated goals.

One way to address this issue is by employing *multiple artificial pedagogical agents*, such as the ones that populate *MetaTutor* to play particular roles. For example, these agents play a key role in facilitating the generation of self-set learning goals by modeling goal generation for learners and providing different types of feedback regarding poorly stated and irrelevant goals. The agents are also critical in engag-

ing in dialogue with the student to prompt students to use several cognitive and metacognitive processes such as prior knowledge activation, assess the quality of their emerging understanding, and explain how these processes may be related to subsequent goal generation. As such, the agents are critical in providing reliable data and therefore increasing our understanding of issues related to goal generation.

Role of Multiple Representations

Understanding how multiple representations of information are used by students to understand the content and meet self-set and experimentally set goals is a critical issue. Trace data collected in *MetaTutor* provide information regarding the selection and sequencing of representations, the duration

associated with the use of each representation, and the specific SRL processes associated with the selection, organization, and integration of verbal and pictorial information from multiple representations (see Mayer, 2005). This data collection is accomplished by examining clicking behavior, mouse movements, reading of content, and resizing of interface windows (to maximize viewing of text and diagrams). These data can be used to make inferences about knowledge gains (declarative and procedural knowledge) and to assess whether the specific representations selected are relevant to the current learning goal.

Despite the wealth of data generated by these methods, there are challenges that still need to be addressed—for example, determining how learners integrate microlevel processes during knowledge construction with multiple representations (Mayer, 2005). We are currently addressing this challenge by augmenting our methods with eye-tracking data that provide evidence of the underlying integration processes that are sometimes not verbalized by learners. Eye-tracking data can be used to determine whether the number of fixations and time spent on relevant areas of interest (AOIs) are associated with mental model development. In our case, relevant AOIs refer to important parts of the MetaTutor interface such as portions of the text and parts of an image, dialogue history (between learner and the agent), and so on. Fixating on these crucial interface components is important for learners to understand the content, process previous feedback from the agent, and so forth. In addition, regressions among relevant AOIs (i.e., subsequent fixations on previously fixated-upon AOIs) can provide evidence that supports verbalizations associated with specific learning strategies such as coordinating informational sources (e.g., visual switching between text and diagram). In contrast, a large number of fixations or prolonged fixations on irrelevant AOIs may indicate that learners do not know what part of a representation is relevant vis-à-vis the current goal. In this case, attentional guidance would be an optimal scaffolding method to be deployed by an agent. Last, eye-tracking data and other trace data can be combined to provide converging evidence of particular cognitive processes. For example, particular eye-tracking signatures may indicate coordinating information sources. Establishing converging data for particular cognitive and metacognitive processes may allow researchers to rely less on time-consuming, concurrent think aloud protocols.

Agent–Learner Dialogue

The dialogue between agents' spoken and learners' typewritten interactions is key to examining the nature of SRL processes during learning. Tutorial dialogues are a fundamental component of intelligent tutoring systems designed to support student learning (Aleven et al., 2010/*this issue*; Graesser & McNamara, 2010/*this issue*; Wolff, 2009). In multiagent environments such as MetaTutor, agent–learner tutorial di-

alogues can serve various functions. First, they serve as a trace of the interactions between the different agents and the learner. As such, we can examine how learners respond; such responses give researchers data on the nature of learners' self-regulatory processes. Prompting by an agent to use a particular strategy such as making an inference will be followed by any number of learner responses that will be indicative of their knowledge of the process, their understanding of its importance, and their ability to effectively deploy it. For example, learners may indicate that they do not know what an inference is, ask to see a model (i.e., a video of an agent making an inference after reading a text), ask what an inference is, attempt to make an inference, or ignore the agent's request. Each of these possible actions is indicative of learners' self-regulatory processes and used by MetaTutor to determine the best course of action. These traces can also be examined to determine if, for example, there are qualitative and quantitative changes that cut across a learning session. Second, these dialogue histories are part of the interface and always available to learners. Therefore, one interesting question is if they actually go back to a previous statement made by an agent so that they can make some kind of adaptation to their regulatory behavior. Third, psycholinguistic aspects of the interactions can be examined to determine the level of coherence and cohesion in agent–student dialogues.

Despite the advances made in computational linguistics and AI methods, there are several challenges that still need to be addressed by interdisciplinary researchers (e.g., Rus et al., *in press*). First, we need algorithms that can accurately assess learners' typewritten input regarding their understanding of the content and trace qualitative changes in their mental models of the topic. This is critical when MetaTutor, for example, asks students to summarize what they have learned in the last 10 min. Invariably, a learner will type a summary that will be of a certain length (e.g., 50–300 words) and the system must be able to parse, analyze, classify, and interpret the summary. The challenge is that the system needs to perform each of these steps accurately; otherwise it will mislead a learner by providing inappropriate scaffolding and feedback. A more challenging issue is the assessment of learners' inferences. Yet another issue to be explored is the role of externally regulated learning by pedagogical agents to facilitate SRL. MetaTutor is an optimal platform for this research because different types of externally regulated learning can be experimentally tested. For example, one version of the system could offer only prompts for students to deploy key cognitive and metacognitive SRL processes, and another version could augment this with feedback about the learners' SRL process. Last, adaptive systems such as MetaTutor can also be used to test the effects of fading (scaffolding) of SRL processes and content on learners' ability to regulate their learning. This approach would go far in terms of answering questions about the development of SRL competencies (Schunk, 2001).

Deployment of SRL Processes During Learning

The last issue we discuss revolves around the challenges in developing a system like MetaTutor that is able to detect, model, and trace learners' SRL processes during learning. We have shown evidence that this can be done in a post hoc fashion using cognitive trace methodologies. However, there are several major challenges involving a system's ability to detect the use of processes in real time. Systems like MetaTutor can detect only a few learning strategies because they have been programmed to detect them when learners perform some behavioral action or series of actions such as picking up a pen to draw or take notes. Even though the system knows when drawing and note-taking occurred, and for how long, it still is not capable of assessing the quality of the notes and drawings. This is a major obstacle in the development of intelligent systems designed to foster SRL. The challenge involves designing methods that in the absence of concurrent think alouds can detect, trace, and model cognitive and metacognitive processes during learning.

Several solutions to this problem are currently being tested. One is to gather enough evidence and determine the mean duration and range of duration of all possible SRL processes (see Tables 2 and 3). Such data allow us to program sensors in our software so that the system can anticipate and then make inferences regarding learners' behavior. More specifically, the system expects a certain SRL process or learning behavior (e.g., reading of content or inspection of a diagram) and then reacts depending on specified thresholds for SRL use. Each sensor is then programmed to detect where learners used a process prematurely (e.g., spent a few seconds on a relevant page), and MetaTutor would then ask whether they know the content. If learners answer that they know the content then they are given a quiz, and depending on their quiz score, they may be told to move on to new content or create a new subgoal. A major challenge has been setting different time thresholds for different cognitive and metacognitive SRL processes that are also capable of accounting for individual differences.

Another possible solution involves the use of an SRL palette (see Figure 3) that we have included in MetaTutor, which learners use to indicate which SRL process they are about to use by clicking on the button that is associated with particular SRL processes. For example, learners click on the content evaluation button to indicate that a diagram is either relevant or irrelevant for the current goal. The system then needs to identify the accuracy (or relevancy) of the learner's perception. The system's response is conveyed through the dialogue box. In this example, the system would need to identify whether the content evaluation (either + or -) is accurate given the content (or is relevant to the overall learning goal). We expect some of these challenges to be overcome in the next decade as the use of eye trackers and other biological sensors become increasingly used and part of computer interfaces. For example, it will be possi-

ble to create a database of reliable eye-tracking signatures for individual cognitive and metacognitive SRL processes. Now imagine a situation where learners' eye-tracking data are collected during learning with MetaTutor, and these data are automatically compared to the database and used in real time to make inferences as to why the system should foster learners' SRL.

In sum, we have briefly raised several issues and challenges related to the role of pedagogical agents, planning and subgoal generation, multiple representations, agent-learner dialogue, and the system's ability to detect, model, and trace learners' cognitive and metacognitive processes during learning. We envision interdisciplinary teams of educational and cognitive psychologists, educational researchers, computer scientists, AI researchers, computational linguists, engineers, and human-computer interaction researchers to continue to work together to address a multitude of theoretical, measurement, and system design issues related to measuring cognitive and metacognitive SRL during hypermedia learning.

CONCLUSION

Self-regulated learning with hypermedia environments involves a complex cycle of temporally unfolding cognitive and metacognitive processes that impacts student learning. In this article we presented several methodological issues related to treating SRL as an event and the use of online trace methodologies to measure these processes by detecting, tracing, and modeling students' SRL processes. We detailed theoretical assumptions, outlined the conceptual basis for the treatment of SRL as an event, described a scenario to illustrate the complex nature of SRL processes during learning with hypermedia, and provided empirical evidence regarding the advantages of treating SRL as an event. We also raised several key issues and challenges related to the measurement of cognitive and metacognitive processes during learning with hypermedia.

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