Exploring relations among college students’ prior knowledge, implicit theories of intelligence, and self-regulated learning in a hypermedia environment

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A B S T R A C T

Researchers and educators continue to explore how to assist students in the acquisition of conceptual understanding of complex science topics. While hypermedia learning environments (HLEs) afford unique opportunities to display multiple representations of these often abstract topics, students who do not engage in self-regulated learning (SRL) with HLEs often fail to achieve conceptual understanding. There is a lack of research regarding how student characteristics, such as prior knowledge and students’ implicit theory of intelligence (ITI), interact with SRL to influence academic performance. In this study, structural equation modeling was used to investigate these issues. It was found that prior knowledge and ITI were related to SRL and performance, and that SRL acted as a benevolent moderator, enhancing the positive effects of prior knowledge upon learning, and diminishing the negative effects of having a maladaptive ITI.

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In the United States and around the world, advancement through scientific understanding has been one of the primary engines of economic development (National Academy of Sciences, 2007). Yet students in the United States continue to struggle with even basic understanding in science, as evidenced by an overall decrease in average student performance on the science portion of the National Assessment of Educational Progress between 1996 and 2005 (Grigg, Lauko, & Brockway, 2006). Deep conceptual understanding in science, which includes declarative as well as procedural knowledge of complex systems (Schraw, 2006), is even less common among U.S. students. A preponderance of evidence supports the claim that, particularly in science domains, complex systems (e.g., the circulatory system) are difficult for students to learn (Chi, 2005; Hmelo-Silver & Azevedo, 2006). Yet this conceptual understanding is necessary if students are to be able to apply and transfer their knowledge to real world problems (Roth, 1990).

Researchers and educators have studied whether hypermedia learning environments (HLEs) might be used to foster conceptual understanding in science (Azevedo, 2005; Jacobson, 2008). While the multiple representations afforded by HLEs can help students acquire sophisticated understanding (Lajoie & Azevedo, 2006), they are most effective when students are able to self-regulate their learning (Azevedo, 2005; Azevedo & Jacobson, 2008; Shapiro, 2008; Shapiro & Niederhauser, 2004; White & Frederiksen, 2005). Models of self-regulated learning (Pintrich, 2000; SRL: Winne & Hadwin, 1998; Zimmerman, 2000, 2001) highlight that successful students actively engage in planning, monitoring, and assessing the efficacy of the strategies and operations they use to acquire knowledge, and that these students have adaptive self-beliefs that foster their use of SRL processes. There is ample research showing a direct relation between the quality of student self-regulation and academic outcomes (cf. Azevedo & Cromley, 2004; Greene & Azevedo, 2007a).

However, more empirical research is needed regarding the role of student characteristics, such as self-beliefs and prior knowledge, in SRL (Muis, 2007; Pintrich, 2002; Winne, 2005). Winne and Hadwin (1998) posit that the more students self-regulate, the more opportunities there are for their self-beliefs to have direct effects upon both the number and kinds of learning processes students enact. Importantly, more frequent, high-quality self-regulation is also posited to influence the quality of the standards these students strive to meet when learning, thus suggesting that SRL processes can moderate the effects of student characteristics, such as self-beliefs, upon the learning process. An influential self-belief that has received little attention in SRL research is a student’s implicit theory of intelligence (ITI). Dweck & Leggett, 1988). Dweck and Master (2008) argue that an adaptive ITI encourages SRL, whereas a maladaptive implicit theory discourages regulation, but it is unclear whether the effects of ITI on learning are moderated by SRL processing. Another student characteristic, prior
knowledge, has been shown to influence academic performance and SRL processing as well (Greene & Azevedo, 2009; Moos & Azevedo, 2008). Finally, while past empirical studies have examined how student characteristics and SRL interact (e.g., Dresel & Haugwitz, 2008), much of this research utilized unreliable self-report measures of SRL (Winne & Jamieson-Noel, 2002). More reliable methods for measuring SRL, such as think-aloud protocols (Ericsson & Simon, 1993), are needed to examine whether SRL moderates (Baron & Kenny, 1986) relations between student characteristics and performance.

In this study, we sought to address the lack of research on the role of student characteristics, including self-beliefs, in SRL, and to investigate SRL’s role as a potential moderator of the relations between student characteristics and performance. We used think-aloud protocol data to examine how college students’ ITI and prior knowledge related to their use of self-regulatory processes and subsequent acquisition of conceptual understanding of a complex science topic, the circulatory system, while using an HLE. The findings from this study can be used to inform pedagogical decisions regarding how to use HLEs to foster conceptual understanding in science.

1. Complex science topics and hypermedia

It is important for students to understand complex scientific topics, but these topics have several inherent features that make them difficult for students to grasp. Fundamentally, complex topics are multilayered and contain intricate relationships that are difficult to master (Azevedo, 2005). Additionally, complex topics are often counterintuitive (Jacobson & Wilensky, 2006). For example, students may reason that both the moon and the sun produce their own light, and thus have trouble understanding that light from the moon is merely reflected. Finally, complex topics are difficult to grasp because they are frequently not readily available for students to view and manipulate in their entirety (e.g., the circulatory system and blood flow). A variety of technology-based alternatives have been explored as a means of overcoming these inherent difficulties in understanding complex scientific topics (Lajoie & Azevedo, 2006).

Hypermedia learning environments (HLE) are computer-based tools that consist of nodes of information interconnected using hyperlinks. HLEs contain multiple representations of information including video, audio, diagrams, text, and animation (Scheiter & Gerjets, 2007). Jacobson and Archodidou (2000) cited several unique advantages that hypermedia learning environments provide students who wish to learn about complex topics. First, HLEs, through their linked structure, encourage students to interact with information in multiple, non-linear ways. Additionally, students can exert control over the environment, moving through a particular section or representation at their own pace, repeating sections as necessary to construct knowledge. In addition, hypermedia learning environments are often more engaging than traditional teaching techniques (Jonassen, 1989). Finally, HLEs can present complex systems that are not otherwise readily available for inspection (e.g., the circulatory system) through the coordination and integration of multiple representations that can be manipulated by users (Delany & Gilbert, 1991; Mayer, 1999).

Despite all these advantages, HLEs are not a panacea when it comes to helping students develop an understanding of complex science topics. For example, research has shown that learners can struggle to coordinate multiple representations of information into understanding (Ainsworth, 2006). Learners have to understand each individual representation on its own, as well as how to translate between and integrate the multiple representations into an accurate construction of knowledge. Learners that lack these skills do not benefit from multiple representations, and can become overwhelmed. Cognitive overload and student disorientation are two other reasons why HLEs do not always meet their full potential as tools for learning complex topics (Gerjets, Scheiter, & Schuh, 2008). Cognitive overload occurs when learners overtax the limits of their working memory, which is responsible for processing and storing information in the brain (Baddeley, 2001). For example, learners’ working memory may become overwhelmed with the number of options HLEs provide. The additional requirements of operating a hypermedia environment, with its numerous linked multiple representations, place a load on working memory that does not exist when students use more linear learning methods (Niederhauser, Reynolds, Salmen, & Skolmoski, 2000). Numerous studies have found that novices in a domain struggle to attend to the relevant aspects of multiple representations, including animations, and instead tend to focus on what is most salient (Liu & Hmelo-Silver, 2009; Lowe, 2003). Finally, the enhanced learner control provided by a hypermedia learning environment can detract from students’ learning if users frequently become disoriented in the environment. For example, as learners move freely within the environment to learn a complex topic, they may spend too much time and too many cognitive resources just trying to learn the navigation procedures of the HLE. Research suggests that the use of self-regulated learning processes can mitigate the effects of disorientation and cognitive overload and improve students’ learning of complex science topics while using hypermedia (Azevedo, Guthrie, & Seibert, 2004).

2. Theoretical frameworks

2.1. Self-regulated learning

Although numerous models of SRL have been proposed (Pintrich, 2000; Winne & Hadwin, 1998; Zimmerman, 2000), there are several enduring and important themes common to each. Researchers agree that students are more likely to be successful when they clearly define the task, make a plan and set standards or criteria for their learning, monitor the effectiveness of the strategies they enact, and reflect upon how they learn. Throughout these phases of SRL, learners use metacognitive skills to self-regulate their cognition, motivation, behavior, and context. In general, learners who effectively self-regulate their learning outperform those who do not (Pressley & Ghatala, 1990; Pressley & Harris, 2006; White & Frederiksen, 2005).

Most models of SRL align with Zimmerman’s (2002) statement that “self-regulation is... the self directive process by which learners transform their mental abilities into academic skills” (p.65). For example, Winne and Hadwin (1998) posit a cognitive system where task and cognitive conditions, including student beliefs and prior knowledge, influence the kinds of operations and processes students enact while learning. These operations and processes, such as establishing sub-goals and enacting strategies, are two of the primary determiners of academic success. Students who use appropriate and powerful operations and processes are more likely to learn the material (e.g., comparing a text description of the flow of blood through the circulatory system with a picture of the process). Therefore, these models show how SRL can have a direct effect upon learning.

Winne and Hadwin’s model illustrates another potential relationship among student characteristics, SRL, and performance. In their model, student characteristics influence the standards students use when they engage in metacognitive monitoring and control. These
standards are the criteria against which students compare their learning, and they are used to determine whether the operations and processes being enacted are leading to success or are in need of revision. Effective self-regulators use these standards when they are helpful, and alter them when they prove unhelpful. When viewed this way, SRL seems to be a moderator (Baron & Kenny, 1986) of the relationship between student characteristics and performance. For example, students with high prior knowledge about a subject are already at an advantage compared to their less knowledgeable peers in terms of their likelihood of learning the material. This advantage can be compounded as the more knowledgeable students iterate through the phases of learning (i.e., task definition, planning, studying, adaptations; Winne & Hadwin, 1998) because these students are more likely to create adaptive standards, and use these standards to effectively drive their self-regulation. In essence, an availing standard (i.e., one created using high prior knowledge in this example) serves as a better guide for SRL metacognitive monitoring and control than a standard created from low prior knowledge. Under this scenario, the effect of prior knowledge would be magnified, or moderated, by the amount of SRL the students enacted.

Effective monitoring, however, can also mitigate the effects of less adaptive student characteristics. Students with an entity ITI, for example, believe that intelligence is fixed and cannot be improved. Successful implementation of SRL processes, and accurate metacognitive monitoring that reveals the maladaptive nature of a standard based upon an entity theory, can lead to adaptation, or at least the mitigation, of the influence of that student belief over the course of learning (Winne, 2001). In this case, the frequent use of SRL processes can moderate the otherwise negative effects of maladaptive student characteristics. Thus, given the conceptual models of SRL, it seems that when investigating exactly how SRL influences the learning process, researchers must account for the possibility that SRL has both a direct effect upon learning, and a moderating effect upon the relations between student characteristics and learning.

Numerous researchers have examined the interactive relations between student characteristics and SRL, including the effects of epistemic beliefs (Hofer, 2004; Muis, 2007) and self-efficacy (Braten & Olaussen, 2005) on metacognition, and the influence of students’ attributions upon SRL (Dresel & Haugwitz, 2008). Further, some empirical studies of SRL have examined its role as a moderator with other student characteristics (e.g., Dresel & Haugwitz, 2008). However, as we discuss in more depth later, these studies have captured SRL using unreliable self-report measures, calling into question the accuracy of their findings (Winne & Jamieson-Noel, 2002). Finally, compared to other student characteristics such as prior knowledge, research into the effects of students’ implicit theories of intelligence (Dweck & Leggett, 1988) has received comparatively little attention within SRL research.

2.2. Implicit theories of intelligence

An individual’s implicit theory of intelligence (Dweck & Leggett, 1988; Hong, Chiu, Dweck, Lin, & Wan, 1999) is one example of a self-belief that has been shown to have a relationship with learning (Schommer, 1993). Individuals are posited to have an ITI that exists on a continuum from an entity theory, the belief that intelligence is fixed at birth and unchangeable, to an incremental theory, or the belief that intelligence develops and is malleable. Both entity and incremental views are equally prevalent in our society (i.e., about 40% entity, 40% incremental, and 20% undecided; Dweck & Master, 2008). Additionally, these beliefs are typically stable over time and do not vary by gender (Robins & Pals, 2002), although they can be influenced by specific teaching strategies (Dweck & Master, 2008).

According to Dweck and Master (2008), there are several aspects of learning that might be influenced by students’ ITI including their goals, desire to learn, regulatory behavior, and thoughts about success, failure, and effort. For instance, students who hold an adaptive (i.e., incremental) view are more likely to persist when learning challenging material and believe that learning occurs through the use of strategies and increased effort, specifically through the self-regulation of learning and motivation. On the other hand, students who hold a maladaptive (i.e., entity) theory believe that appearing smart is more important than learning and that failure is diagnostic of low intelligence. These students tend to use lower-level strategies that result in shallow processing, particularly when working with difficult material.

Mueller and Dweck (1998) investigated the effects of praising effort versus ability (i.e., intelligence) on fifth grade students’ achievement behaviors (e.g., goal setting) and beliefs (i.e., ITI). They found that praising effort fostered a desire to learn and an incremental ITI, while praising intelligence fostered a desire to demonstrate acceptable task performance and an entity theory. These results suggest that students praised for ability are likely to seek out opportunities to demonstrate accurate performance as opposed to seeking opportunities to increase their learning. In addition, Blackwell, Trzesniewski, and Dweck (2007) conducted a quasi-experimental study in which they examined the impact of teaching ITI ideas to students. The experimental group received information regarding how the brain functions and changes, stressing that intelligence is malleable and that individuals can control the development of intelligence. After the intervention, the participants in the experimental group more strongly endorsed an incremental ITI, whereas there was no difference in ITI from pretest to posttest in the control group. Also, significantly more students in the experimental group were reported to show increased motivation, based on teacher report.

Overall, while Dweck and Master (2008) review a number of studies showing an influence of ITI upon students’ choice of activity, and self-reported or teacher-reported motivation and learning strategies, to date we are aware of no studies that have utilized specific observations of students’ SRL processing. Our use of think-aloud protocol data, described later, allowed us to show the influence of ITI on actual student behavior, rather than relying upon self- or teacher-report to assess ITI’s influence, and thus make an important contribution to this literature. Further, while past studies have shown independent effects of ITI and SRL on learning, this study contributes to the literature by examining potential moderator relations between these constructs, and their interactive influence upon the acquisition of conceptual understanding while using an HLE.

3. Empirical research on SRL, hypermedia, and complex science topics

3.1. Overview of SRL and performance research

Previous research has investigated the relation between SRL and students’ learning. Azevedo and Cromley (2004) examined the hypothesis that specific training in self-regulated learning skills would improve college students’ ability to learn a complex topic using hypermedia. In this study, the researchers created two groups. Each individual in the control group was tasked to learn as much as possible about the circulatory system while using a hypermedia learning environment for 45 min. On the other hand, the researchers gave students
in the experimental group 30 min of training on self-regulated learning followed by an opportunity to practice SRL skills using a different learning task, before asking them to learn about the circulatory system in the same manner as the control group. Azevedo and Cromley concluded that students in the experimental group reached a deeper conceptual understanding than students in the control group due to the SRL training. Additional research using the Azevedo et al.’s model (Azevedo, Guthrie, et al. 2004; Greene & Azevedo, 2007a) showed that students who effectively regulated their learning while working in a hypermedia environment were more likely to gain a conceptual understanding than students that failed to regulate their own learning.

Other researchers have also explored the relationship between the use of SRL and performance. Kramarski and Gutman (2006) worked with students learning math in an electronic learning environment. Students in this study were split into two groups. Students in the experimental group were exposed to self-regulated learning training that focused on self-metacognitive questioning, mathematical explanations, and metacognitive feedback. Students in the control group were not given this training, but received all the other lessons that the experimental group received. Students that received the self-regulated learning training significantly outperformed the control group in both problem solving and mathematical explanations. Santhanam, Sasidharan, and Webster (2008) investigated the effects of self-regulated learning on students learning an information technology skill in an e-learning environment. The researchers found that students could be taught to self-regulate their learning while learning to build a web page using an electronic tutorial. Students that received the training self-regulated their learning more and performed better on learning outcomes than students that did not receive the training. Camahalan (2006) explored the effects of self-regulated teaching and training for young mathematics students in southeast Asia. This research also found a positive effect for the instruction and use of SRL among students.

3.2. Research on prior knowledge

Prior knowledge has been shown to be a predictor of posttest performance in numerous SRL studies (Azevedo & Cromley, 2004; Azevedo, Cromley, Winters, Moos, & Greene, 2005; Azevedo, Moos, Greene, Winters, & Cromley, 2008; Greene & Azevedo, 2007a; Greene, Moos, Azevedo, & Winters, 2008). This is not surprising, as students who know a great deal about a complex system are well prepared to make good use of the vast amounts of information presented in HLEs (Liu & Hmelo-Silver, 2009). However, research suggests that prior knowledge is not simply a covariate that must be accounted for (Moos & Azevedo, 2008). Rather, prior knowledge also seems to have a relationship with the quality and quantity of SRL processes enacted during learning. Moos and Azevedo found that, while using an HLE to learn about the circulatory system, students with high prior knowledge engaged in high-quality self-regulated learning processes, including planning and monitoring processes. Students with low prior knowledge used more surface-level SRL strategies such as summarizing. Based upon these findings, Moos and Azevedo suggested that students with low prior knowledge have less working memory space available for high-quality SRL processes, and instead must focus their limited working memory capacity on knowledge acquisition rather than integration or verification. Moos and Azevedo did not examine whether the frequency of SRL processing had an influence upon the relationship between prior knowledge and learning. To expand upon these empirical findings, in this study we examined whether more frequent use of high-quality SRL moderated the relation between prior knowledge and posttest conceptual understanding.

3.3. Measuring SRL

Many empirical studies utilize self-report measures to capture inter-individual differences in how students regulate their learning (cf., Duncan & McKeachie, 2005), and numerous relations between these measures and various academic and social outcomes have been established (Zimmerman, 2008). However, Winne and Jamieson-Noel (2002) have shown that students are poor reporters of their SRL activities, calling into question the validity of inferences based upon scores from self-report measures. Further, the use of self-report instruments presupposes that self-regulation is akin to an aptitude (Winne & Perry, 2000), implying that SRL is a relatively domain-general, static disposition or trait. This characterization of SRL that underlies self-report measures does not align well with process or phase models of SRL (Pintrich, 2000; Winne & Hadwin, 1998; Zimmerman, 2000) that suggest students enact monitoring and control of learning in a dynamic manner, over time, with variance within and across tasks and context. Such dynamic activity cannot be captured with a survey administered at one time point prior to a learning task.

Given these concerns with self-report measures, we have chosen to utilize think-aloud protocols (Ericsson, 2006; Ericsson & Simon, 1993) to capture students’ SRL. These protocols involve asking students to verbalize all of their thoughts while learning, and recording what the students say. These verbalizations, once transcribed, can be used as indicators of SRL processes, and provide information about what learners do over the entire course of the learning task. Capturing SRL this way aligns well with conceptual models of SRL, and allows for detailed information regarding what processes learners enact, as well as when, how frequently, and in what context these processes occur. Numerous authors (Azevedo, Cromley, & Seibert, 2004; Azevedo, Guthrie, & Seibert, 2004; Azevedo et al., 2005, 2008; Greene & Azevedo, 2007a, 2009) have used think-aloud protocols to demonstrate relations between SRL and learning in HLEs. This study builds upon Azevedo et al.’s work by examining how a self-belief relates to the quality and frequency of SRL processing, and by analyzing whether SRL processing, captured using think-aloud protocol data, moderates the influence of student characteristics upon learning.

3.4. Azevedo et al.’s model of SRL

Azevedo et al.’s (2008) model of SRL integrates the work of Pintrich (2000), Winne and Hadwin (1998), and Zimmerman (2000) into a scheme that can be used to assess students’ SRL process use while learning. A major contribution of this model is the clear connection made between observable SRL processes that students enact while learning and conceptual models of the phases and areas of self-regulation (Pintrich, 2000; Winne & Hadwin, 1998; Zimmerman, 2000). For example, Winne and Hadwin describe how students enact different operations (e.g., strategies) depending upon what they are in their learning process. As such, students who are defining the task might activate their prior knowledge regarding the content studied whereas students who are in the process of learning the material might make inferences that are derived from two or more pieces of information. Across all four phases of learning (i.e., task definition, goal setting and planning, studying, and adaptation), Azevedo et al.’s model identifies over 30 SRL processes, including those addressing the areas of...
cognition, motivation, metacognition, and context. In addition, the model includes a coding scheme that defines how SRL process data might be inferred from think-aloud protocols.

The coding scheme developed by Azevedo et al. (2008) focuses upon what Greene and Azevedo (2009) call the micro- and macro-level SRL processes that students enact when learning. Micro-level SRL processes include such actions as setting sub-goals, evaluating content for its usefulness, and using strategies such as drawing or taking notes. While there is certainly value in examining what micro-level SRL codes are associated with learning in an HLE, each of these micro-level SRL codes can also be characterized as an instance of a macro-level SRL code (see Appendix A for a complete list of micro- and macro-level SRL codes). In Azevedo et al.’s model there are 5 macro-level SRL codes or processes: planning, monitoring, strategy use, handling task difficulty and demands, and displaying interest. These macro-level SRL codes align well with the processes that are outlined in conceptual models of SRL, yet often measured using self-report instruments (e.g., Bembenutty, 2007; Bendixen & Hartley, 2003; Kramarski & Gutman, 2006; Sterling, Howard, Staley, & DuBois, 2004). The benefit of using Azevedo et al.’s model is that micro-level SRL processes can be inferred from verbal report (i.e., think-aloud protocols) rather than using unreliable self-report data, and these processes can then be used as indicators of macro-level SRL processes that have been shown to be predictive of learning performance.

We believe frequent use of micro-level SRL processes is predictive of learning, particularly given that Zimmerman (2000) has shown that more frequent use of SRL processes in one phase of learning has been found to be associated with greater SRL process use in all other phases of learning. However, prior research has shown that certain micro-level SRL processes in Azevedo et al.’s scheme are associated with learning about complex science topics, while other micro-level SRL processes are actually predictive of a failure to learn (Azevedo & Cromley, 2004; Azevedo, Greene, & Moos, 2007; Greene & Azevedo, 2007a). Therefore, we felt it important to be selective when determining which micro-level SRL processes to include in the creation of our macro-level SRL process variables so that the latter represented only adaptive, or high-quality, processes. Later we outline which specific micro-level SRL processes from Azevedo et al.’s coding scheme were included as indicators of high-quality macro-level SRL processing. Next, we describe issues regarding how SRL can be modeled as a function of these macro-level SRL processes.

4. Modeling SRL

Numerous researchers (Azevedo & Cromley, 2004; Greene & Azevedo, 2009; Moos & Azevedo, 2008) have used think-aloud protocols to capture SRL data. However, researchers continue to explore how to handle the vast amounts of information provided by think-aloud protocols. To reduce this information to a manageable amount, and account for idiosyncratic differences in micro-level SRL process use, Greene and Azevedo (2009) summed micro-level SRL processes into macro-level SRL variables, and used the latter in regression analyses. Modeling SRL at the macro-level reduces the number of variables to be used in analyses, resulting in lower sample size requirements for adequate statistical power.

To our knowledge, researchers have not tried to model SRL data from think-aloud protocols using structural equation modeling (SEM). It seems plausible to attempt to model SRL as a latent factor given that researchers have treated it “as a metacognitive, motivational, and behavioral construct” (Zimmerman, 2008, p. 167), and that there is empirical research showing high positive correlations between SRL process use in each phase of learning (Zimmerman & Kitsantas, 1999). Modeling SRL using SEM would allow for both a test of the validity of inferences from macro-level SRL process scores as well as the disattenuation of error from those scores, leading to a stronger measure of SRL and more statistical power in analyses of relations among SRL, student characteristics, and learning (Kline, 2005). Given these potential benefits, in this study, we modeled SRL as a latent factor indicated by participants’ scores on the macro-level SRL process variables planning, monitoring, and strategy use (see Appendix A). Using macro-level SRL variables as indicators for a latent SRL factor gave us sufficient statistical power to examine whether SRL moderated the relations among student characteristics, such as prior knowledge and ITI, and posttest performance.

5. Overview of the current study

There is a clear need for a better understanding of how to foster conceptual understanding of complex science topics. While HLEs show great promise due to their ability to present vast amounts and kinds of information, students seem to need strong SRL skills to benefit from these systems. Previous research has shown that prior knowledge and the quality of students’ SRL skills influence their learning. In addition, conceptual models of SRL suggest that student beliefs are related to how students self-regulate, and the quality of their metacognition. There is a great deal of research showing that ITI influences learning through its effects upon motivation and SRL. Yet, to our knowledge, no study has examined how students’ ITI relates to prior knowledge, SRL, and learning in HLEs; nor has any study investigated the effect of ITI upon SRL processing as captured with think-aloud protocols, rather than self- or teacher-report data. Finally, most of the research on ITI, prior knowledge, and SRL has focused upon these factors’ independent influence upon learning. In our study, we examined how SRL moderated the influence of student characteristics such as prior knowledge and ITI upon performance. If a study were to show an interactive effect between these student characteristics and SRL, this would bolster the arguments regarding the importance of SRL training in classroom contexts, and suggest that the introduction of HLEs into classrooms must be accompanied by not only technological training, but also interventions designed to foster students’ declarative knowledge and adaptive self beliefs.

This study makes a number of methodological contributions to the field as well. Given the strong theoretical and empirical arguments against self-report measures of SRL (Zimmerman, 2008), we have chosen to examine these relations using data from think-aloud protocols coded with Azevedo et al.’s (2005) scheme. This study is the first to address Greene and Azevedo’s (2007b) call to use think-aloud protocol data to model learning while also including both prior knowledge and self-belief predictors. Further, this is the first study to utilize latent variable modeling to examine the construct validity and reliability of scores from Azevedo’s and Dweck’s measures, and model these relations within a structural equation modeling framework.

Research Question 1: Using confirmatory factor analysis (CFA), is there evidence that scores from our measures of ITI, knowledge of the human circulatory system, and SRL were valid indicators of their respective underlying constructs? This research question was used to determine
whether our measures were valid indicators of the latent variables we posited. If adequate data-model fit was found, this would serve as evidence of the construct validity of scores from our measures.

Research Question 2: Does SRL directly affect learning, and moderate the relations between prior knowledge, implicit theory of intelligence, and posttest knowledge? Conceptual models indicate that SRL process use influences learning. However, SRL also influences the relations between student characteristics, including prior knowledge (i.e., pretest performance), and learning performance. We sought to test this idea by examining SRL as both a direct effect on posttest performance and a moderator of two separate relations: the one between pretest knowledge and posttest performance, as well as the relation between ITI and posttest performance.

6. Method

6.1. Participants

During the 2007–2008 academic year, 171 undergraduate students at a university in the southeastern United States received extra credit in an Education course in exchange for their participation in this study. However, one student chose to withdraw from the study, leaving 170 participants. The students’ mean age was 19.92 years (SD = 2.14) and 103 (60%) of them were female. Pretest scores confirmed that the majority of the participants had minimal to average prior knowledge of the circulatory system, with 42.1% of them receiving the lowest score in terms of their mental model of the circulatory system, and 40.9% percent receiving an intermediate mental model score.

6.2. Measures

Several documents were used to gather information about the participants, including a consent form, participant questionnaire, implicit theories of intelligence measure, pretest, and posttest.

6.2.1. Demographic questionnaire

Each participant was asked to fill out a questionnaire gathering basic demographic information (e.g., gender, age, academic major). Additionally, it included items concerning biology courses in which the participant was previously or currently enrolled, as well as other experiences related to health and medicine (e.g., work, volunteer).

6.2.2. Implicit theories of intelligence measure

A self-report measure constructed by Dweck and Henderson (1988), was used to determine the participant’s implicit theory of intelligence. Three statements were judged on a six-point Likert scale ranging from strongly agree (one) to strongly disagree (six). Dweck, Chiu, and Hong (1995) have demonstrated that agreement with each item signifies an entity view while disagreement indicates an incremental view. The statements include, (1) “You have a certain amount of intelligence, and you really can’t do much to change it.”; (2) “Your intelligence is something about you that you can’t change very much.”; (3) “You can learn new things, but you can’t really change your basic intelligence.” (Dweck et al., 1995; Hong et al., 1999).

Dweck’s (1999) eight-item measure of ITI is more recent than the one we used and contains additional items crafted so that agreement with them indicates an incremental view of intelligence. However, Dweck et al. (Dweck & Henderson, 1988; Dweck et al., 1995; Hong et al., 1999) report that their three-item scale captures the phenomenon equally well with fewer items and less chance of respondent apathy or social desirability bias. Further, when incremental items were added participants showed a tendency to select them (Dweck, 1999; Dweck & Henderson, 1988; Hong et al., 1999), suggesting that they may bias participants’ responses. As well, researchers have repeatedly noted robust reliability and validity evidence for scores from the three-item measure (Dweck et al., 1995; Hong et al., 1999; Leonardelli, Hermann, Lynch, & Arkin, 2003), even though there are a small number of items. Thus, we chose to use the reduced scale.

6.2.3. Pretest and posttest

The paper- and -pencil pretest and posttest used to capture a participant’s conceptual knowledge of the human circulatory system were the same measures successfully used in several previous studies (Azevedo, Cromley, et al., 2004; Azevedo et al., 2005; Greene & Avevedo, 2007b, 2009; Moos & Azevedo, 2006). The pre- and posttests were identical and included three sections: a) a matching task that required the participant to identify the definitions for 13 words; b) a task that required the participant to label 14 components on a full-color picture of the human heart; and c) an open-ended mental model essay, asking each participant to, “Please write down everything you can about the circulatory system. Be sure to include all the parts and their purpose, explain how they work both individually and together, and also explain how they contribute to the healthy functioning of the body.” The first two tasks were intended to measure participants’ declarative knowledge of the human circulatory system, while the third task captured their conceptual understanding. The fact that the pretest and posttest were identical may have created a testing effect (Campbell & Stanley, 1963) or cued participants in terms of their self-regulation. The former concern could have been addressed by using a different posttest, but given the strong psychometric findings from other studies using these measures (e.g., Azevedo et al., 2005; Greene & Azevedo, 2009), we did not wish to introduce a new, potentially less adequate, measure. The latter concern would be valid no matter the pretest measure used, and given our desire to measure how the HLE and SRL processing influenced the acquisition of new conceptual understanding over the course of the task, we felt the necessity of using the pretest to measure prior knowledge outweighed its potential influence upon SRL.

6.3. Hypermedia learning environment

The participants were asked to learn about the circulatory system using the hypermedia learning environment Microsoft Encarta (2007). This multimedia encyclopedia software covers the parts and the purpose of a circulatory system in three articles (i.e., circulatory system, heart, and blood). These articles consisted of 41,380 words divided into 18 sections, with 256 hyperlinks, 40 illustrations and one digitized animation. The participant navigated within the articles and through the encyclopedia using two different search options, as well as
introduced the participant to Encarta. By reading descriptions of the various parts and their functions, and by engaging in interactive activities, the participant was able to learn about the different parts and their purpose, how they work both individually and together, and how they support the human body.

Microsoft Encarta (2007) was used to provide a hyperlinked learning environment (HLE). The HLE was structured with a navigation function and the three articles deemed most useful for reaching the learning goal: the "Heart, Blood, and Circulatory System." The participant was asked to return to Encarta, and all participants did so.

6.4. Procedure

We used a procedure similar to that used by Azevedo et al. (Azevedo & Cromley, 2004; Azevedo, Guthrie, et al., 2004; Greene & Azevedo, 2009). The first author trained four graduate students in the experimental procedures, and watched videotapes of the students running participants to ensure consistency among researchers in terms of the procedures. Each session took place in a room with one participant and one researcher present. First, the participant was informed of the time commitment and told that he or she could opt out at any time without penalty. Once the participant agreed to participate, he or she read and signed a consent form. Then the participant was given as much time as needed to complete the demographic questionnaire and the ITI measure.

Next, the participant was given 20 min to complete the pretest. The researcher asked the participant to complete each page of the test in the order in which it was provided, without skipping or returning to a previous section. The participant did not have access to any instructional materials during the pretest. Participants were aware that there would be a posttest, but they were given no information about it. In particular, participants did not know that the posttest was identical to the pretest.

Once the pretest was complete, the participant received instructions about the learning task and goal, and was given a tour of the HLE. Microsoft Encarta (2007) was used to provide a HLE that was similar to the one used in the previous study. The participant was told that the learning task was to use the HLE to learn as much as possible about the circulatory system in 30 min focusing on this learning goal, which was presented in written form and read aloud to the participant: "Make sure you learn about the different parts and their purpose, how they work both individually and together, and how they support the human body." The learning task instructions and goal remained visible to the participants throughout the 30 min learning session. Next, the researcher introduced the participant to Encarta's navigation functions and the three articles deemed most useful for reaching the learning goal: the heart, blood, and circulatory system.

Next, the think-aloud process was described in detail to the participant. This included instructing the participant to verbalize all thoughts and reading while navigating through the HLE (Ericson & Simon, 1993). To ensure the participant was comfortable with think-aloud, the participant practiced the process using an article from the HLE unrelated to the circulatory system, and received feedback from the researcher. Ericson and Simon have shown that think-aloud protocols do not interfere with cognitive processes as long as individuals are asked to simply report, rather than explain, what they are thinking. Thus, we asked participants to report but not explain their thinking and activity. Ericson and Simon (1993; Ericson, 2006) have systematically reviewed research studies that claimed to have found an influence of think-aloud protocols on cognitive processing or performance (e.g., Short, Evans, Friebert, & Schachtschneider, 1991; Short, Schachtschneider, Cuddy, & Evans, 1991) and shown them to be flawed. Further, SRL research into the influence of think-aloud protocols has shown no effects (e.g., Bannert & Mengelkamp, 2008; Veenman, Elshout, & Groen, 1993).

Once the participant was reminded of the learning task and all final questions were answered, the 30 min learning session began. During this time the participant was both audio and video taped. The participant was allowed to take notes, although not all did so. If the participant was silent for more than 2 s, the researcher prompted the participant to verbalize his or her thoughts. We did not gather data on the number of prompts to think-aloud given to participants, but researchers reported that it varied across participants and that on average they did not have to prompt participants often over the course of the study. Verbal time prompts were given to the participant when there were 20, 10, and 2 min remaining. After 30 min all recording was terminated, the participant's notes (if any) were removed from the testing area, and the HLE was closed.

Finally, the participant was given 20 min to complete the posttest. The participant did not have access to any instructional materials or notes during this time. After the posttest was complete, the participant was debriefed and asked to refrain from sharing the details of the procedure with other potential participants. The components of the procedure followed in the order described and did not last longer than 90 min.

6.5. Coding and scoring

Scoring and coding of the measures and transcripts were done based on the method developed by Azevedo et al. (2005, pp. 393–397). In this section, we describe the processes of scoring the participants' declarative measures and mental model essays, as well as the process of segmenting and coding the students' verbalizations. We also discuss the coding scheme used to analyze student self-regulation.

6.5.1. Declarative measures

The matching and labeling portions of each student's pretest and posttest were scored for accuracy. The scores on these sections of the tests reflect the number of correct answers provided by the student. Each matching and labeling pretest and posttest was scored by a trained graduate student.

6.5.2. Mental models

We used Azevedo et al.'s (Azevedo & Cromley, 2004; Azevedo, Cromley, et al., 2004; Azevedo, Guthrie, et al., 2004; Azevedo et al., 2005, 2007, 2008; Greene et al., 2008) method to score participants' mental model pretest and posttest essays. This method includes 12 mental models that progress from no understanding of the circulatory system to the most complete understanding. The 12 models are: (1) no understanding, (2) basic global concept, (3) basic global concept with purpose, (4) basic single loop model, (5) single loop with purpose, (6) advanced single loop model, (7) single loop model with lungs, (8) advanced single loop model with lungs, (9) double loop concept, (10) basic double loop model, (11) detailed double loop model, and (12) advanced double loop model. Two trained graduate students individually scored each mental-model essay by assigning one of the 12 model values (inter-rater agreement was .994; agreement on 334/336 essays). The first author resolved the two disagreements.

Each of the pretest and posttest mental model scores was further classified into one of three qualitatively different mental model categories: low (i.e., 1 through 6), intermediate (i.e., 7 and 8), and high (i.e., 9 through 12). Use of these broader categories allowed us to capture the qualitative variation in participants' conceptual knowledge of the circulatory system. Models one through six are indicative of
quantitative, but not qualitative differences in students’ understanding of the circulatory system. An increase from a score of six to a score of seven represents the first qualitative shift in student understanding. This move shows that a student understands that the lungs play a role in the circulation of blood. The next qualitative shift is seen in the move from model eight to model nine, shifting from the idea of a single to a double loop (see Azvedo et al., 2005 for more details regarding these qualitative shifts). Models nine through twelve represent quantitative differences in participants’ understanding of the double loop human circulatory system (see Appendix B).

6.5.3. ITI measure

Each of the three items was written such that higher scores were indicative of an incremental ITI, and lower scores indicative of an entity theory. Participant item score responses were used as data in the analysis, with no transformation or alteration.

6.5.4. SRL coding

Think-aloud protocols were used to capture students’ SRL. All participant sessions were transcribed and coded using a version of Azvedo et al.’s (Azvedo & Cromley, 2004; Azvedo et al., 2005) SRL coding scheme that, in consultation with Azvedo, we adapted for this study. The scheme includes 31 micro-level self-regulatory processes used by learners to regulate their learning of complex science topics with hypermedia (see Azvedo et al., 2005, pp. 394–397). Each of the micro-level codes is further categorized into one of five macro-level processes: planning (e.g., activating prior knowledge), monitoring activities (e.g., judgment of learning), strategy use (e.g., drawing, coordinating informational sources, knowledge elaboration), handling task difficulties and demands (e.g., help-seeking behavior), and interest to learn the content or complete the task (see Appendix A). Differences between the Azvedo et al.’s (2005) coding scheme and the one used in this study include minor changes to the definitions of some codes, and the inclusion of plus and minus variations of some codes, described later.

The above mentioned coding scheme was used to group participants’ think-aloud verbalizations into segments. To qualify as a codeable segment, a word or group of words had to correspond to one of the 31 micro-level SRL processes. For example, if a participant said, “So blood goes from the left atrium to the left ventricle just like it goes from the right atrium to the right ventricle, okay that makes sense” the statement would be divided into two segments, each of which would be considered a different SRL process. “So it goes from the left atrium to the left ventricle just like it goes from the right atrium to the right ventricle” would be the first segment and would be coded as an inference (INF, i.e., the participant reached a conclusion based upon two pieces of information recently read; see Appendix A for a list of codes and explanations) whereas the second segment “okay that makes sense” would be coded as judgment of learning plus (JOL+, i.e., the participant judged that the learning was adequate, as opposed to JOL– which would indicate that the learning was not adequate). None of the hypermedia text reading was coded, unless the participant re-read a section of five or more words. Some text segments could not be coded as indicative of any of the micro-level SRL processes, and these were labeled as “not codeable” and ignored in the analysis.

Audio tape from each participants’ think-aloud process was transcribed by trained students. Every utterance, spoken both by the participant and the experimenter, was included in the transcript. Italics were used for sections of the transcript where the participant read directly from Microsoft Encarta, so as to easily identify the participant’s codeable thoughts. Each transcript was coded using both the transcription and the video recording, to ensure accuracy. Due to a computer failure, video data for 10 participants were lost; therefore we did not transcribe the audio data nor were any SRL data gathered for these participants. A total of 80 h of audio tape was transcribed and coded. The first author trained a group of graduate researchers to code the data. Two researchers coded each transcript, independently, and then came together to compare their coding. Differences were resolved through discussion between the two coders. The total number of codeable segments for all participants was 17,111 (M = 110 per participant).

6.5.5. Interrater agreement

The coding scheme used in this study has been successfully and consistently utilized in over 20 studies, including eight that involved the first author (see Azvedo, 2005 for an overview). The scheme has been revised and refined over the past six years, with the various codes shown to be robust and present in multiple studies.

As noted above, all transcriptions were coded twice. Two trained researchers independently coded each transcript and then compared their coding. The researchers discussed and resolved all coding differences. If the researchers could not come to agreement on a particular segment, the first author was consulted to make the final decision. Of the total 17,111 codeable segments, the first author was consulted on less than ten occasions. This indicated a high-degree of interrater agreement. Statistical calculations of interrater agreement are not appropriate for this study since every segment was coded independently by two raters, with any disagreements resolved through consultation. Reliability measures are more appropriate when raters are allowed to code some subset of the data without having another person verify their coding. This was not the case for this study.

6.6. Missing data

One participant’s handwriting was illegible, therefore we could not determine mental model essay scores for this participant. There were no other missing data except for the SRL data for the 10 participants whose video files were lost. Given the arbitrary nature of these data losses, we treated these data as missing completely at random (Little & Rubin, 2002). This allowed us to keep these participants’ other data in the analysis using Mplus 5.2’s (Muthén & Muthén, 2009) missing data handling features, including full information maximum likelihood estimation (FIML; see Enders, 2001 for a description of why FIML is superior to other means of missing data handling such as list-wise deletion, pair-wise deletion, and mean imputation).

6.7. Data preparation

The matching and labeling data, as well as the ITI data, were treated as continuous, normally distributed variables. The mental model data were treated as ordinal. To create macro-level SRL data, we summed the frequency of each participant’s relevant micro-level SRL processes. However, past research using Azvedo et al.’s (2008) coding scheme has shown that certain micro-level SRL processes are not associated with learning (see Azvedo et al., 2007 and Greene & Azvedo, 2007a for more information). Therefore, we did not include certain
micro-level SRL codes in the summation. Specifically, for the planning macro-level SRL process variable, we summed the micro-level SRL processes planning and sub-goal, but not recycle goal in working memory. For the monitoring macro-level SRL process variable, we summed all micro-level SRL process variables listed in Appendix A except time monitoring and task difficulty. For the strategy use macro-level SRL process variable, we summed all of the micro-level SRL process variables listed in Appendix A except control video and selecting a new informational source. Overall, past research and theory suggest that more frequent use of these omitted micro-level SRL processes (i.e., recycle goal in working memory, time monitoring, task difficulty, control video, and selecting a new information source) is not indicative of adaptive self-regulation, nor is it associated with positive learning outcomes.

Finally, the macro-level SRL process variables were used as indicators of the latent SRL factor. For the purposes of this study, we modeled SRL using only the macro-level SRL processes planning, monitoring, and strategy use. Participants were not allowed to seek help, thus the macro-level SRL process task difficulty and demands had no data. The macro-level process interest is a student characteristic that will be used in future research.

7. Results

Descriptive statistics were computed using SPSS 16.0. All other analyses were performed using Mplus 5.2.

7.1. Descriptive statistics

Evaluation of the descriptive statistics for both pretest and posttest shows that, on average, participants’ mean or median scores increased on all three sections of the test: matching, labeling, and mental model essay (see Table 1). In addition, the proportion of participants scoring “high” on the mental model increased greatly from the pretest to the posttest (see Table 2). Thus, descriptive data show that participants, on average, did learn from pretest to posttest.

The descriptive statistics for the macro-level SRL variables (see Table 3) reveal that, on average, participants employed micro-level processes associated with strategy use more than those associated with any other macro-level SRL variable (M = 46.73). Strategy use also had the largest standard deviation (SD = 28.809) and range (Range = 103), indicating that the frequency of strategy use micro-level self-regulation processes varied greatly among participants. The next most frequently used macro-level SRL process was monitoring (M = 16.97).

7.2. Research question 1: using confirmatory factor analysis (CFA), is there evidence that scores from our measures of ITI, knowledge of the human circulatory system, and SRL were valid indicators of their respective underlying constructs?

CFAs (Kline, 2005) were used to assess our measurement model, which included our pretest, posttest, ITI, and SRL measures. The measurement model consisted of three pretest and posttest measures as indicators of latent pretest and posttest conceptual understanding of the human circulatory system, respectively; three indicators for the ITI factor; and the planning, monitoring, and strategy use macro-level SRL variables as indicators of the latent SRL variable. The mental model variables, pretest and posttest, were modeled as ordinal variables and the planning and monitoring macro-level SRL variables were modeled as count variables due to their non-normal distributions (see Table 3). The strategy use macro-level SRL variable had a roughly normal distribution thus we modeled it as a continuous variable. While all four latent variables could be modeled together, the inclusion of the SRL latent variable, with count variables as indicators, precluded the reporting of the fit indices typically used to assess data-model fit (e.g., chi-square test, CFI, RMSEA). Therefore, to bolster our argument regarding the validity of inferences from scores from the pretest and posttest measures, we ran one CFA without the SRL latent variable, and then another with that variable included. The chi-square test of the first CFA model (i.e., without the SRL latent variable) was statistically non-significant, indicating good data-model fit \( \chi^2 (11, N = 170) = 12.214, p = .348 \). The Comparative Fit Index (CFI) was .989; the Root Mean Square Error of Approximation (RMSEA) was .025, also indicating good data-model fit. All factor loadings in this model were also statistically significant and positive (see Table 4). Coefficient \( H \) (Hancock & Mueller, 2001) was used to calculate construct reliability, with each latent variable (i.e., pretest knowledge, posttest knowledge, ITI) having reliability above .7, and the variance extracted from each set of indicators was equal to or greater than .50 (see Table 5). All latent variables had a statistically significant amount of variance to be modeled.

The second CFA included the SRL latent variable, thus no fit indices were reported. However, all factor loadings in this model were also statistically significant and positive. We interpreted this as support for modeling SRL as a latent variable. The correlations between pretest and posttest, and posttest and SRL, were statistically significant and positive (see Table 5). The findings from both CFAs supported our claims regarding the reliability and validity of scores from our pretest and posttest measures, as well as the validity of modeling SRL as a latent variable using our macro-level SRL variables. Given these findings, we moved on to test our conceptual model.

7.3. Research question 2: does SRL directly affect learning, and moderate the relations between prior knowledge, implicit theory of intelligence, and posttest knowledge?

Through their conceptual models, researchers posit that SRL is the means by which student characteristics and abilities are converted into performance (Winne & Hadwin, 1998; Zimmerman, 2000). In our structural model we allowed for a test of SRL’s role as both a direct

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Table 1

<table>
<thead>
<tr>
<th>Pretest</th>
<th>Posttest</th>
</tr>
</thead>
<tbody>
<tr>
<td>M(SE)</td>
<td>M(SE)</td>
</tr>
<tr>
<td>SRL</td>
<td>SRL</td>
</tr>
<tr>
<td>K(SE)</td>
<td>K(SE)</td>
</tr>
<tr>
<td>Matching</td>
<td>8.01(1.479)</td>
</tr>
<tr>
<td>Labeling</td>
<td>1.39(2.542)</td>
</tr>
<tr>
<td>Mental model</td>
<td>Intermediate</td>
</tr>
</tbody>
</table>

* M is the mean for matching and labeling and the mean for mental model. S is skewness. K is kurtosis. SE is standard error.
influence upon learning and a moderator of the relation between prior (i.e., pretest) knowledge and posttest knowledge, as well as the relation between implicit theory of intelligence and posttest knowledge (see Fig. 1).

While no fit indices are available for our structural model, again because they are not provided when one of the latent variables has count indicators, all of the factor loadings for our latent variables were statistically significant. Likewise, there were numerous statistically significant paths between our latent variables, as well as between our latent interaction variables and posttest knowledge. First, given that ITI was scaled such that higher scores on the measure indicated a more incremental-like theory of intelligence, the negative correlation between ITI and pretest knowledge suggests that participants with more prior knowledge tended to have a more entity-like theory of intelligence. This finding seems counterintuitive given Dweck’s (1999) claim that an incremental ITI is associated with more knowledge acquisition, compared to an entity ITI, but the effect size is quite small (see Fig. 1; Cohen, 1992).

Pretest knowledge was statistically significantly related to posttest knowledge, with a positive path coefficient. Thus, these findings, coupled with those from the descriptive statistics, show that participants, on average, did learn from pretest to posttest. Pretest knowledge was not statistically significantly related to SRL, but ITI was negatively related, indicating that participants with more incremental-like ITI scores engaged in somewhat less SRL overall than participants with ITI scores closer to the entity pole. Again, this small effect was a counterintuitive finding, but it must be considered in tandem with the moderate effect discussed later. SRL was statistically significantly related to posttest knowledge, thus, on average, participants who engaged in more SRL had higher posttest knowledge scores. Evidence of partial mediation is shown in the statistically significant, but practically small indirect path effect (beta = −.074, z = −2.029, p < .05) from ITI through SRL to posttest knowledge.

There was evidence of SRL’s role as a moderator as well. The direct effects of pretest knowledge and ITI on posttest knowledge (.928 and .068, respectively, see Fig. 1) must be interpreted in light of these moderation effects. The moderation effect of SRL on the relation between pretest and posttest indicated that, on average, while holding ITI constant, as participants engaged in more SRL, the effect of pretest knowledge on posttest score increased somewhat. This supported our claim that the influence of prior knowledge increases for students who engage in SRL as they iterate through the learning process (see Fig. 2). The moderation effect of SRL on the relation between ITI and posttest knowledge is shown in Fig. 3. Holding pretest constant, on average, ITI’s effect upon predicted posttest scores was stronger when participants engaged in less SRL. When participants engaged in more SRL, the effect of ITI was reduced to almost zero, as indicated in Fig. 3 by the relatively flat slope for participants with an SRL score two standard deviations above the mean. Therefore, our examination of the interaction between ITI and SRL was important as it clarified that, despite no statistically significant main effect, it does influence posttest scores, but only for those participants who engaged in little high-quality SRL. This finding, along with the moderation effect of SRL on the relation between pretest and posttest, suggests that engaging in frequent use of high-quality SRL may have a virtuous effect on student characteristics in that, in this study, it was associated with an increase in the positive influence of prior knowledge and a decrease in the negative effect of having an entity ITI.

Finally, the residual variance of the posttest factor in the structural model was quite small; meaning the amount of variance to explain in the posttest latent factor, thus participants did vary in terms of the conceptual understanding. This finding seems counterintuitive given Dweck’s (1999) claim that an incremental ITI is associated with more knowledge acquisition, compared to an entity ITI, but the effect size is quite small (see Fig. 1; Cohen, 1992).

7.4. Summary of results

Our statistical findings provide evidence regarding our research questions. Scores from our pretest, posttest, and ITI measures appear to have strong evidence of construct validity and reliability. Likewise, our findings support modeling SRL as a latent variable indicated by participants’ frequency of planning, monitoring, and strategy use. Prior knowledge and ITI were directly related to posttest performance. The relation between ITI and SRL supports Dweck and Master’s (2008) claim that this self-belief influences how self-regulation is enacted, although in a direction not anticipated, and with a small effect size (Cohen, 1992). In support of numerous conceptual models, we found that the frequency of high-quality SRL had a direct effect upon posttest conceptual understanding.

In addition, our findings suggest that as students engage in more SRL processes throughout learning, the positive effects of student characteristics are amplified (i.e., moderated), while the negative effects are mitigated, perhaps through the revision of inappropriate standards based upon these maladaptive student characteristics. These findings support Winne and Hadwin’s (1998) claim that SRL is recursive, and that monitoring and control interact with student characteristics throughout the learning process.

8. Discussion

There continues to be a focus upon improving science education in the United States, and researchers are struggling to determine how conceptual understanding of complex systems can be fostered (Hmelo-Silver & Azevedo, 2006). There is great potential for HLEs to promote scientific

<table>
<thead>
<tr>
<th>Variable</th>
<th>M(SD)</th>
<th>Median</th>
<th>Range</th>
<th>S(SE)</th>
<th>K(SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning</td>
<td>4.40(3.972)</td>
<td>4</td>
<td>16</td>
<td>1.115(195)</td>
<td>656(387)</td>
</tr>
<tr>
<td>Monitoring</td>
<td>16.57(13.696)</td>
<td>13</td>
<td>77</td>
<td>1.388(195)</td>
<td>2.057(387)</td>
</tr>
<tr>
<td>Strategy use</td>
<td>46.73(23.809)</td>
<td>43</td>
<td>103</td>
<td>0.250(195)</td>
<td>6.80(387)</td>
</tr>
</tbody>
</table>
conceptual understanding, but students must possess the self-regulatory skills to take advantage of affordances such as multiple representations and learner control (Goldman, 2003; Kozma, 2003). Azevedo et al.'s model and coding scheme allow for think-aloud protocol data to be converted into measures of SRL that are more accurate and have stronger psychometric properties than self-report instruments. Once measured in a manner congruent with conceptual models such as Winne and Hadwin’s (1998), SRL processing can then be examined as both a direct effect upon learning and an influence upon the magnitude of the effect of student characteristics upon learning, as posited in conceptual models of SRL.

Our study expands upon prior research by examining the influence of prior knowledge and self-beliefs on the use of SRL processes and the role of SRL as a moderator of the relations between student characteristics and learning about complex systems with HLEs. Most significantly, our findings suggest that SRL can act as a benevolent moderator of these relations, magnifying the positive effects of prior knowledge and diminishing the negative effects of an entity ITI. These findings provide support for the claims of Winne and Hadwin (1998) and Zimmerman (2000), among others, who posit that learner goals and standards can have multiple influences upon students’ processing in each phase of the learning process if students engage in the hallmarks of self-regulation: metacognitive monitoring and control. Accurate standards should buoy learning, whereas effective self-regulation should ameliorate the influence of standards created under the influence of maladaptive beliefs. Likewise, this study further illustrates the importance of assessing and fostering students’ SRL skills when using HLEs in educational environments. Simply providing students with an HLE is not enough; student characteristics must be taken into account.

Our work has several methodological strengths, including using think-aloud rather than self-report data, and employing SEM both to test the reliability and validity of scores from the measures and as a way of modeling SRL. The strong psychometric findings of this study afford more confidence in the accuracy of the relations described between student characteristics, SRL, and academic performance. This study also provides further evidence of the utility of Azevedo et al.’s model and coding scheme for SRL processing.

It was surprising to find that ITI had a negative relation with both prior knowledge and the amount of high-quality self-regulation enacted during learning. However, the effect sizes associated with these relations were quite small, and thus may not be a practically significant indicator of any main effects between ITI and prior knowledge or SRL. Nonetheless, these findings could be explored further by including ITI measures in future studies of SRL and other phenomena related to knowledge, such as expertise development (Alexander, 1997; Alexander, Sperl, Buehl, Fives, & Chiu, 2004).

8.1. Limitations

There are certain limitations regarding the design of this study. This was a non-experimental, correlational study, thus casual inferences cannot be made. The findings for this study are also circumscribed by the scientific topic, the circulatory system, and the HLE used, Microsoft’s Encarta. Likewise, the sample for this study consisted of undergraduate students at a single University in the South, thus the generalizability of the findings is limited. While using the same instruments at pretest and posttest allowed us to make strong claims regarding the change in participants’ learning after using the HLE, it may have led to a testing effect (Campbell & Stanley, 1963). Future studies could include multiple instruments to assess this concern. Likewise, administering a pretest may cue participants as to which aspects of the HLE to attend. To address this concern, future research could compare SRL processing between groups who do and do not receive a pretest, rather than focusing solely upon posttest performance. Also, while there is ample evidence that the think-aloud protocol does not influence cognitive processing (Bannert & Mengelkamp, 2008; Ericsson & Simon, 1993; Veenman et al., 1993), we did not specifically assess the protocol’s influence, if any, in this particular study.

Within these limitations, there are some concerns regarding the findings themselves. First, the ITI measure used in this study was written at a broad, domain–general level. It may be that using an ITI measure tailored to science content produces stronger and more accurate relations between ITI and SRL or academic performance. Second, the think-aloud protocol data coding scheme has been used most often to capture student

### Table 4

<table>
<thead>
<tr>
<th>Factor</th>
<th>Indicator</th>
<th>Standardized loading&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pretest knowledge</td>
<td>Matching</td>
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<td></td>
<td>Labeling</td>
<td>.569</td>
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<td></td>
<td>Mental model essay</td>
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<td>Posttest knowledge</td>
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<td>Labeling</td>
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<tr>
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<td>.736</td>
</tr>
<tr>
<td>Implicit theory of intelligence</td>
<td>Item 1</td>
<td>.870</td>
</tr>
<tr>
<td></td>
<td>Item 2</td>
<td>.879</td>
</tr>
<tr>
<td></td>
<td>Item 3</td>
<td>.870</td>
</tr>
</tbody>
</table>

<sup>a</sup> All loadings statistically significant at p < .001.

### Table 5

<table>
<thead>
<tr>
<th></th>
<th>Pretest knowledge</th>
<th>Implicit theory of intelligence</th>
<th>Posttest knowledge</th>
<th>SRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pretest knowledge</td>
<td>.79</td>
<td>–.096</td>
<td>.861*</td>
<td>.175</td>
</tr>
<tr>
<td>Implicit theory of intelligence</td>
<td>.91</td>
<td>–.121</td>
<td>–.119</td>
<td>–</td>
</tr>
<tr>
<td>Posttest knowledge</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variance extracted</td>
<td>.50</td>
<td>.76</td>
<td>.58</td>
<td></td>
</tr>
</tbody>
</table>

<sup>*p < .05; **p < .01.</sup>

Note: Construct reliability estimates (Coefficient H) on diagonal.

<sup>Construct reliability and variance extracted not able to be calculated for a latent variable with count indicators.**</sup>
regulation while learning about the circulatory system. Whether these processes would be applicable or be similarly predictive of outcomes with other topics is not clear, but recent research has shown that the coding scheme can be used productively in the content area of history (Greene, Bolick, & Robertson, 2010). The lack of a statistically significant relationship between pretest knowledge and SRL was surprising. It may be that the HLE content was not sufficiently advanced enough to warrant SRL use from high prior knowledge students. Perhaps these students could simply read the material and integrate it with their prior knowledge, rather than needing to plan, use strategies, and monitor their learning.

8.2. Future directions

There are numerous future directions for research implied by the findings of this study. While the moderating effect of SRL on the relation between ITI and academic performance is intriguing, whether student beliefs change over the course of learning needs to be investigated empirically. A study with ITI measures used before and after learning would help address this issue. Likewise, an experimental intervention designed to change students’ ITI would aid in determining whether differences in ITI truly influence the kinds of SRL processing enacted during learning. Similar intervention studies, focused on training students to enact high-quality SRL, could establish more convincing links between metacognition and learning than a correlational study such as this one. Finally, as mentioned previously, more research is needed with populations other than college students, and with content outside of the circulatory system. If SRL is truly one of the keys to successful acquisition of conceptual understanding with HLEs, then these findings should be detectable in multiple contexts.

8.3. Application in the classroom

In terms of practice, our findings provide support for educational interventions designed to foster SRL and more adaptive self-beliefs. Specifically, the results of this study suggest that teaching students to adaptively self-regulate their learning may enhance their likelihood of
academic success when using HLEs. Further, while other research has shown that prior knowledge is a strong predictor of SRL (Liu & Hmelo-Silver, 2009; Moos & Azevedo, 2008), our study is the first to show a multiplicative effect between knowledge and self-regulation. We believe that students who have a sufficient level of prior knowledge about the content are less likely to experience the disorientation or cognitive load that can occur while using HLEs, and are therefore more likely to enact productive SRL processes. In terms of educational implications, this multiplicative effect suggests that implementing either declarative knowledge interventions or SRL training alone is helpful, but together the effects are far greater. This finding aligns with research showing that SRL training must be content- and context-specific, rather than general (Paris & Paris, 2001).

Likewise, helping students adopt an incremental, rather than entity, theory of intelligence may improve their learning, although care must be taken to ensure they also increase their use of adaptive SRL processes. As Mueller and Dweck (1998) discussed, the ways teachers attribute student performance (i.e., attributing it to either ability or effort) has a direct influence upon students’ future academic success. The introduction of HLEs into classrooms presents numerous opportunities for teachers to respond to both student success and difficulty using computers. In particular, HLEs that address complex topics in science, such as the circulatory system, may prove to be quite challenging for learners, initially. Teachers whose language encourages students who struggle with HLEs to adopt an incremental theory of intelligence are more likely to have students who benefit from the use of adaptive SRL strategies. On the other hand, teachers who attribute student difficulties with computers to ability may be aggravating the detrimental effects of poor SRL processing. Again, our study contributes to the literature by showing that the combined effects of having an entity ITI and poor SRL skills are far greater than what would be expected if students had just one or the other deficit on its own. These findings build on previous research by suggesting that the introduction of computers into the classroom should be done in tandem with interventions designed to foster positive self-beliefs and adaptive SRL skills.

Overall, our findings have direct implications for the ways in which computers are introduced into classrooms. Very often, computers are used to address teacher bandwidth issues (Wiley & Edwards, 2002). Computers can provide a rich, individualized educational experience to as many students as there are computers in the classroom, and HLEs never get tired or distracted. However, students must be positioned for success when using these computers, particularly since they spend a great deal of time working with these computers on their own. When using computers to foster learning, educators should consider the technology as just one aspect of a comprehensive intervention that includes providing students with the sufficient declarative knowledge, adaptive beliefs about learning, and SRL knowledge to successfully learn academic content. Additionally, computers can play a diagnostic role. When students who have sufficient declarative knowledge fail to learn with HLEs, it may indicate that these students have maladaptive self-beliefs or poor SRL skills. Educators can then attempt to surface these beliefs or assess these SRL skills, and provide targeted support to address these concerns. In the realm of science, student difficulties with HLEs may reveal maladaptive strategies or beliefs about the nature of science that would be difficult to discern from more linear learning technologies.

8.4. Conclusion

In this study we expanded upon the empirical literature demonstrating interactive relations among student characteristics, SRL, and learning with HLEs. Specifically, we showed that SRL both directly influenced learning and moderated how prior knowledge and student beliefs influenced the acquisition of scientific conceptual understanding. Further, we demonstrated how SRL can be investigated using think-aloud protocol methodology and latent variable modeling. This study has numerous conceptual and practical implications, not the least of which are that the importance placed upon SRL by researchers is well supported, and that students might benefit greatly if educators were to place a similar emphasis upon teaching SRL in the classroom before introducing HLEs.

Acknowledgements

The authors would like to thank Sonya Harris, Kristin Dellige, Leigh Anna Hutchison, Banu Binbasaran Tuysuzoglu, and Alexandra Earl for their assistance in collecting, transcribing, and coding data. This research was supported by a grant from the University of North Carolina at Chapel Hill (University Research Council Research Grant) awarded to the first author.
### Appendix A

Classes, descriptions and examples of the macro- and micro-level processes used to code students’ regulatory behavior (based upon Azevedo et al., 2008).

<table>
<thead>
<tr>
<th>Macro-level process: planning (plan)</th>
<th>Description</th>
<th>Student example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning (plan)</td>
<td>Stating two or more sub-goals simultaneously or stating a sub-goal and combining it with a time requirement.</td>
<td>“First I’ll look around to see the structure of environment and then I’ll go to specific sections of the circulatory system.”</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Micro-level process: monitoring</th>
<th>Description</th>
<th>Student example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content evaluation (plus and minus) (CE+/−)</td>
<td>Monitoring content relative to goals. Learner states content is or is not useful toward reaching the goal. Expecting that a certain type of representation will prove either adequate or inadequate given the current goal</td>
<td>“I’m reading through the info but it’s not specific enough for what I’m looking for” – “the video will probably give me the info I need to answer this question” or “I don’t think this section on blood pressure will answer my question”</td>
</tr>
<tr>
<td>Sub-goal (SG)</td>
<td>Learner articulates a specific sub-goal that is relevant to the experiment provided overall goal. Must verbalize the goal immediately before taking action.</td>
<td>“I’m looking for something that’s going to discuss how things move through the system.”</td>
</tr>
<tr>
<td>Feeling of knowing (plus and minus) (FOK+/−)</td>
<td>Learner is aware of having read something in the past and having some understanding of it, but not being able to recall it on demand or learner states this information not seen before.</td>
<td>“I get it” or “I don’t know this stuff, it’s difficult for me”</td>
</tr>
<tr>
<td>Judgment of learning (plus and minus) (JOL+/−)</td>
<td>Learner makes a statement that they understand what they’ve read or becomes aware that they don’t know or understand everything they read.</td>
<td></td>
</tr>
<tr>
<td>Monitor progress toward goals (MPG)</td>
<td>Assessing whether previously-set goal has been met.</td>
<td>“Those were our goals, we accomplished them”</td>
</tr>
<tr>
<td>Monitor use of strategies (MUS)</td>
<td>Participant comments on how useful a strategy was</td>
<td>“Yeah, drawing it really helped me understand how blood flow throughout the heart”</td>
</tr>
<tr>
<td>Time monitoring (TM)</td>
<td>Participant refers to the number of minutes remaining</td>
<td>“I only have 3 min left”</td>
</tr>
<tr>
<td>Task difficulty (TD)</td>
<td>Learner indicates the task is hard or easy.</td>
<td>“This is harder than reading a book.”</td>
</tr>
<tr>
<td>Macrol-level process: strategy use</td>
<td>Using pause, start, rewind, or other controls in the digital animation</td>
<td>“Clicking pause during the video”</td>
</tr>
<tr>
<td>Control video (CV)</td>
<td>Coordinating multiple representations, e.g., drawing and notes.</td>
<td>“I’m going to put that [text] with the diagram”</td>
</tr>
<tr>
<td>Coordinating informational sources (COIS)</td>
<td>Making a drawing or diagram to assist in learning</td>
<td>“...I’m trying to imitate the diagram as best as possible”</td>
</tr>
<tr>
<td>Draw (DRAW)</td>
<td>Making inferences based on what was read, seen, or heard in the hypermedia environment</td>
<td>“...[learner sees the diagram of the heart] and states “so the blood...through the...then goes from the atrium to the ventricle...and then...” after inspecting a picture of the major valves of the heart] the learner states “so that’s how the systemic and pulmonary systems work together”</td>
</tr>
<tr>
<td>Inferences (INF)</td>
<td>Searching memory for relevant prior knowledge before beginning performance of a task or during task performance</td>
<td>“I’m going to try to memorize this picture”</td>
</tr>
<tr>
<td>Knowledge elaboration (KE)</td>
<td>Elaborating on what was just read, seen, or heard with prior knowledge.</td>
<td>“It’s hard for me to understand, but I vaguely remember learning about the role of blood in high school”</td>
</tr>
<tr>
<td>Memorization (MEM)</td>
<td>Searching memory for relevant prior knowledge either before beginning performance of a task or during task performance</td>
<td>“Carry blood away. Arteries—away.”</td>
</tr>
<tr>
<td>Prior knowledge Activation (PKA)</td>
<td>Searching the hypermedia environment with or without the Encarta search feature</td>
<td>“I’m reading this again.”</td>
</tr>
<tr>
<td>Read notes (RN)</td>
<td>Reviewing learner’s notes.</td>
<td>“I’m going to type blood pressure in the search box”</td>
</tr>
<tr>
<td>Search (SEARCH)</td>
<td>Re-reading or revisiting a section of the hypermedia environment</td>
<td>[Learner reads about location valves] then switches to watching the video to see their location</td>
</tr>
<tr>
<td>Selecting a new informational source (SNIS)</td>
<td>The selection and use of various cognitive strategies for memory, learning, reasoning, problem solving, and thinking. May include selecting a new representation, coordinating multiple representations, etc.</td>
<td>“This says that white blood cells are involved in destroying foreign bodies”</td>
</tr>
<tr>
<td>Summarization (SUM)</td>
<td>Summarizing what was just read, inspected, or heard in the hypermedia environment</td>
<td>“I’m going to write that under heart”</td>
</tr>
<tr>
<td>Taking notes (TN)</td>
<td>Copying text from the hypermedia environment</td>
<td></td>
</tr>
<tr>
<td>Macro-level process: task difficulty and demands</td>
<td>Learner seeks assistance regarding either the adequateness of their answer or their instructional behavior</td>
<td>“Do you want me to give you a more detailed answer?”</td>
</tr>
<tr>
<td>Macro-level process: interest (plus and minus) (INT+/−)</td>
<td>Learner has a certain level of interest in the task or in the content domain of the task</td>
<td>“Interesting”, “This stuff is interesting”</td>
</tr>
</tbody>
</table>

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* All codes refer to what was recorded in the verbal protocols (i.e., read, seen, or heard in the environment and/or during discussions).
* Plus and minus indicates that there are two separate codes. Plus is used when a participant notes the presence of the attribute and minus is used when the participant notes the absence of the attribute i.e., Content Evaluation (−) when the content is deemed not helpful by the participant.
Appendix B

Necessary Features for Each Type of Mental Model (based on Azevedo & Cromley, 2004)

Low Mental Model Category
1. No understanding
2. Basic Global Concepts
   - blood circulates
3. Global Concepts with Purpose
   - blood circulates
   - describes “purpose” – oxygen/nutrient transport
4. Single Loop – Basic
   - blood circulates
   - heart as pump
   - vessels (arteries/veins) transport
5. Single Loop with Purpose
   - blood circulates
   - heart as pump
   - vessels (arteries/veins) transport
   - describe “purpose” – oxygen/nutrient transport
6. Single Loop – Advanced
   - blood circulates
   - heart as pump
   - vessels (arteries/veins) transport
   - describe “purpose” – oxygen/nutrient transport
   - mentions one of the following: electrical system, transport functions of blood, details of blood cells

Intermediate Mental Model Category
7. Single Loop with Lungs
   - blood circulates
   - heart as pump
   - vessels (arteries/veins) transport
   - mentions lungs as a “stop” along the way
   - describe “purpose” – oxygen/nutrient transport
8. Single Loop with Lungs – Advanced
   - blood circulates
   - heart as pump
   - vessels (arteries/veins) transport
   - mentions Lungs as a “stop” along the way
   - describe “purpose” – oxygen/nutrient transport
   - mentions one of the following: electrical system, transport functions of blood, details of blood cells

High Mental Model Category
9. Double Loop Concept
   - blood circulates
   - heart as pump
   - vessels (arteries/veins) transport
   - describes “purpose” – oxygen/nutrient transport
   - mentions separate pulmonary and systemic systems
   - mentions importance of lungs
10. Double Loop – Basic
    - blood circulates
    - heart as pump
    - vessels (arteries/veins) transport
    - describe “purpose” – oxygen/nutrient transport
    - describes loop: heart – body – heart – lungs – heart
11. Double Loop – Detailed
    - blood circulates
    - heart as pump
    - vessels (arteries/veins) transport
    - describe “purpose” – oxygen/nutrient transport
    - describes loop: heart – body – heart – lungs – heart
    - structural details described: names vessels, describes flow through valves
References


Educational Technology Research and Development, 56(1), 45–72.


