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Adaptive Content and Process Scaffolding: A key to facilitating students' self-regulated learning with hypermedia

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Abstract

In this mixed-method study, we converged product and process data to examine the effectiveness of three human scaffolding conditions in facilitating students' learning about the circulatory system and the deployment of key self-regulatory processes during a 40-minute hypermedia learning task. Undergraduate students (N = 123) were randomly assigned to one of three scaffolding conditions (adaptive content and process scaffolding [ACPS], adaptive process scaffolding [APS], and no scaffolding [NS]) and were trained to use a hypermedia environment to learn about the circulatory system. The product data revealed that the students in the ACPS condition gained significantly more declarative knowledge than did those in the other two comparison conditions. In addition, ACPS was statistically significantly associated with qualitative shifts in the students' mental models of the topic, whereas the other two conditions were not. The verbal protocol data revealed that students in the ACPS condition utilized only a few regulatory processes, engaged in help-seeking behavior, and relied on the tutor to regulate their learning. By contrast, the verbal protocol data indicated that learners in the APS condition regulated their learning by using several key monitoring activities and learning strategies, while those in the NS condition were less effective at regulating their learning and used fewer key self-regulatory processes during the activity. We propose several design principles for adaptive hypermedia learning environments based on these findings.

Key words: self-regulated learning; scaffolding conditions; hypermedia

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Computer-based learning environments (CBLEs) such as intelligent tutoring systems (ITSs) are effective to the extent that they can adapt to the needs of individual students by systematically and dynamically providing scaffolding of key learning processes (Koedinger & Corbett, 2006; Lajoie & Azevedo, 2006; Shute & Zapata-Rivera, 2008). The ability of these environments to provide adaptive, individualized scaffolding is based on an understanding of how learner characteristics, system features, and the mediating learning processes interact during learning. A critical aspect of providing individualized instruction is scaffolding, or instructional support in the form of guides, strategies, and tools, which are used during learning to support a level of understanding that would be impossible to attain if students learned on their own (Puntambekar & Hubscher, 2005). While providing adaptive scaffolding to students learning about well-structured tasks with CBLEs has been shown to be effective (e.g., Koedinger, 2001), providing adaptive scaffolding to students learning about conceptually-challenging domains remains a challenge for hypermedia instruction (e.g., Azevedo, Moos, Johnson, & Chauncey, 2010; Jacobson, 2008; Shapiro, 2008). We argue that harnessing the full power of hypermedia learning environments will require empirical research aimed at understanding what kinds of scaffolds are effective in facilitating individualized instruction, and when they are best deployed (Azevedo & Hadwin, 2005; Azevedo & Jacobson, 2008; Bannert, Hildebrand, & Mengelkamp, 2009; Opfermann, Azevedo, & Leutner, in press).

Adaptive scaffolding has been used successfully in non-hypermedia CBLEs designed to teach students about well-structured tasks such as math, geometry, and physics (e.g., Aleven, Roll, McLaren, & Koedinger, 2010). However, the recent widespread use of hypermedia has outpaced our understanding of *how* learners can effectively learn with such environments, and *how* scaffolding can be designed to best meet students' individual needs during hypermedia learning (Azevedo 2005, 2008; Gerjets & Scheiter, 2007; Greene & Azevedo, 2010; Greene, Moos, & Azevedo, in press; Jacobson, 2008). Several studies on fixed, embedded scaffolds in hypermedia (e.g., Jacobson & Archodidou, 2000; Shapiro, 2008) demonstrate that these types of scaffolds are insufficient for fostering conceptual understanding with hypermedia. We argue that adaptive scaffolding (by human or computerized tutor or pedagogical agent) will more likely foster conceptual understanding in hypermedia environments. However, very little research has been conducted on the effectiveness of adaptive scaffolding and how it may facilitate students' learning with hypermedia (e.g., Azevedo, Cromley, & Seibert, 2004b; Azevedo, Cromley, Winters, Moos, & Greene, 2005; Azevedo et al., 2007, 2008). It is critical that researchers conduct more empirical research in this area to determine how different adaptive scaffolding methods prompt self-regulatory processes that facilitate students' learning of challenging topics with hypermedia.

In this study, we focus on the effectiveness of content and process scaffolding to determine how human tutors help students regulate their learning about a challenging science topic. It is our hypothesis that human tutor-initiated content and process scaffolding, as compared to only process scaffolding and a control condition, will lead to students more effectively regulating their learning about a challenging science topic, and subsequent better performance on a set of posttest knowledge measures. The empirical results from our human tutoring studies can be used to inform the design of adaptive hypermedia learning environments.

Challenges in self-regulated learning with hypermedia

Using hypermedia to learn about a complex and challenging topic, such as the human circulatory system, requires a student to regulate their cognitive and metacognitive processes throughout the task while navigating the system and managing the content. Learners also need to monitor their emerging understanding, how content presented in the hypermedia system relates to their prior knowledge, relevancy of content given their current sub-goal, and monitor their progress towards completing goals. Each of these monitoring processes leads to metacognitive judgments that impact how a student adapts and which learning strategy a student may select to rectify the judgment. For example, a judgment of learning (e.g., "I do not understand these sentences on the role of the tricuspid valve") may lead a student to re-read the sentences over again to see if they can improve their comprehension of the role of the valve. However, the choice of learning strategies is based on student's making accurate metacognitive judgments, and having metacognitive knowledge and the regulatory skills needed to continuously regulate during learning with hypermedia. They also need to monitor their understanding and modify their plans, goals, strategies, and effort in relation to contextual conditions (cognitive, motivational, and task conditions), and, depending on the learning task, reflect on the learning episode (Winne & Hadwin, 1998, 2008). Furthermore, having access to a wide range of information represented as text, graphics, animation, audio, and video, all of which is structured in a non-linear fashion (Azevedo & Jacobson, 2008; Jacobson & Azevedo, 2008), requires a student to decide which representations to use during learning, and in what sequence. Students must plan their learning session by activating prior knowledge to facilitate the anchoring of new knowledge with prior knowledge. They need to generate sub-goals to maximize their efforts at filling their own knowledge gaps and then select relevant content. Students also need to deploy several monitoring activities which allow the learner to determine whether he/she is understanding the content, whether the content is adequate given the current learning (sub)goal, how much effort to invest given the amount of time left to complete the task, and whether to test his/her learning to determine if new goals, strategies, and content are necessary to meet the overall learning goal. In addition, students must deploy several strategies in order to meet the overall learning (and sub-goals) while traversing non-linear, multi-representational hypermedia environments. Some strategies such as summarizing, drawing, making inferences, re-reading, knowledge elaboration, hypothesizing, and coordinating informational sources have been characterized as effective for learning about complex topics with hypermedia (e.g., Azevedo, Guthrie, & Seibert, 2004a). Sometimes students deploy less effective strategies such as copying information and engaging in free search of the hypermedia environment, which have been associated with little or no learning gains (Greene & Azevedo, 2009). In addition to planning, monitoring, and strategy deployment, students must also dynamically handle the difficulties by engaging in help-seeking behavior, expressing difficulty with the task and content, using features of the hypermedia environment (e.g., expanding a diagram to examine an anatomical structure) to maximize learning, and intentionally controlling their time and effort depending on goals which may still need to be accomplished. These processes are collectively known as self-regulated learning (SRL) (Azevedo et al., 2004a; Azevedo & Witherspoon, 2009; Greene & Azevedo, 2009; Moos, 2010; Moos & Azevedo, 2008).

Learning about complex science topics: The circulatory system

Complex science topics such as the human circulatory system are challenging for students to learn (Chi, 2005) since this topic must be understood at multiple levels in order to have deep conceptual understanding of how the system works. According to Chi (2005), the circulatory system is considered a direct process and as such it has certain inherent characteristics. First, fundamental difficulties encountered by students typically include understanding the role of the lungs in the circulatory system, and in particular that the lungs are the site of oxygen and carbon dioxide exchange, and that there are two paths (i.e., systemic and pulmonary circulations). Second, there are multi-level processes, which make it challenging for students. For example, the circulatory system has global patterns and components, which can be described by direction and speed. More specifically, the direction of the flow of blood is from the heart to the lungs, then back from the lungs to the heart before moving being pumped out to the body. Also, the components of the circulatory system can be discussed at multiple levels. For example, the aggregate components include the heart and veins, which can be further decomposed into a constituent level, comprising of cells (e.g., red blood cells) and tissues (for valves, chambers, and heart). Third, the components interact, for example, the heart interacts with blood by pumping it while the veins interact with blood by contracting and pushing it along the venous pathway. Fourth, the system involves numerous simple and complicated mechanisms and principles about both the pattern and components, which need to be learned in order to understand the process completely. Lastly, various factors, conditions, and variables can influence both the global patterns of flow and the local specific behavior of the components. These may include factors such as thickening of the arterial walls, which can affect the speed of blood flow. In sum, the circulatory system has many processes with components that interact at multiple levels. Deep conceptual understanding of the circulatory system requires knowledge of the cause-and-effect relationships in the system and the underlying mechanisms that determine the patterns of interaction that these processes exhibit.

One way to measure students' learning and understanding of the circulatory system is to examine changes in their mental models (e.g., Chi et al., 2001; Greene & Azevedo, 2009). Similar to other studies examining students' mental models (e.g., Azevedo et al., 2005; Chi et al., 2004), we operationally define a mental model as a conceptual knowledge structure that represents the underlying declarative knowledge (e.g., the septum is a membrane that divides the left and right sides of the heart), procedural knowledge (e.g., deoxygenated blood is pumped from the heart to the lungs to become oxygenated), and inferential knowledge (e.g., blood from the right ventricle is pumped to the lungs in order to be oxygenated) that is constructed by a student during a task such as using a hypermedia environment to learn about the circulatory system. Constructing an accurate mental model is a cognitively-demanding task, and understanding a complex system like the circulatory system requires integrating multiple information sources (i.e., text, diagrams) to achieve an understanding of the structure, function, and behavior of the system (Hmelo-Silver & Pfeffier, 2003). Hypermedia learning environments have been promoted as one means of providing students with these multiple information sources (e.g., Azevedo et al., 2005; Niederhauser, 2008; Shapiro, 2000), but these cognitive tools come with their own set of challenges.

Self-regulated learning and hypermedia

Models of self-regulation (e.g., Azevedo, Moos, et al., 2010; Greene & Azevedo, 2007; Pintrich, 2000; Winne & Hadwin, 1998, 2008; Zimmerman & Shunk, in press) describe a recursive cycle of cognitive activities central to learning and knowledge construction activities. Self-regulated learning models suggest that students may experience difficulties learning with hypermedia because students are not actively and efficiently managing their own learning. Students also may not be metacognitively, motivationally, or behaviorally active during the learning process. In sum, self-regulated learning involves the dynamic and adaptive deployment of a complex set of processes, which must be used to learn about complex and challenging topics with hypermedia.

Unfortunately, research has shown that learners of all ages have difficulty regulating their learning when they use hypermedia environments to learn about complex topics and that they gain little conceptual understanding (Azevedo & Cromley, 2004; Azevedo et al., 2004a, 2004b, 2005, 2007, 2008; Greene & Land, 2000; Jacobson & Archodidou, 2000; Hannafin & Land, 1997; Moos & Azevedo, 2006; Oliver & Hannafin, 2000). Therefore, researchers have begun investigating whether SRL can be scaffolded in hypermedia environments, to help students deploy these processes and attain conceptual understanding.

The role of scaffolding in facilitating students' learning

Scaffolding is a critical component in facilitating students' learning about challenging topics (Chi, et al., 1994, 2001, 2004). Scaffolds are tools, strategies, and guides which are used by human and computer tutors, and teachers during learning to support students' understanding (Aleven & Koedinger, 2002; Graesser et al., 2000; Graesser, Bowers, Hacker, & Person, 1997). Our definition of scaffolding is quite similar to the original conception of scaffolding articulated by Wood, Bruner, and Ross (1976). Specifically, we believe scaffolding requires a shared understanding of the goal of the task between the tutor and tutee. The tutor must *calibrate* support based on an ongoing diagnosis of the student's level of understanding. This calibrated support requires the tutor to constantly fine-tune the support based on the student's changing knowledge and skills. This support is individualized not only for different learners with varying levels of prior knowledge and skills, but it also changes for each learner over the course of the task. This ongoing dynamic assessment and adaptation of support enables the tutor to monitor progress, and then provide appropriate support and feedback.

Vygotksy's (1934/1978) work suggests that learners can be guided or scaffolded by a more capable peer to solve a problem or carry out a task that would be beyond what they could accomplish independently. Scaffolding involves providing assistance to students on an as-needed basis and fading the assistance as learner competence increases (Brown, Collins, & Duguid, 1989). Traditionally, scaffolding in education has emphasized the role of dialogue and social interaction to foster comprehension and monitoring activities (e.g., Palinscar & Brown, 1984) and student-generated self-explanations (e.g., Chi et al., 1994, 2001). Tutors can also scaffold by providing hints and feedback on performance, as well as motivating students to continue the task (Graesser et al., 1997; Lepper, Drake, & O'Donnell-Johnson, 1997; Merrill, Reiser, Merrill, & Landes, 1995).

Using adaptive scaffolding to facilitate students' self-regulated learning with hypermedia

Several studies have provided evidence that when students learn about complex topics with hypermedia that does not include scaffolding, they do not regulate their learning, which leads to a failure to gain conceptual understanding (Azevedo et al., 2004b, 2005; Azevedo, Winters, & Moos, 2004; Hill & Hannafin, 1997; Greene & Land, 2000). For example, a recent study by Azevedo and Cromley (2004) on college students' learning about a complex science topic with hypermedia revealed that students in the control condition (i.e., those who were not trained to regulate their learning) did not show substantial learning pretest-posttest gains. These students used ineffective (e.g., memorizing) strategies, and did not engage in much monitoring of their learning. In contrast, those who were trained in SRL showed significant learning gains from pretest to posttest by using effective strategies, planning their learning by creating sub-goals and activating prior knowledge, monitoring their emerging understanding, and planning their time and effort. This study established that failure to deploy key self-regulatory processes during learning with hypermedia environments is associated with little or no learning gains, and suggests that introducing scaffolds might facilitate conceptual understanding for those who do not regulate their learning on their own.

Human tutors can provide adapative scaffolding to foster students' self-regulated learning. More specifically, a human tutor can provide adaptive scaffolding by monitoring both a student's emerging content understanding and the student's deployment of key self-regulatory processes. This monitoring can be used to create an ongoing diagnosis of the student's learning and likelihood of achieving conceptual understanding. Based on this ongoing diagnosis, the tutor can support student understanding through the prompting of key self-regulatory process (e.g., prior knowledge activation, self-questioning, hypothesizing, etc.). This adaptive scaffolding enhances student learning through timely feedback and calibrated support (see Chi et al., 1994, 2001, 2004; Graesser et al., 1997, 2000; Hogan & Pressley, 1997; Lepper et al., 1997; Merrill et al., 1995; VanLehn, Siler, Yamauchi, & Baggett, 2003). Furthermore, studying adaptive scaffolding by human tutors can extend current contextual models of SRL (Winne, 2001) by explicating the complex, dynamic nature of self- and other-regulatory processes used to foster students' SRL in particular learning contexts. It is therefore critical that researchers not only examine *what* students do but also determine *how* students regulate their learning and how external regulating agents, such as human tutors, can facilitate students' self-regulated learning.

A few recent studies (Azevedo et al., 2004b, 2005; Biemans & Simons, 1995; Kao & Lehman, 1997; Kramarski & Hirsch, 2003) have provided evidence to support the notion that providing students with adaptive scaffolding during learning of biology, geography, algebra, and statistics with hypermedia leads to enhanced student understanding. For example, Azevedo and colleagues (2004b) recently conducted a study to determine whether adaptive scaffolding was effective in facilitating college students' ability to regulate their learning of complex science topics with hypermedia. The students were randomly assigned to one of three scaffolding conditions (adaptive scaffolding [AS], fixed scaffolding [FS], and no scaffolding [NS]) and were trained to use a hypermedia environment to learn about the circulatory system. Results indicated that students in the adaptive scaffolding condition based on Chi's (2001) tutor-centered hypothesis (learning with the aid of a tutor) developed a significantly deeper conceptual understanding of the science topic, but relied extensively on the tutor to regulate their learning. However, it should be noted that (according to the tutor-centered hypothesis) the significant shifts in the adaptive scaffolding students' learning are based on the tutor dominance of the tutoring session, thus leaving little if any chance for the student to regulate his/her own learning. Students in the other two conditions learned significantly less, were less effective at regulating their learning, and exhibited great variability in self-regulation of their learning during the knowledge construction activity.

Subsequently, Azevedo and colleagues (2005) conducted a near-replication of their previous (2004b) study examining the effect of the same scaffolding conditions on facilitating adolescents' ability to regulate their learning of the circulatory system with hypermedia. The two major changes in this study were the number of items on certain pretest and posttest measures and a reduction in the length of the learning task to 40 minutes (from 45 minutes). Similar to their findings from the 2004 study, results indicated that a significant number of students (i.e., 30%) in the adaptive scaffolding (AS) condition shifted from a low to a high mental model of the circulatory system (from pretest to posttest). Also, these same students outperformed their counterparts on measures of declarative knowledge. As for self-regulatory processes, the students in the AS condition deployed key self-regulatory processes related to planning, monitoring activities, and effective strategies. Students in the AS condition relied heavily on the tutor for external regulation. On average, each student in the AS condition engaged in 7.32 help-seeking behaviors (or approximately once every 5 minutes during a 40-minute learning task).

More recently, Azevedo and colleagues (2007, 2008) conducted two studies that experimentally compared the role of no scaffolding (SRL condition) with a human tutoring condition provided to college or adolescent students. The tutoring in this study focused exclusively on a very rigid scaffolding approach that prompted process scaffolding based on the time remaining in the session and the particular section and sub-section on the hypermedia environment (ERL: externally-regulated learning condition). In both studies, the researchers found that students in both age groups benefited tremendously from the process scaffolding offered by the human tutor, as evidenced by their use of significantly more key SRL processes related to planning, monitoring, and learning strategies and significant pretest-posttest mental model shifts. There were, however, no significant differences between groups (and across ages in both studies) on measure of declarative knowledge. While the results demonstrated the benefits of processes scaffolding, the current study extends these studies by empirically testing the differences between process and content scaffolding. These studies are part of a larger research agenda aimed at testing the effectiveness of human tutoring and scaffolding of SRL processes and biology content on adolescents' and college students' learning outcomes with hypermedia.

Research in these areas leads to a hypothesis that adaptive scaffolding may support students' self-regulated learning about complex topics with hypermedia only if a balance can be achieved between providing support and fostering a student's self-regulatory behavior. Thus, despite the wealth of research on the effectiveness of scaffolding during human and computerized tutoring in complex domains, and the emerging research on human tutors' adaptive scaffolding during students' learning of challenging science topics with hypermedia (e.g., Azevedo et al., 2004a, 2004b, 2005, 2007, 2008), these lines of research have not used self-regulated learning as a comprehensive framework to analyze the complex interaction between learner characteristics, system features and the mediating learning processes. Furthermore, they have not examined how scaffolding by a more experienced tutor might assist a student in regulating his or her learning with a hypermedia environment and developing a deep conceptual understanding of a complex science topic. Furthermore, relatively few studies have been done regarding how human scaffolding processes can inform the design of adaptive hypermedia environments intended to foster students' understanding of such challenging topics.

Overview of the current study and hypotheses

In this study, we investigated the effectiveness of three different scaffolding methods for facilitating undergraduate students' ability to regulate their learning with hypermedia and also investigated *why* and *how* different types of scaffolding varied in their effectiveness. We have adopted an approach similar to that of other cognitive scientists and human tutoring researchers by analyzing what kinds of scaffolds are effective in learning with hypermedia and how they affect students' self-regulatory skills. We focused on three research questions: (1) Do different scaffolding conditions influence students' ability to shift to more sophisticated mental models of the circulatory system?; (2) Do different scaffolding conditions lead students to gain significantly more declarative knowledge of the circulatory system?; and, (3) How do different scaffolding conditions influence students' regulation of their learning with hypermedia?

We created three scaffolding conditions (adaptive content and process scaffolding [ACPS], adaptive process scaffolding [APS], and no scaffolding [NS]) based on Winne and colleagues' (1998, 2001, 2008) model of self-regulated learning and the current empirical literature on scaffolding and learning with hypermedia (e.g., Azevedo & Cromley, 2004; Azevedo et al., 2004a, 2004b, 2005, 2007, 2008). Each condition is described below.

In the *adaptive content and process scaffolding (ACPS)* condition, students were provided with an overall learning goal. They had access to a human tutor who provided two types of adaptive scaffolding during learning – 1) *content scaffolding*, i.e., scaffolding students' learning by assessing their emerging understanding of the circulatory system to ensure that they met their overall learning goal – and 2) *process scaffolding* – i.e., scaffolding students' learning by helping them enact various key self-regulatory processes, such as planning their learning, monitoring their emerging understanding, and using different strategies to learn about the circulatory system. These two types of scaffolding were both used dynamically and adaptively by the tutor during learning to ensure that the learner reached the overall learning goal.

In the *adaptive process scaffolding (APS) condition*, the students were given the same overall learning goal and also had access to a tutor. This condition was identical to the ACPS condition, but the tutor provided only the *process scaffolding* described above. The tutor never provided content scaffolding. In the *no scaffolding* (NS) condition, the students were given the same overall learning goal but no tutoring of any kind was provided. This control condition resembles the one used by Azevedo and colleagues (e.g., Azevedo et al., 2008).

With regard to the first research question, we hypothesized that the ACPS condition would be associated with a significant shift in the quality of the students' mental models (from pretest to posttest) compared to both the APS and NS conditions. Based on previous research (Azevedo, 2005; Azevedo et al., in press), we also hypothesized that all students, regardless of scaffolding condition, would improve significantly on both declarative knowledge measures, the matching and labeling tasks, from pretest to posttest. As for the third research question, we hypothesized that students in ACPS would overrely on the human tutor and deploy fewer key self-regulatory processes as compared to participants in the other two conditions. We also hypothesized that the students in the NS would not deploy key self-regulatory processes.

Method

Participants

123 undergraduate students (83% women), from a large state university in the mid-Atlantic region of the US received extra credit in their Educational Psychology course for their participation in this study. Their mean age was 21.0 years, and mean GPA was 3.20. Forty-two percent (n = 52) were seniors, 26% (n = 32) were juniors, 9% (n = 11)

were sophomores, and 23% (*n* = 28) were freshmen. Seventy-four percent (74%) of students reported not having taken a biology course in the last 4 years, while 26% reported to have taken one biology course. The students were non-biology majors, and the pretest confirmed that all participants had low prior knowledge of biology and the circulatory system.

Scaffolding procedures

Human tutors. All three tutors had completed a bachelor's degree; when we collected data, two of the tutors were enrolled in a doctoral program, and one was enrolled in a Master's program, all in Educational Psychology. Their mean age was 33 (range = 29–39); there were one male and two female tutors.

All tutors had completed a six-hour tutor training, including viewing videotapes, analyzing coded transcriptions of tutoring sessions, and reading our previously published studies. Two hours of that training were specific to the condition (ACPS or APS) assigned to the tutor. Each tutor had also been responsible for collecting data from 50-150 participants in our previous studies (e.g., Azevedo et al., 2004a, 2004b, 2005). They were therefore very familiar with the experimental protocol, including all sections of the hypermedia encyclopedia, prompting participants to verbalize their thinking, administering the pre- and posttest measures, and all other experimental materials and procedures.

All tutors also had prior experience in both one-on-one tutoring and classroom teaching. Tutor A (who tutored in the ACPS condition) had a BS in biology and eight years of tutoring experience in all science topics (including human biology) with a variety of age groups. She also had six years' experience as a classroom teacher in all science topics, predominantly with elementary school students. She was assigned to the ACPS condition because she had an undergraduate degree in biology and extensive experience in teaching biology.

Tutor B (who tutored in the APS condition) had a BA in history and three years of tutoring experience in multiple academic subjects, including one and a half years' experience tutoring high school students. She also had 15 years' experience as a classroom teacher/trainer, predominantly with low-literate adults, across multiple subject areas (including human biology and other science topics). Tutor C (who also tutored in the APS condition) had a BA in psychology and four years of summer tutoring experience in several non-science topics. He also had four years of experience as a classroom teacher, predominantly with middle-school students, in all core subjects.

Tutoring scripts. We developed standardized scripts for both tutoring conditions. For the APS condition, the script was designed to be relatively content-independent, whereas the script for the ACPS condition necessarily included content relevant to the human circulatory system.

The script for the *APS condition* was as follows:

1. Student selects a paragraph to read, and reads it out loud.

2. If the student stops reading after Step 1 and enacts an effective SRL process, take no action. If the student does not enact any SRL process, prompt the student with, *"Can you think of anything that you could do to help you learn this?"*

   2a. If the student then enacts an effective SRL process, take no action. If the student does not enact any SRL process, prompt the student with, either "Do you think that strategy will help you learn?" ([TIMUS[6]] if the student had previously used a strategy) or "Do you think [name of strategy; e.g., summarizing] would help you learn this?"
3. If the student does not stop reading after Step 1, interrupt and prompt the student with, "You have read a lot, can you think of anything that you could do to help you learn this?"

   3a. If the student then enacts an effective SRL process, take no action. If the student does not enact any SRL process, prompt the student with, either "Do you think that [name of process] will help you learn?" (scaffolding monitoring of strategy if the student had previously used a strategy) or "Do you think [name of strategy; e.g., coordinating informational sources] would help you learn this?".
4. At time prompts, prompt student to Monitor Progress towards Goal (e.g., "You have 20 minutes left, do you feel like you've met your learning goal?")
5. Then prompt student to activate prior knowledge (e.g., "Can you tell me back in your own words what you just learned").
6. Repeat from Step 1.

The script for the *ACPS condition* was as follows:

1. Student selects a paragraph to read, but before student reads

   1.a Prompt student to activate prior knowledge (e.g., "Tell me what you already know about [topic of paragraph]"). Regardless of students' responses, prompt with "Let's read on and see what the paragraph says."
2. If the student stops reading after Step 1a and enacts an effective SRL strategy, take no action. If the student does not enact any SRL strategy, prompt the student to use a specific effective strategy, for example, "I want you to summarize what you just read"
3. If the strategy in Step 2 was enacted correctly, give positive feedback. If the strategy was enacted incorrectly,

   3a. Give negative feedback (optional), or

   3b. Prompt the student to use a fix-up strategy, such as re-reading or

   3c. Tutor gives a correct explanation, and tells student to correct his/her summary, drawing, etc.

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[6] Please refer to Azevedo et al (2004b; pages 364-367) for a list, description, and examples of the SRL processes.

4. Ask student to continue reading, following Steps 1-4.
5. At time prompts, prompt student to Monitor Progress towards Goal (e.g., "You have 20 minutes left, do you feel like you understand [topic]?")
6. Prompt student to select next passage to be read, ensuring that at least 5 minutes are spent in each of the three main articles. Give feedback about the relevance of the passage the student selected.
   6a. If the passage is relevant, tell student so (TIIAI)
   6b. If the passage is irrelevant, tell student so (TICE), and suggest a more relevant passage (TIIAI)
7. Repeat from Step 1.

Research design

We used a mixed factorial design, with students randomly assigned to one of three scaffolding conditions – adaptive content and process scaffolding [ACPS], adaptive process scaffolding [APS], and no scaffolding [NS]), to examine qualitative shifts in students' mental models and their gains on two measures of declarative knowledge from pretest-posttest. During the 40-minute learning task with hypermedia, we used a think-aloud protocol methodology (Ericsson & Simon, 1993) to examine the complex, dynamic nature of students' self-regulated learning.

Paper and pencil measures

All of the paper-and-pencil materials, except for the consent form and questionnaire, were constructed in consultation with a nurse practitioner who is a faculty member at a school of nursing in a large mid-Atlantic university. Prior to taking part, all participants signed a letter that stated the purpose of the study and gave their informed consent. The participant questionnaire solicited information concerning age, sex, current GPA, number and title of undergraduate biology courses completed, and experience with biology and the circulatory system.

There were three parts to the pretest: (1) a sheet on which students were asked to match 13 words with their corresponding definitions related to the circulatory system (matching task), (2) a color picture of the heart on which students were asked to label 14 components (labeling task), and (3) another sheet which contained the instruction, *"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"* (mental model essay). The essay was open-ended in order not to encourage the participants to tailor their learning to the test. The posttest was identical to the pretest.

Hypermedia learning environment

Participants learned about the circulatory system by using Microsoft Encarta's Reference Suite™ (2003) hypermedia environment that was installed on a laptop with an 11-inch color monitor and a sound card. They were limited to using the DVD-based encyclopedia portion of the package. During the training phase, learners were shown the three most relevant articles in the environment including the circulatory system, blood, and heart, which contained multiple informational sources – text, static diagrams, photographs, and a digitized animation depicting the functioning of the circulatory system. Together these three articles comprised 16,900 words, 18 sections, 107 hyperlinks, and 35 illustrations. During learning, participants were allowed to use all of the features incorporated in Encarta such as the search functions (e.g., use "find" to locate content anywhere on the DVD, and "find in the article"), table of contents, hyperlinks, and multiple sources of information, and were allowed to navigate freely within the environment.

Procedure

The authors tested the participants individually in all conditions. Participants were randomly assigned to one of three scaffolding conditions: ACPS (n = 43), APS (n = 43), and NS (n = 37). First, the participant questionnaire was handed out, and participants were given as much time as they wanted to complete it. Second, the pretest was handed out, and participants were given 20 minutes to complete it. Participants wrote the answers on the pretest and did not have access to any instructional materials. Third, participants were trained on how to use the hypermedia environment to learn about the circulatory system. Fourth, the experimenter provided instructions for the learning task. The following instructions were read and presented to the participants in writing.

No scaffolding (NS) condition. For the NS condition the instructions were: "You are being presented with a hypermedia encyclopedia, which contains textual information, static diagrams, and a digitized video clip of the circulatory system. We are trying to learn more about how students use hypermedia environments to learn about the circulatory system. Your task is to learn all you can about the circulatory system in 40 minutes. 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. We ask you to 'think aloud' continuously while you use the hypermedia environment to learn about the circulatory system. I'll be here in case anything goes wrong with the computer and the equipment. Please remember that it is very important to say everything that you are thinking while you are working on this task."

Adaptive content and process scaffolding (ACPS) condition. Participants in this condition were provided with an overall learning goal (same as above, "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.") and had access to a tutor who provided two types of adaptive scaffolding during learning – 1) *content scaffolding*, i.e., scaffolding students' learning by assessing their emerging understanding of the circulatory system to ensure that they met their overall learning goal, 2) and *process scaffolding* – i.e., scaffolding students' learning by assisting them to enact various self-regulatory process, helping them plan their learning by activating their prior knowledge, monitoring their emerging understanding, using different strategies to learn about the circulatory system, handling task difficulties and demands, and assessing their emerging understanding. Similar to published human tutoring studies that exemplified naturalistic tutoring (e.g., Chi et al., 2001; Graesser et al., 2001), these two types of scaffolding were both used dynamically and adaptively by the tutor during learning to ensure that the learner reached the overall learning goal.

Adaptive process scaffolding (APS) condition. The participants were given the same overall learning goal and also had access to a tutor. This condition was identical to the ACPS condition, except that the tutor provided only *process scaffolding* – i.e., scaffolding students by helping them enact various self-regulatory processes, such as planning their learning, monitoring their emerging understanding, using different strategies to learn about the circulatory system, and handling task difficulties and demands, all based on their assessment of the students' emerging understanding. However, students were never provided content scaffolding in the APS condition.

Think-aloud training and learning task. Following the instructions, a practice task on how to perform a think-aloud was administered to familiarize all participants with the think-aloud procedure while they used the hypermedia environment to learn about the circulatory system. In all three conditions, an experimenter sat next to the participant and simply reminded the participant to keep verbalizing when they were silent for more than three seconds (e.g., "say what you are thinking"). All participants were reminded of the global learning goal ("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") as part of their instructions for learning about the circulatory system. Participants had access to the instructions (which included the learning goal) during the entire learning session. Participants in the ACPS and APS conditions had access to the tutor. All participants were given 40 minutes to use the hypermedia environment to learn about the circulatory system. Participants were allowed to takes notes and draw during the learning session, although not all chose to do so.

Posttest procedures. All participants were given 20 minutes to complete the posttest immediately following the learning task. They were not allowed to use their notes or any other instructional materials during the posttest.

Coding and scoring the product and process data

We ensured that the coders were blind to conditions by having them code and score photocopies of the data that did not have any identifying information.

Qualitative mental model shifts. Our analyses focused on the qualitative shifts in students' mental models based on the different scaffolding conditions. We used Azevedo and colleagues (2008; p. 65-66) method for analyzing the learners' mental models. A student's initial mental model of how the circulatory system works was derived from their statements on the pretest essay. Similarly, a student's final mental model of the circulatory system was derived from their statements on the posttest essay. The scheme consists of 12 mental models, which represent the progression from no understanding to the most accurate understanding (i.e., the advanced double loop model).

The second and fifth authors scored the students' pretest and posttest mental models by assigning the numerical value associated with the mental models described in Azevedo et al (2008). We followed the procedure for assigning numeric values to each student's pretest and posttest mental models based on the procedure outlined in Azevedo and colleagues (2008). The values for each student's pretest and posttest mental model were recorded and subsequently used in a statistical analysis to determine the qualitative shifts in their conceptual understanding.

Matching task and labeling of the heart diagram. The second and fifth authors scored the matching task by giving each student either a 1 (for a correct match between a concept and its corresponding definition) or a 0 (for an incorrect match between a concept and definition) on his/her pretest and posttest (range 0-13). Similarly, the second and fifth authors scored the heart diagram by giving each student either a 1 (for each correctly labeled component of the heart) or a 0 (for each incorrect label; range 0-14). The scores for each student's pretest and posttest on the matching task and heart diagram were tabulated separately and used in subsequent analyses.

Segmenting and coding students' and tutors' verbalizations. The raw data collected from this study consisted of 4,720 minutes (78.7 hr) of audio and video tape recordings from the 118 participants, who gave extensive verbalizations while they learned about the circulatory system. Data from five participants were excluded due to poor audio quality. During the first phase of data analysis, a graduate student transcribed the audiotapes and created a text file for each participant. Transcripts were prepared for all 118 participants. This phase of the data analysis yielded a corpus of 2,755 double-spaced pages (M = 23.3 pages per participant) with a total of 629,850 words (M = 5,337 words per participant). A second graduate student verified the accuracy of the transcriptions by comparing each text file with the video tape recording of the participant and the original text was verified and no inconsistencies were found.

Students' and tutors' regulatory behavior. Azevedo and colleagues' (2004a; see pages 364-367 for details) coding scheme was used to analyze both learners' and tutor's regulatory behaviors. The coding scheme captures the following – (a) *Planning* processes including planning, goal setting, activating prior knowledge, and recycling goal in working memory; (b) *Monitoring judgments* including feeling of knowing, judgment of learning, monitoring progress towards goals, content evaluation, identifying the adequacy of information, evaluating the content as the answer to a goal, and self-questioning; (c) *Learning strategies* including hypothesizing, coordinating informational sources, inferences, mnemonics, drawing, summarizing, goal-directed search, selecting new informational sources, free search, re-reading, taking notes, knowledge elaboration, finding location in environment, memorizing, reading notes, and reading new paragraph; (d) *Handling task difficulties and demands* including help-seeking behavior, expect adequacy of information, control of context, time and effort planning, and task difficulty; and, (e) *Interest* in the task or the content domain of the task.

The coding scheme also has corresponding codes to account for the two types of tutors' scaffolding behavior. *Tutor-initiated* (T-I) scaffolding was used to refer to any tutor code designed to instruct a student to use a particular self-regulatory process (e.g., "Now *I want you* to put what you just read with the diagram of the heart and draw and label your own diagram"). In contrast, *tutor-scaffolding* (T-S) involved the tutor making a suggestion to the students about using a particular self-regulated learning process (e.g., "Now *do you think it would help if you* put what you just read with the diagram and draw and label your own diagram?").

The coding scheme was designed to segment the data from the previous data analysis phase. This phase of the data analysis yielded 18,256 segments (M = 92 per student transcript, and M = 98 tutor codes per session) with corresponding SRL processes. A graduate student with extensive training on the use of our coding scheme coded all of the transcriptions by assigning one of the self-regulated learning processes to each coded segment in the transcriptions.

Inter-rater agreement. Inter-rater agreement was established by having two trained graduate assistants to independently code all selected protocols (pre- and posttest essays of the circulatory system from each participant). There was agreement on 237 out of a total of 246 student descriptions, yielding an inter-rater agreement of .96. Inter-rater agreement was also established for the coding of the learners' and tutors' regulatory behavior by comparing the individual coding of the second author with that of the first author. The second author independently re-coded 13,393 randomly selected protocol segments (73% of the 18,256 coded protocols with corresponding self-regulated learning variables). There was agreement on 13,203 out of 13,393 segments yielding an inter-rater agreement of .98. Inconsistencies were resolved through discussion between the experimenters and the student.

Results

Question 1: Do different scaffolding conditions influence students' ability to shift to more sophisticated mental models of the circulatory system? A 4 X 3 (mental model pretest-posttest shift by scaffolding condition) chi-square test revealed a statistically significant difference in the frequency distribution of learners' mental model shifts by scaffolding condition (χ^2 [6, N = 123] = 17.628, p < .01). The ACPS condition was associated with a significantly higher number of learners shifting to more sophisticated mental models (ACPS = 82% vs. APS = 70%, NS = 44%). More specifically, the ACPS condition was associated with the highest frequency of learners shifting from a low level of understanding to a high level of understanding (AS = 55% vs. APS = 35%, NS = 18%). In contrast, the APS condition was associated with the highest frequency of learners shifting from an intermediate to high level of understanding (APS = 25% vs. ACPS = 22%, NS = 14%). The NS condition was associated with the highest frequency of learners shifting from a low level to medium level of understanding (NS =12% vs. APS = 9%, ACPS = 5%).

Furthermore, the NS condition was associated with the highest frequency of students whose mental models did not change from pretest to posttest (NS = 56% vs. APS = 30%, NS = 18%; see Table 1).

Question 2: Do different scaffolding conditions lead students to gain significantly more declarative knowledge of the circulatory system? We used a 3 (condition: adaptive content and process scaffolding [ACPS], adaptive process scaffolding [APS], no scaffolding [NS]) X 2 (time: pretest, posttest) mixed design to analyze gains in students' declarative knowledge based on their scores on the matching and labeling tasks. The first factor, scaffolding condition, was a between-subjects factor; while the second factor, time, was a within-subjects factor. The number of participants in each cell is 37 for the ACPS condition, 43 for the APS condition, and 43 for the NS condition for all analyses pertaining to this question.

Matching. A 3 X 2 repeated measures ANOVA on the pretest and posttest data showed a significant main effect of time, F (1, 120) = 128.717, MSE = 304.448, $p < .05$, $\eta^2 = .518$, but no significant interaction between condition and time, F (2, 120) = .620, MSE = 304.448, $p > .05$, $\eta^2 = .010$. Participants in all conditions gained significantly from pretest to posttest (see Table 2).

Labeling. A 3 X 2 repeated measures ANOVA on the pretest and posttest data showed a significant main effect of time, F (1, 120) = 479.017, MSE = 205.795, $p < .05$, $\eta^2 = .800$, and a significant interaction between condition and time, F (2, 120) = 6.806, MSE = 205.795, $p < .05$, $\eta^2 = .102$. Simple main effect analyses found no significant differences

Table 1:
Frequency of Learners' Qualitative Mental Model Shifts, by Scaffolding Condition

	Scaffolding Conditions		
Qualitative Shift in Students' Mental Models from Pretest to Posttest	Adaptive Content and Process Scaffolding (ACPS) *n* (%)	Adaptive Process Scaffolding (APS) *n* (%)	No Scaffolding (NS) *n* (%)
No Shift	7 (18%)	13 (30%)	**24 (56%)**
Low to Intermediate (L-I) Understanding	2 (5%)	4 (9%)	**5 (12%)**
Intermediate to High (I-H) Understanding	8 (22%)	**11 (25%)**	6 (14%)
Low to High (L-H) Understanding	**20 (55%)**	15 (35%)	8 (18%)

Note: Bold indicates which scaffolding condition contributed most to that shift category

Table 2:
Means (and Standard Deviations) for the Pretest and Posttest Learning Measures by Scaffolding Conditions

Scaffolding Conditions			
	No Scaffolding (NS) (n = 43)	Adaptive Process Scaffolding (APS) (n = 43)	Adaptive Content and Process Scaffolding (ACPS) (n = 37)
	M (*SD*)	*M* (*SD*)	*M* (*SD*)
Matching (%)			
Pretest	52.42 (26.82)	54.87 (25.15)	59.39 (28.84)
Posttest	74.32 (26.77)	82.32 (21.19)	85.95 (14.14)
Labeling (%)			
Pretest	5.34 (10.78)	6.25 (14.92)	10.00 (17.76)
Posttest	32.47 (20.96)	38.77 (20.92)	48.09 (20.31)

between the conditions at pretest (F [2, 120] = 1.117, $p > .05$), but there were differences at posttest, F (2, 120) = 8.836, MSE= 524.842, $p < .05$, $\eta^2 = .049$ (see Table 2). A follow-up LSD test showed that the labeling posttest score for participants in the ACPS condition was significantly greater than that for the NS condition ($p < .05$), and ACPS was significantly greater than APS ($p < .05$), but APS and NS did not differ from each other ($p > .05$). The results indicate that the ACPS condition led to the highest mean "jump," or improvement, in students' labeling score (see Table 2). On average, students in the ACPS condition "jumped" from 10% correct on the pretest to 48% correct on the posttest. Students in the APS and NS conditions jumped considerably less, from 6% correct on the pretest to 39% correct on the posttest and from 5% correct on the pretest to 32% correct on the posttest, respectively.

Question 3: How do different scaffolding conditions influence students' ability to regulate their learning from hypermedia? In this section we present the results of a series of chi-square analyses that were performed to determine whether there were significant differences in the distribution of students' use of self-regulated learning variables, across the three scaffolding conditions. We examined how learners regulated their learning of the circulatory system by calculating how often they used each of the variables related to the five main self-regulated learning categories related to *planning, monitoring, strategy use, handling task difficulty and demands,* and *interest*. The raw counts for each coded self-regulated learning variable across scaffolding conditions and the number of learners using each self-regulated learning variable above the median proportion across conditions and the results of the chi-square tests are presented in leftmost columns of Tables 3 and 4, respectively.

Table 3:
Raw Frequency of Codes for Self-Regulated Learning Processes for Students (S-I) and Tutors (T-I and T-S), by Scaffolding Condition

	Student-Initiated (S-I) Moves				Tutor-Instructional (T-I) and Tutor-Scaffolding (T-S) Moves		
Self-Regulated Learning Process	*Grand Total of Coded Raw Frequencies*	Adaptive Content and Process Scaffolding (ACPS) (n = 34)	Adaptive Process Scaffolding (APS) (n = 42)	No Scaffolding (NS) (n = 42)	*Grand Total of Coded Raw Frequencies*	Adaptive Content and Process Scaffolding (ACPS) (n = 34)	Adaptive Process Scaffolding (APS) (n = 42)
Planning							
Prior Knowledge Activation	*714*	387	235	92	*939*	930	9
Planning	*121*	10	101	10	*163*	49	114
Sub-Goals	*390*	47	177	166	*286*	146	140
Recycle Goal in Working Memory	*25*	3	8	14	*19*	8	11
Monitoring							
Feeling of Knowing (FOK)	*1445*	740	462	243	*1270*	1162	108
Judgment of Learning (JOL)	*797*	322	320	155	*18*	16	2
Content Evaluation	*299*	139	152	108	*173*	124	49
Self-Questioning	*83*	1	45	37			
Monitoring Progress Toward Goals	*176*	44	101	31	*191*	80	111
Monitor Use of Strategy	*107*	19	71	17	*61*	22	39
Identify Adequacy of Information	*178*	45	89	44	*479*	183	296

Strategy Use							
Draw	*164*	64	81	19	*219*	162	57
Coordinating Informational Sources	*283*	76	186	21	*151*	54	97
Read Notes	*122*	39	65	18	*42*	18	24
Re-Reading	*518*	90	226	202	*56*	35	21
Hypothesizing	*36*	7	28	1	*4*	2	2
Goal-Directed Search	*56*	3	30	23	*62*	11	51
Selecting New Informational Source	*239*	28	83	128	*235*	190	45
Free Search	*58*	3	11	44			
Taking Notes	*860*	183	309	368	*70*	42	28
Find Location in Environment	*52*	19	24	9	*50*	30	20
Knowledge Elaboration	*121*	46	41	34	*342*	342	0
Summarization	*1532*	506	556	470	*207*	188	19
Inferences	*235*	102	75	58	*114*	113	1
Read New Paragraph	*39*	10	19	10	*98*	69	29
Memorization	*73*	17	24	32	*4*	4	0
Mnemonics	*63*	18	21	32	*84*	77	7
Task Difficulty and Demands							
Help Seeking Behavior	*897*	655	227	15			
Time and Effort Planning	*134*	15	79	40	*162*	60	102
Expect Adequacy of Information	*140*	15	96	29	*156*	53	103
Task Difficulty	*111*	47	46	18	*85*	51	34
Control of Context	*537*	65	190	282	*503*	141	362
Interest							
Interest Statement	*237*	73	53	111	*53*	49	4
Positive Feedback					*1214*	1102	112
Negative Feedback					*73*	73	0

Table 4:
Number and Proportion of Learners Using Self-Regulated Learning Processes (S-I) Above the Median Proportion, by Scaffolding Condition

	Student-Initiated (S-I) Moves [1]			
Self-Regulated Learning Process	Adaptive Content and Process Scaffolding (ACPS) (n = 34)	Adaptive Process Scaffolding (APS) (n = 42)	No Scaffolding (NS) (n = 42)	χ^2
Planning				
Prior Knowledge Activation	**28 (82%)**[a]	**21 (50%)**	10 (24%)	25.759*
Planning	8 (24%)	**37 (88%)**[b]	5 (12%)	56.869*
Sub-Goals	5 (15%)	**26 (62%)**	**28 (67%)**[c]	23.989*
Recycle Goal in Working Memory	3 (9%)	7 (17%)	6 (14%)	1.015
Monitoring				
Feeling of Knowing (FOK)	**29 (85%)**[a]	19 (45%)	11 (26%)	26.846*
Judgment of Learning (JOL)	**23 (68%)**[a]	**23 (55%)**	13 (31%)	10.711*
Content Evaluation	6 (18%)	**27 (64%)**[b]	**26 (62%)**	20.045*
Self-Questioning	1 (3%)	20 (48%)[b]	17 (40%)	19.223*
Monitoring Progress Toward Goals	15 (44%)	**31 (74%)**[b]	13 (31%)	16.090*
Monitor Use of Strategy	10 (29%)	**23 (55%)**[b]	8 (19%)	12.413*
Identify Adequacy of Information	14 (41%)	**27 (64%)**	18 (43%)	5.345
Strategy Use				
Draw	**19 (56%)**[a]	19 (45%)	11 (26%)	7.192*
Coordinating Informational Sources	14 (41%)	**35 (83%)**[b]	10 (24%)	31.249*
Read Notes	10 (29%)	**23 (55%)**[b]	7 (17%)	14.030*
Re-Reading	8 (24%)	**27 (64%)**[b]	**24 (57%)**	13.815*
Hypothesizing	6 (18%)	14 (33%)[b]	1 (2%)	13.753*
Goal-Directed Search	2 (6%)	16 (38%)[b]	12 (29%)	10.624*
Selecting New Informational Source	3 (9%)	**22 (52%)**	**33 (79%)**[c]	36.845*
Free Search	3 (9%)	8 (19%)	14 (33%)[c]	6.938*
Taking Notes	11 (32%)	**23 (55%)**	**25 (60%)**[c]	6.140*
Find Location in Environment	13 (38%)	16 (38%)	8 (19%)	4.590
Knowledge Elaboration	**19 (56%)**	**22 (52%)**	18 (43%)	1.423
Summarization	15 (44%)	**21 (50%)**	**23 (55%)**	.852
Inferences	**19 (56%)**	20 (48%)	20 (48%)	.661
Read New Paragraph	5 (15%)	7 (17%)	8 (19%)	.255
Memorization	9 (26%)	12 (29%)	13 (31%)	.186
Mnemonics	11 (32%)	13 (31%)	12 (29%)	.133
Task Difficulty and Demands				
Help Seeking Behavior	**31 (91%)**[a]	**25 (60%)**	3 (7%)	55.440*
Time and Effort Planning	6 (18%)	**32 (76%)**[b]	**21 (50%)**	25.759*
Expect Adequacy of Information	8 (24%)	**30 (71%)**[b]	14 (33%)	20.538*
Task Difficulty	**20 (59%)**	**25 (60%)**[b]	10 (24%)	13.627*
Control of Context	8 (24%)	**22 (52%)**	**29 (69%)**[c]	15.720*
Interest				
Interest Statement	17 (50%)	17 (40%)	**25 (60%)**[c]	3.048
Positive Feedback	NA	NA	NA	
Negative Feedback	NA	NA	NA	

[1] Degrees of freedom = 2 and N = 118 for all analyses. The **bold** type indicates the variable was used above the median frequency by more than 50% of participants. [a] ACPS group made the greatest contribution to chi-square for this variable. [b] APS group made the greatest contribution to chi-square for this variable. [c] NS group made the greatest contribution to chi-square for this variable. [d] Yates correction applied. * Chi-square value is statistically significant at $\alpha = .05$

Students' regulatory moves

Planning. Chi-square analyses revealed significant differences in the number of participants who used three of the four planning variables above the median proportion across the scaffolding conditions (see Table 4 for all chi-square results). Overall, a significantly larger number of students in the ACPS condition planned their learning by *activating prior knowledge*, while learners in the APS condition engaged in *planning* their learning session. By contrast, the learners in the NS condition planned their learning by *setting sub-goals*.

Monitoring. Chi-square analyses revealed significant differences in the number of participants who used six of the seven monitoring variables above the median proportion across the scaffolding conditions (see Table 4). Students in the ACPS condition monitored their learning by using *feeling of knowing (FOK)* and *judgment of learning (JOL)*. By contrast, learners in the APS condition monitored their learning by *content evaluation, self-questioning, monitoring progress towards goals,* and *monitoring their use of strategies*.

Strategies. Chi-square analyses revealed significant differences in the number of participants who used nine of the sixteen strategies above the median proportion across the scaffolding conditions (see Table 4). A significantly larger number of students in the ACPS condition learned by *drawing,* while learners in the APS condition *coordinated informational sources, read their notes, and engaged in re-reading, hypothesizing, and goal-directed search*. By contrast, those in the NS condition used *selecting a new informational source, free search,* and *taking notes* to learn about the circulatory system.

Handling Task difficulty and demands. Chi-square analyses revealed significant differences in the number of participants who used all five variables related to handling task difficulties and demands above the median proportion across the scaffolding conditions (see Table 4). A significantly larger number of students in the ACPS condition dealt with task difficulty and demands by engaging in *help seeking* from the tutor; while those in the APS condition handled task difficulty by *planning their time and effort, expecting the adequacy of representations in the hypermedia environment,* and *expressing task difficulty.* By contrast, those in the NS condition handled task difficulties by using *control of context*.

Interest. A significantly larger number of students in the NS condition expressed *interest* in the topic (above the median proportion) during learning (see Table 4).

Tutors' role in fostering students' conceptual understanding

In this section, we discuss three comparable examples of discourse from the NS, APS, and ACPS conditions. These excerpts serve to illustrate the differences in the tutoring conditions and how they contributed to both the participants' use of regulatory processes during learning and qualitative shifts in their mental models of the circulatory system.

The students in each of the excerpts are reading the same passage in the hypermedia environment. This passage was chosen for comparison because it contains crucial information for conceptual understanding about blood flow through the circulatory system. Specifically, this passage explains blood flow of deoxygenated blood from the right ventricle out to the lungs to pick up oxygen, and then it describes the blood's return to the heart directly from the lungs. A student who understands this has a "high" mental model. A common misconception among students is that blood flows directly to the body from the lungs. Another common misconception is that the blood does not even go to the lungs from the heart. Clearly, understanding the double loop of blood flow from body to the heart, to the lungs, and then back to the heart is critical to fully understanding the multi-level processes of the circulatory system.

The first example is from a learner in the NS condition who read the passage and was provided with no support for understanding or process. The second excerpt demonstrates a learner in the APS condition who read the passage with regulatory support from the tutor. The third excerpt shows a student in the ACPS who was provided support for both regulation of her learning and understanding of content. The three columns in each excerpt correspond to the segment number, the transcription (with participants' initials, normal typeface to indicate think aloud, and italics to indicate reading from the hypermedia environment), and the associated SRL code.

No scaffolding condition. Within the no scaffolding condition, students received no assistance in either regulating their learning or understanding the content. This condition most resembles independent learning. In the segment presented below, the student had just begun looking at the picture of the heart that has accompanying text describing blood flow through the heart.

1	**HR:** I want to see more about the heart…Let's see.. Superior.. Right atrium, and then right ventricle..Right is blue, then the red ones – left atrium and…left ventricle. Right ventricle to left ventricle. Ok	**[SUM]**
2	Ok. The atrium are circles, little circles in the heart..Let's see, *Oxygen-poor blood from the body enters the heart from two large blood vessels, the inferior vena cava and the superior vena cava, and collects in the right atrium. When the atrium fills –…..Anatomy.*	**[RR]**
3	Atrium, where is that? Ok	**[COIS]**
4	*it contracts, and blood passes - into the right ventricle. When the ventricle becomes full, it starts to contract.*	***No code***
5	Ok. Structure of the heart…Ok	**[COC]**

In segment 1, the student looked at the diagram and did not understand that blood flow goes to the lungs in between moving from the right to left side of the heart. In segment 2, the student began to read the important passage, the first portion of which he had read previously, and looked at the diagram to coordinate what he had just read with the picture (segment 3). The student continued to read (segment 4), but then made the decision to move onto a different section of text (segment 5) before confirming his summary above. In doing so, the student missed key information about blood flow from the heart to the lungs and then back to the heart, which was a common problem with students in the no-scaffolding condition. Even though it was mentioned in several places in the text, students often failed to recognize the lungs' vital role in the circulatory system. In particular, this student never went back to learn more about blood flow through the heart, and consequently had a low mental model score at posttest.

Adaptive process scaffolding condition. In the APS condition, the tutor provided support for regulating of learning, but did not provide any support for content understanding. The interaction below represents a typical tutor-student episode within this condition. In this episode, the student was reading the passage that explains the direction of blood flow between the heart and lungs.

1	**LB:** *As the right ventricle contracts, it forces blood into the pulmonary artery, which carries blood to the lungs to pick up fresh oxygen. When blood exits the right ventricle, the ventricle relaxes and the pulmonary valve shuts, preventing blood from passing back into the ventricle.*	***[No code]***
2	**Tutor:** So, you just read a lot of information. Can you think of anything you can do to help you understand it?	**[TSSTRAT]**
3	**LB:** No, I didn't really get anything from that.	***[No code]***
4	Tutor: Okay, I would suggest a strategy of putting what you read together with the picture. So, if you are going to read it over again, you know, read the first sentence, and then go to the picture and try to figure that, that, part or parts in the picture.	**[TICOIS]**
5	**LB:** Okay. The heart is made of muscle..inferior vena cava..is here…and the superior vena..and..*collects in the right atrium... ...After the blood in the left ventricle has been forced out, the ventricle begins to relax, and the aortic valve at the opening of the aorta closes*	**[COIS]**
6	So, basically, what I got from that was that the valves do the closing and opening, when it is full..um..okay	**[SUM]**
7	I understand more as to where it starts and stops and it starts in the right side of the heart and…	**[FOK]**
8	When the blood is leaving, it is leaving from the right side and returns, it is coming to the left…	**[SUM]**

In segment 1, the student read about the contraction of the right ventricle, the role of the pulmonary valve, and how blood is pumped to the lungs to pick up oxygen. At this point, the tutor (segment 2) stopped the student to ensure that he used a strategy to learn this important information. The tutor followed this prompt with the suggestion that the student coordinate informational sources (segment 4). Following this prompt, the student coordinated informational sources (segment 5) when he read about the inferior and superior vena cava, by finding these parts on the heart diagram. At the end of this episode, the student also summarized the text (segments 6 and 8) and monitored his emerging understanding by expressing feeling of knowing (segment 7). However, it is important to note that when the student summarized the blood flow from the right to the left side of the heart, he did not mention the lungs, a crucial piece of information he read about in the beginning of this segment. Because the tutor in the APS condition provided support for regulating learning, but did not provide any support for content understanding, this student did not receive any feedback on the content of his summarization and therefore did not recognize the role of the lungs in the process.

Adaptive content and process scaffolding condition. In the ACPS conditions, the tutor provided support for regulating learning as well as content understanding. The exchange below represents a typical tutor-student episode within this condition. In this episode, the student was reading the passage that explains the direction of blood flow between the heart and lungs.

1	**SC:** Okay. So, I'm going start from [reading quietly and quickly through the paragraph they read previously] *As the right ventricle contracts, it forces blood into the pulmonary artery, which carries blood to the lungs to pick up fresh oxygen.*	**[RR]**
2	[slower and more out loud]*When* the *blood exits the right ventricle, the ventricle relaxes and the pulmonary valve shuts, preventing blood from passing back into the ventricle.*	***[No code]***
3	So, it's like the whole process as the blood is leaving um from where it started, everything's shutting back to prevent the blood from going back.	**[SUM]**
4	**Tutor:** Yup.	**[PF]**
5	**SC:** So, it's continuing. *Blood returning from.. the lungs to the heart collects in the left atrium.*	***[No code]***
6	**Tutor:** Okay, let's talk for just a second. Here's another problem I have with this diagram. Okay the blood goes out, goes to the lungs. Picks up oxygen, but they don't talk about what happens after that. They just said, "Blood returning from the lungs"	**[TICE]**
7	**SC:** Mhm	***[No code]***

8	**Tutor:** Well, basically what happens is a big loop. So, the blood is in the pulmonary artery, goes out, goes to the lungs, and then, it comes right back to the heart.	**[TIFOK]**
9	**SC:** Mhm….. So, the blood is going to go out of the uh pul-pulmonary and it's gonna travel to um lungs to get oxygen and it's going to return.	**[FOK]**

In segment 1, the student re-read the part of a passage that explains blood flow to the lungs from the heart. In segment 2 and 3, she read a new part of the passage and then summarized the action of the valve. The tutor (segment 4) then provided her with positive feedback about her summary. In segment 5, the student read that the blood returns from the lungs to the heart. At this point, the tutor stopped the student (segment 8) to ensure that she understood this process, by reiterating what the student had read up to that point. The student confirmed her understanding with a feeling of knowing statement in segment 9, including the important point that the blood picks up oxygen in the lungs. Throughout the rest of the transcript, the student continued to demonstrate understanding of this important concept, and the tutor often checked this understanding. This student subsequently demonstrated this understanding on their posttest and thus had a "high" mental model.

Discussion

Our results show that students' learning of a challenging science topic with hypermedia can be facilitated if they are provided with adaptive content and process scaffolding designed to regulate their learning. We have demonstrated the effectiveness of adaptive content and process scaffolding (ACPS) in facilitating students' learning as indicated by the shifts in their mental models, gains in declarative knowledge from pretest to posttest, and process data on students' self-regulatory behavior. In contrast, providing students with either adaptive process scaffolding or no scaffolding was associated with less substantial shifts in students' mental models and smaller gains in declarative knowledge. Verbal protocols provided evidence that students across the three scaffolding conditions differentially deployed key self-regulated learning processes associated with these differences in mental model shifts and declarative knowledge gains. We conclude that the tutors' role in providing both content and process scaffolding is a key to facilitating students' self-regulated learning with hypermedia.

With regard to the first research question, the results of this study showed that a higher number of students in the ACPS condition shifted to more sophisticated mental models than did students in the other two comparison conditions. In contrast, the results indicated that a higher number of students in the APS failed to shift to more sophisticated mental models of the circulatory system, and that the NS condition is related to no shifts in students' mental models. We conclude that providing students with adaptive content and process scaffolding is beneficial for learning about challenging science topics with hypermedia. In other words, providing students with adaptive scaffolding aimed at both assessing their emerging understanding and helping them enact various key self-regulated learning processes during learning about complex science topics with hypermedia (e.g., planning their learning, monitoring their emerging understanding, using effective strategies to learn about the circulatory system) is associated with qualitative mental model shifts.

This finding is consistent with previous research, which indicates that providing learners with adaptive process and content scaffolding that deals with specific learning needs in real time is optimal for facilitating their ability to regulate their learning (e.g., Azevedo et al., 2005, 2007, 2008; Azevedo, Moos, et al., 2010). This finding relates to the significant learning gains seen across a variety of domains and tasks such as algebra, computer programming and physics with traditional learning CBLEs (Aleven et al., 2010). This finding also contributes to the literature on learning with hypermedia by demonstrating that adaptive scaffolding is effective in facilitating students' ability to regulate their learning of challenging science topics (e.g., Azevedo et al., 2005; Azevedo et al., 2004b; Biemans & Jacobson, 2008; Simmons, 1995; Kao & Lehman, 1997). In addition, this finding contributes to several other bodies of literature by providing evidence that not all adaptive scaffolding methods are equally effective in facilitating students' learning of challenging science topics with hypermedia. The question of *how* and *why* both adaptive scaffolding conditions were not equally effective can be explained by a close examination of the process data. The process data reveals the nature of students and tutors' regulatory behavior. An implication of these findings is that an empirical approach to understanding how learners regulate their learning and the role of tutors' as external regulating agents should guide the design of adaptive hypermedia learning environments (Azevedo, 2008; Brusilovsky, 2001; Hannafin, Hill, & Land, 1999; Jacobson, 2008; Saye & Brush, 2002).

With regard to the second research question, our results demonstrated that all students showed similar gains in declarative knowledge of the topics when learning with a hypermedia environment. This finding is consistent with the majority of studies using undergraduate students to examine learning with hypermedia environments that allow non-linear access to content and a high degree of learner control (e.g., Azevedo et al., 2008; Greene et al., 2008; Greene & Azevedo, 2009; Jacobson, 2008; Moos & Azevedo, 2006, 2008; Shapiro, 2008). Further, most of the recent studies on learning with hypermedia indicate that students of all ages learn some declarative knowledge when using a hypermedia environment to learn about complex and challenging science topics (e.g., Azevedo, et al., 2004a, 2004b, 2005). Our results suggest that using hypermedia with or without adaptive scaffolding will lead to increases in students' declarative knowledge, but factual information alone is not sufficient for conceptual understanding.

With regard to the third research question, our lengthy think-aloud protocols indicate that not only did the learners in the ACPS shift to more sophisticated mental models of the circulatory system, but they did so by deploying a select number of key self-regulatory processes. The verbal protocols provide process data to indicate that learners in the ACPS group used different self-regulated learning processes, and the chi-square analyses together with the product data show that the use of these processes is associated with significant increases in their conceptual understanding of the science topic (see Tables 3 and 4). The process data indicate that learners in the ACPS condition regulated their learning by activating their prior knowledge, metacognitively monitoring their cognitive system (FOK) and emerging understanding (JOL), drawing, and engaging in a significant amount of help seeking behavior. We argue that these are some of the key SRL processes that students need to use when learning with hypermedia environments. These key SRL processes are related to learning gains and the development of conceptual development (Azevedo, Moos et al., 2010; Greene & Azevedo, 2009; Moos, 2010). In general, they relied on the tutor to regulate their learning since a high proportion of tutor moves involved deploying key self-regulated learning mechanisms such as planning (prior knowledge activation), monitoring (FOK), using a few effective strategies (re-reading, knowledge elaboration, summarizing, inferences, and mnemonics), and also providing a significant amount of different types of feedback during learning. This finding is consistent with the literature on the effectiveness of scaffolding during human tutoring (e.g., Graesser et al., 1997, 2000; Lepper et al., 1997) and contributes to this literature by delineating *how* and *which* key self-regulated learning processes are used by students and tutors during learning about complex science topics with hypermedia. These findings are also consistent with recent research indicating that students who are provided with adaptive scaffolding gain deep conceptual understanding but fail to deploy the self-regulated learning mechanisms because of their reliance on the tutor to regulate their learning (e.g., Azevedo et al., 2007).

In contrast, the process data indicate that learners in the APS condition regulated their learning by planning, monitoring several aspects of the hypermedia system and progress during the task, engaging in self-questioning, using several effective strategies (coordinating multiple representations, goal-directed search, hypothesizing, reading notes, and re-reading notes), and handling task difficulties and demands. We argue that the lack of adaptive content scaffolding was the critical missing element in these students' failure to achieve significant qualitative mental model shifts, since the presence of content scaffolding was the only difference between learners in the ACPS condition and those in the APS condition. This finding contributes to the literature by highlighting the importance of content and process scaffolding in facilitating self-regulated learning with hypermedia.

When comparing the tutoring sessions across both adaptive scaffolding conditions, it is remarkable to examine the differences in the tutors' scaffolding (see Table 3). For example, the process data provide critical evidence that the deployment of self-regulated learning processes by students and tutors can lead to different learning gains. We hypothesize that tutors in the ACPS condition played a compensatory role, given that students did very little to regulate their learning and relied almost exclusively on help-seeking behavior. The tutors used tutor-initiated and tutor scaffolding; including planning, monitoring, using effective strategies, generating interest, and providing a wealth of feedback. Despite the overall effectiveness of this condition as measured by the mental model shifts and declarative knowledge gains, the compensatory role of the tutor as an external regulatory agent seems to have attenuated students' own self-regulatory behavior during learning (similar to Chi et al., 2001). In contrast, most of the tutoring sessions in the APS condition were characterized by an equal amount of tutor instructional and tutor scaffolding moves aimed at getting students to plan, monitor, and use effective strategies. These students regulated their learning by using more key self-regulated learning processes than did those in the ACPS condition. In fact, the use of student-initiated processes mirrors the tutors' scaffolding (see Table 4). We hypothesize that tutors in this condition played a modeling role given that the tutor's scaffolding (T-S and T-I codes) mirror the S-I processes (see Table 4). For example, tutors in the APS condition frequently scaffolded students by having them coordinate representations of information and students responded by more frequently using coordination of information sources. This finding contributes to the literature since no other study we know of has tested the effectiveness of providing students with process scaffolding and its relationship to students' deployment of key self-regulated learning processes during learning with hypermedia.

Finally, not only did more than 60% of the students in the NS condition fail to show qualitative shifts in the mental model of the topic, but they also deployed different self-regulated learning processes as they attempted to learn. Their failure to demonstrate qualitative mental model shift of the circulatory system is associated with their lack of use of key self-regulated learning processes (i.e., using fewer and less effective strategies; see Table 4). These findings are consistent with the recent results regarding self-regulated learning with hypermedia (e.g., Azevedo et al., 2005, 2007, 2008).

Future research should test the long-term retention of students' conceptual understanding to determine why it is more effective to "compensate" for students' lack of knowledge and minimal use of self-regulatory behavior by having them rely on a tutor, and what the effects of this type of scaffolding may have on students' content understanding and the deployment of the key self-regulatory skills in transfer tasks. In addition, future studies should also investigate the students' handling of task difficulties, including help-seeking behavior, motivational factors during learning (including interest in the topic) and the role of different types of feedback as a key factor in mediating between self-regulation and an external regulatory human agent. These investigations would contribute to learning and instruction by examining the complex and dynamic interactions between students' self-regulatory learning and the role of tutors and teachers as external regulating agents. This focus could also lead to theoretical advances through a conceptualization of externally-regulated learning by human agents during learning. This is in line with recent self-regulated learning research that extends existing research on learning with technology-based learning environments by converging both process (i.e., verbal protocols) and product data (i.e., mental models of students' understanding of the circulatory system) (Azevedo, Moos, et al., 2010).

Instructional implications of adaptive scaffolding in learning with hypermedia

Our results have implications for the design of hypermedia environments designed to foster students' learning about complex and challenging science topics. In this section, we offer several suggestions for designing hypermedia environments based on the results of the current study. Given the effectiveness of the ACPS condition in fostering students' mental models shifts, it would make sense to emulate the regulatory behaviors (i.e., T-S and T-I) of the tutors in this condition. However, these design decisions must also be based on the limitations and successes of current adaptive CBLEs for well-structured tasks (e.g., Aleven etal., 2010), technological limitations in assessing learning of challenging and conceptually-rich, ill-structured topics (e.g., Azevedo & Witherspoon, 2009; Biswas, Jeong, Kinnebrew, Sulcer, & Roscoe, in press; Jacobson, 2008), and conceptual discussions regarding "what, when, and how" to model certain key self-regulated learning processes in hypermedia environments (Azevedo, 2002, 2005, 2009; Witherspoon, Azevedo, & D'Mello, in press). In order to facilitate students' understanding of complex topics, the system would ideally need to provide adaptive scaffolding by dynamically modifying its scaffolding methods and supporting the students' self-regulatory behavior during learning. First, there needs to be a complex interaction between several system components. The system could be designed to deploy several key self-regulated learning mechanisms such as planning (e.g., plan the learning session), monitoring the contents of the hypermedia environment (e.g., identifying the adequacy of information, monitoring progress toward goals), using effective strategies (e.g., coordinate information sources, draw), and handling task difficulties and demands (e.g., time and effort planning, control the context, and acknowledge task difficulty). Given current technological advances in AI and computational modeling (e.g., Aleven et al., 2010; Azevedo, Johnson, Chauncey, & Graesser, in press; Azevedo, Witherspoon, Chauncey, & Burkett, 2010; Biswas et al., 2011), it may be possible for a system to emulate the T-S and T-I used by the tutors in the ACPS condition – to monitor students' emerging understanding of a challenging science topic and provide adaptive scaffolding by modifying its scaffolding methods based on student requests for assistance (e.g., through help seeking behavior).

Limitations and future directions

Recent advances in AI methods have contributed to the development complex and adaptive hypermedia systems (e.g., Azevedo, Johnson, et al., in press; Azevedo, Witherspoon, et al., 2010). Therefore, in assessing the educational value of hypermedia, we recommend keeping in mind that we are at a very early stage of understanding how students learn with these environments. The conclusions we have drawn are limited by the participants' low prior knowledge, the nature of the hypermedia environment, and the specific tasks measured used. It is possible that high prior knowledge students would have benefited differentially from our scaffolding conditions. More research is also needed to determine how different adaptive scaffolding methods can enhance students' ability to regulate their learning. More specifically, more research is needed on the effects of different adaptive scaffolding methods designed to foster the deployment of key self-regulatory processes. Furthermore, future research would be well served to consider an emerging model of self-regulated learning that has predictive adequacy in determining learning gains, is able to identify the deployment of various key self-regulatory processes, and establishes the role of human tutors as external regulating agents. In addition, a comprehensive understanding of learning with hypermedia can be achieved by conducting research that converges process (i.e., trace on-line self-regulated learning variables) with product data (learning outcomes) in complex topics. In sum, future research in this area has the potential to advance our current understanding of self-regulated learning and scaffolding methods in facilitating students' understanding of challenging topics and informing the design of adaptive hypermedia learning systems.

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