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RESEARCH ARTICLE

Why is externally-facilitated regulated learning more effective than self-regulated learning with hypermedia?

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Abstract We examined how self-regulated learning (SRL) and externally-facilitated self-regulated learning (ERL) differentially affected adolescents' learning about the circulatory system while using hypermedia. A total of 128 middle-school and high school students with little prior knowledge of the topic were randomly assigned to either the SRL or ERL condition. Learners in the SRL condition regulated their own learning, while learners in the ERL condition had access to a human tutor who facilitated their self-regulated learning. We converged *product* (pretest-posttest shifts in students' mental models and declarative knowledge measures) with *process* (think-aloud protocols) data to examine the effectiveness of self- versus externally-facilitated regulated learning. Findings revealed that learners in the ERL condition gained statistically significantly more declarative knowledge and that a greater number of participants in this condition displayed a more advanced mental model on the posttest. Verbal protocol data indicated that learners in the ERL condition regulated their learning by activating prior knowledge, engaging in several monitoring activities, deploying several effective strategies, and engaging in adaptive help-seeking. By contrast, learners in the SRL condition used ineffective strategies and engaged

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in fewer monitoring activities. Based on these findings, we present design principles for adaptive hypermedia learning environments, engineered to foster students' self-regulated learning about complex and challenging science topics.

Keywords Self-regulated learning · External regulation · Human tutoring · Hypermedia · Science · Mental models · Metacognition · Mixed methods

Introduction

Can adolescents effectively use hypermedia environments to learn about complex and challenging science topics such as the circulatory system? Learning with a hypermedia environment requires a student to regulate his or her learning; that is, to make decisions about what to learn, how to learn it, how much time to spend on it, how to access other instructional materials, and to determine whether he or she understands the material (Azevedo 2005, in press; Azevedo and Cromley 2004). Specifically, students need to analyze the learning situation, set meaningful learning goals, determine which strategies to use, assess whether the strategies are effective in meeting the learning goal(s), and evaluate their emerging understanding of the topic. They also need to monitor their understanding and modify their plans, goals, strategies, and effort in relation to changing contextual conditions (e.g., cognitive, motivational, and task conditions; Pintrich 2000; Winne 2001; Zimmerman 2000, 2001). However, most students have difficulty regulating their learning, which severely affects their learning of challenging topics. One potential solution is to examine the effectiveness of a human tutor as an external regulating agent who facilitates students' learning with hypermedia. In this study, we compared the effectiveness of self-regulated learning (SRL) and externally-facilitated self-regulated learning (ERL) on adolescents' learning about the circulatory system with hypermedia. We also examined the self- and external regulatory processes used by students and tutors while working on this task.

Learning with hypermedia

Contemporary cognitive and educational research has shown that the potential of hypermedia as a learning tool may be undermined by students' inability to regulate several aspects of their learning (Azevedo 2005; Jacobson in press; Lajoie and Azevedo 2006; Shapiro and Neiderhauser 2004). For example, students do not always deploy key metacognitive monitoring activities such as feeling of knowing (FOK) and judgment of learning (JOL) during learning (e.g., Azevedo and Cromley 2004). They do not always engage in the planning activities, such as creating learning goals and activating prior knowledge, needed to anchor their learning of new material in previously learned material (e.g., Azevedo et al. 2004a). When attempting to self-regulate their learning, students predominantly use ineffective strategies such as copying information from the hypermedia environment to their notes and free searching when they navigate the hypermedia environment, as opposed to having any specific learning goals (e.g., Azevedo et al. 2004b). Also, they rarely engage in help-seeking behavior such as requesting assistance with their emerging understanding (e.g., Azevedo et al. 2005). One method for improving students' regulation of their learning with hypermedia may be to provide them with an external regulating agent, such as a human tutor. The tutor can facilitate a student's learning with hypermedia by prompting the student to deploy certain key SRL processes during learning. Based on how the external regulating agent facilitates self-regulated learning, guidelines for designing adaptive hypermedia learning environments can then be developed.

A theoretical framework: self-regulated learning with hypermedia

We have chosen Winne and colleagues' (1998, 2001) model of SRL as a comprehensive theoretical framework to conceptualize students' self-regulated learning about complex topics with hypermedia. Using their model as a guiding framework has allowed us to examine the complex interplay between learner characteristics (e.g., prior knowledge, developmental level), elements of the hypermedia environment (e.g., non-linear structure of hypermedia), and mediating self-regulatory processes used by students (e.g., planning, strategy use, monitoring activities, handling task difficulties and demands). Based on an adaptation of Winne and colleagues' model for the particular context in our study, we hypothesize that students learning with hypermedia need to analyze the learning situation, set meaningful learning goals, determine which strategies to use, assess whether the strategies are effective in meeting the learning goal, and evaluate their emerging understanding of the topic. Students also need to monitor their understanding and modify their plans, goals, strategies, and effort in relation to task conditions (e.g., cognitive, motivational) that are contextualized in a particular learning situation (e.g., learning about the circulatory system with a hypermedia environment). Depending on the learning task, students may need to reflect on the learning episode in order to modify their existing understanding of the topic. Because of these many sometimes overwhelming demands, hypermedia environments may be ineffective if learners do not regulate their learning (e.g., Azevedo and Cromley 2004; Azevedo et al. 2004a, b, 2005, Bendixen and Hartley 2003; Greene and Land 2000; Land and Greene 2000; Land and Zembal-Saul 2003).

The role of a human tutor in externally facilitating self-regulated learning

A human tutor can provide adaptive scaffolding designed to facilitate a student's use of self-regulatory processes, which may then foster a student's self-regulation (Azevedo and Hadwin 2005). Adaptive scaffolding enhances student learning through timely feedback and calibrated support (see Chi et al. 1994, 2001, 2004; Graesser et al. 1997, 2000, 2005; Hogan and Pressley 1997; Lepper et al. 1997; Lepper and Wolverton 2002; Merrill et al. 1995). Furthermore, by studying how adaptive scaffolds can externally facilitate self-regulated learning, we are expanding current information processing theory (IPT) models (Winne 2001) and Vygotskyian models of SRL (McCaslin and Hickey 2001) by explicating the complex, dynamic nature of self- and externally-facilitated regulatory processes that can foster students' SRL in particular learning contexts.

The current study is part of a research agenda aimed at examining the effectiveness of different scaffolding conditions in facilitating middle-school, high school, and college students' self-regulated learning with hypermedia. Our definition of scaffolding is similar to the original conception of scaffolding proposed by Wood et al. (1976). First, scaffolding includes a shared understanding of the goal of the task between the tutor and tutee. Second, the tutor provides calibrated support based on an ongoing diagnosis of the student's level of understanding. This calibration requires the tutor to constantly fine-tune support based on the tutor's assessment of the student's changing knowledge and skills. This support is individualized not only for different learners with various levels of prior knowledge and skills, but it also changes for each learner over a particular task. Third, ongoing dynamic assessment and continually adapted support enables the tutor to monitor progress, and then provide appropriate support (e.g., metacognitive prompt, strategy use) and feedback during the learning episode. Fourth, while the learning situation in the current study is characterized by temporary fading, there is never a total fading of support to the point where the learner must learn completely on his or her own.

Some scaffolding researchers question whether complete fading is necessary for effective scaffolding (e.g., Pea 2004). This has been a contentious issue in recent research in the cognitive and learning sciences, particularly as researchers have extended the original conception of scaffolding to include on-line support for students' learning with CBLEs, which traditionally have not incorporated fading techniques (see Pea 2004; Puntambekar and Hubscher 2005). Empirically examining the effectiveness of different types of scaffolds provided by adaptive human tutors is a critical next step toward extending current models of SRL and providing evidence to inform the design of adaptive hypermedia learning environments (Azevedo 2005).

According to Winne and colleagues' (1998, 2001) model, any scaffold (human or non-human, static or dynamic) that is designed to guide or support students' learning is considered a part of the task conditions. Scaffolding provided by a human tutor to a student during learning with a hypermedia system needs to be experimentally examined to determine its effectiveness in fostering self-regulated learning. In this study, a human tutor used a tutoring script based on prior research to assist students in building their understanding of the topic. The tutor provided students with dynamic scaffolding during learning in the form of assistance with deploying specific self-regulatory skills (e.g., activating students' prior knowledge). In so doing, the human tutor was conceptualized as a external regulatory agent who monitored, evaluated, and provided feedback regarding the student's self-regulatory skills, based on the student's emerging understanding of the topic.

This tutor-delivered feedback involved scaffolding a student's learning by assisting him/her in planning (e.g., creating sub-goals, activating prior knowledge), having him/her monitor several activities during learning (e.g., monitoring progress towards goals, facilitating recall of previously learned material), prompting him/her to use effective strategies (e.g., hypothesizing, drawing, constructing his/her own representation of the topic), and facilitating his/her ability to handle task demands and difficulty (e.g., help-seeking, time and effort planning). Recent studies (Azevedo et al. 2004a, 2005) have demonstrated the effectiveness of human adaptive tutoring in facilitating students' learning with hypermedia. However, both of these tutoring studies were unscripted; interactions were dominated by the tutor who assumed control of the entire session. We argue that future research needs to adopt a more structured approach to studying externally-facilitated self-regulated learning. The human tutor should explicitly prompt students to deploy specific self-regulated processes during the instructional sequence. This approach extends contemporary notions of adaptive learning with computer-based learning environments (Brusilovsky 2004; Shute and Psotka 1996) and human tutors as adaptive regulating agents designed to regulate students' learning (Zimmerman and Schunk 2001; Zimmerman and Tsikalas 2005). Empirically testing the effectiveness of externally-facilitated self-regulated learning can elucidate how this scaffolding method facilitates students' SRL during learning with hypermedia. Evidence then can be used to inform the design of adaptive hypermedia learning environments. This new direction in research studying SRL with hypermedia has recently become an important means of bridging research on self- and externally-facilitated self-regulated learning with hypermedia (e.g., Azevedo et al. 2004b, 2005). In particular, this line of research investigates an unexplored area between the fields of self-regulated learning and instructional technology where there is a need to not only examine how much students learn with hypermedia, but also to determine *how* students regulate their learning and *how* external regulating agents, such as human tutors, can facilitate students' self-regulated learning.

Current study and hypotheses

In this study, we investigated the effectiveness of SRL and ERL in facilitating adolescents' ability to learn about the circulatory system with hypermedia. We focused on three research questions: (1) Do different scaffolding conditions influence learners' ability to shift to more sophisticated mental models of the circulatory system? (2) Do different scaffolding conditions lead learners to gain more declarative knowledge of the circulatory system? (3) How do different scaffolding conditions influence learners' ability to regulate their learning?

Students in the *self-regulated learning* (SRL) condition were given an overall learning goal to guide their learning of the circulatory system during the 40-min session. In the *externally-facilitated self-regulated learning* (ERL) condition, students were provided with the same overall learning goal, topic, and time limit. However, they also had access to a human tutor who used a tutoring script to provide dynamic and adaptive scaffolding, which included prompting students to deploy specific self-regulatory processes at various stages of learning.

With regard to the first research question, we hypothesized that the ERL condition would be associated with a statistically significantly different distribution of mental model categories as compared to the SRL condition. With regard to the second research question, we hypothesized that all students, regardless of scaffolding condition, would improve significantly from pretest to posttest on all three matching, labeling, and blood flow tasks. For the third research question, we hypothesized that students in the ERL condition would use key self-regulatory processes (e.g., activating prior knowledge, JOL, FOK, deploy effective strategies) during learning due to external regulating offered by the human tutor, while students in the SRL condition would not use key self-regulatory processes.

Method

Participants

A total of 128 adolescents from two secondary schools located in the suburbs of a mid-Atlantic city received community service credit in the Fall of 2003 for participating in this study. The mean age of the 67 high-school students was 15 years ($SD = 0.9$; 51% girls and 49% boys), and the mean age of the 61 middle school students was 12 years ($SD = 0.6$; 60% girls and 40% boys). The participants in our sample reflect the ethnic composition of the schools in the county, which was 57% White, 20% African American, 16% Hispanic, and 7% Asian American. Participants were given a pretest which confirmed that all participants had average or little knowledge of the topic, the circulatory system. Also, participating teachers confirmed that they had not covered the topic in their classes.

Pretest and posttest measures

The paper-and-pencil materials consisted of a consent form, a participant questionnaire, a pretest, and a posttest. All of the paper-and-pencil materials were identical to the ones previously used by the authors (Azevedo et al. 2004a, b, 2005), who have examined student learning about the circulatory system with hypermedia. The participant questionnaire solicited information concerning age, gender, number and title of science or health courses completed, and experience with biology and the circulatory system.

There were four parts to the pretest: (a) a sheet on which students were asked to match 13 words with their corresponding definitions related to the circulatory system (matching task); (b) a color picture of the heart on which students were asked to label 14 components (labeling task); (c) a 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); and, (d) a sheet with a list of eight body structures related to the circulatory system and an outline of the human body on which the students were asked to list the structures in the correct sequence to represent blood flow through the body (flow diagram). The pretest and posttest were identical.

Hypermedia learning environment

During the training phase, participants were shown the contents and features of the circulatory system, blood, and heart articles in the hypermedia environment. Each of these relevant articles contained multiple representations of information—text, static diagrams, and a digitized animation depicting the structure, behavior, and functioning of the circulatory system. Together these three articles comprised 16,900 words, 18 sections, 107 hyperlinks, and 35 illustrations. During the experimental phase, the participants used the hypermedia environment to learn about the circulatory system. Participants were allowed to use all of the system features including the search functions, hyperlinks, table of contents, multiple representations of information, and were allowed to navigate freely within the environment.

Experimental procedure

The authors tested participants individually in all conditions. Participants were randomly assigned within age groups to one of two conditions: SRL ($n = 65$) or ERL ($n = 63$). In both conditions, the participant questionnaire was handed out, and participants were given as much time as they wanted to complete it. Next, the pretest was handed out, and participants were given 20 min to complete it. Participants wrote their answers on the pretest and did not have access to any instructional materials. Next, in both conditions, the experimenter read and presented the following instructions to the participants in writing: "You are being presented with a hypermedia learning environment, 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 min. 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 or the equipment. Please remember that it is very important to say everything that you are thinking while you are working on this task." The instructions for the ERL condition were identical to those for the SRL condition. The participants in the ERL condition worked on meeting the same overall learning goal as the participants in the SRL condition.

In both conditions, a practice task was administered to familiarize participants with the think-aloud procedure (Ericsson and Simon 1993) to be used during the learning task. In addition, in both conditions, an experimenter remained nearby to remind participants 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. All participants had access to the instructions (which included the learning goal) during the learning session. In the SRL condition, participants did not have access to the tutor. In the ERL condition, the fourth author—who has 6 years experience as a classroom science teacher—acted as the tutor. All participants were given 40 min to use the hypermedia environment to learn about the circulatory system.

In the ERL condition, the human tutor was instructed to avoid providing the student with content knowledge extraneous to the information in the hypermedia environment. The human tutor was allowed to facilitate students' self-regulated learning (SRL) by prompting students to:

(1) activate their prior knowledge;
(2) plan their time and effort and monitor their progress towards goals,
(3) use several effective strategies, such as summarizing, coordinating informational sources, hypothesizing, drawing, and using mnemonics.

We designed a tutoring script for our human tutor based the human tutoring literature (see Chi 1996; Graesser et al. 1995) and recent empirical findings on SRL and hypermedia (Azevedo and Cromley 2004; Azevedo et al. 2004a, b, 2005). More specifically, the tutor used the following script to assist the learner in regulating his/her learning (see Fig. 1):

(1) Ask the student what he/she already knows about the circulatory system, to set some goals, and to determine how much time to spend on each goal.
(2) Suggest that student read the introduction section of the *circulatory system* article: Prompt student to summarize; have student learn about blood flow through the heart by using several strategies (e.g., coordinating informational sources); ask several questions to determine student's understanding of the various issues related to blood flow; make sure student understands the purpose of lungs; suggest watching the animation to integrate all the information; assess whether student has good understanding (i.e., can he/she explain the entire process in his/her own words). If no, then have student draw and label a diagram of the heart and assess his/her understanding [repeat (2)]. If yes, then proceed to the *blood vessel diagram.*
(3) Revisit global learning goal, give time reminder, state which goals have been met and which still need to be satisfied.
(4) Suggest that student read text for the *blood vessels diagram*; prompt student to summarize content; prompt student to use a mnemonic to remember definitions of arteries, veins and capillaries. Assess student's understanding. If the student did not

understand, then have him/her re-read the introduction, major components, and diagrams comparing veins and arteries, and then assess understanding again [repeat (4)]. If the student demonstrates that he/she understood, then proceed to the *blood article*.

(5) Revisit global learning goal, give time reminder, state which goals have been met and which still need to be satisfied.

(6) Activate student's prior knowledge about blood. Prompt student to read about the role of blood and the components of blood in the *blood* article; prompt the student to summarize, and take notes. Assess the student's understanding. If the student did not understand, then have him/her re-read the role of blood and components section, and then assess understanding again [repeat (6)]. If the student demonstrates that he/she understood, then proceed to (7).

(7) Assess progress towards global learning goal, give time reminder, and spend remaining time reviewing notes and drawings.

All participants were given 20 min to complete the posttest after using the hypermedia environment to learn about the circulatory system. All participants independently completed the posttest without their notes or any other instructional materials by writing their answers on the sheets provided by one of the experimenters.

Coding and scoring of the product and process data

In this section we describe: (a) the coding of the participants' mental models, (b) the participants' answers for the matching task, (c) the labeling of the heart diagram and the blood-flow diagram, (d) the segmentation of the participants' verbalizations while they were learning about the circulatory system, (e) the coding scheme we used to analyze the participants' regulatory behavior, and (f) inter-rater agreement. We ensured that the coders were blind to experimental condition by having them score and code photocopies of the pretest and posttest which did not have any identifying information. The transcriptions could not be blindly coded, because only transcriptions for the ERL condition included tutor utterances.

Mental model shifts

Our analyses focused on the shifts in participants' mental models based on the different conditions. We followed Azevedo and colleagues' method (Azevedo and Cromley 2004; Azevedo et al. 2004a, b, 2005; Greene and Azevedo 2005) for analyzing the participants' mental models, which is based on Chi and colleagues' research (Chi et al. 1994, 2001, 2004). A student's initial mental model of how the circulatory system works was derived from his or her statements on the pretest essay. Similarly, a student's final mental model of how the circulatory system works was derived from his or her statements on the essay section of the posttest. The coding scheme consists of three mental model categories which represent the progression from no understanding to the most accurate understanding. The model categories were designed to capture qualitative, not quantitative changes in participants' understanding of the circulatory system. A participant was placed in the "low" mental model category if he or she displayed any of the following levels of understanding:

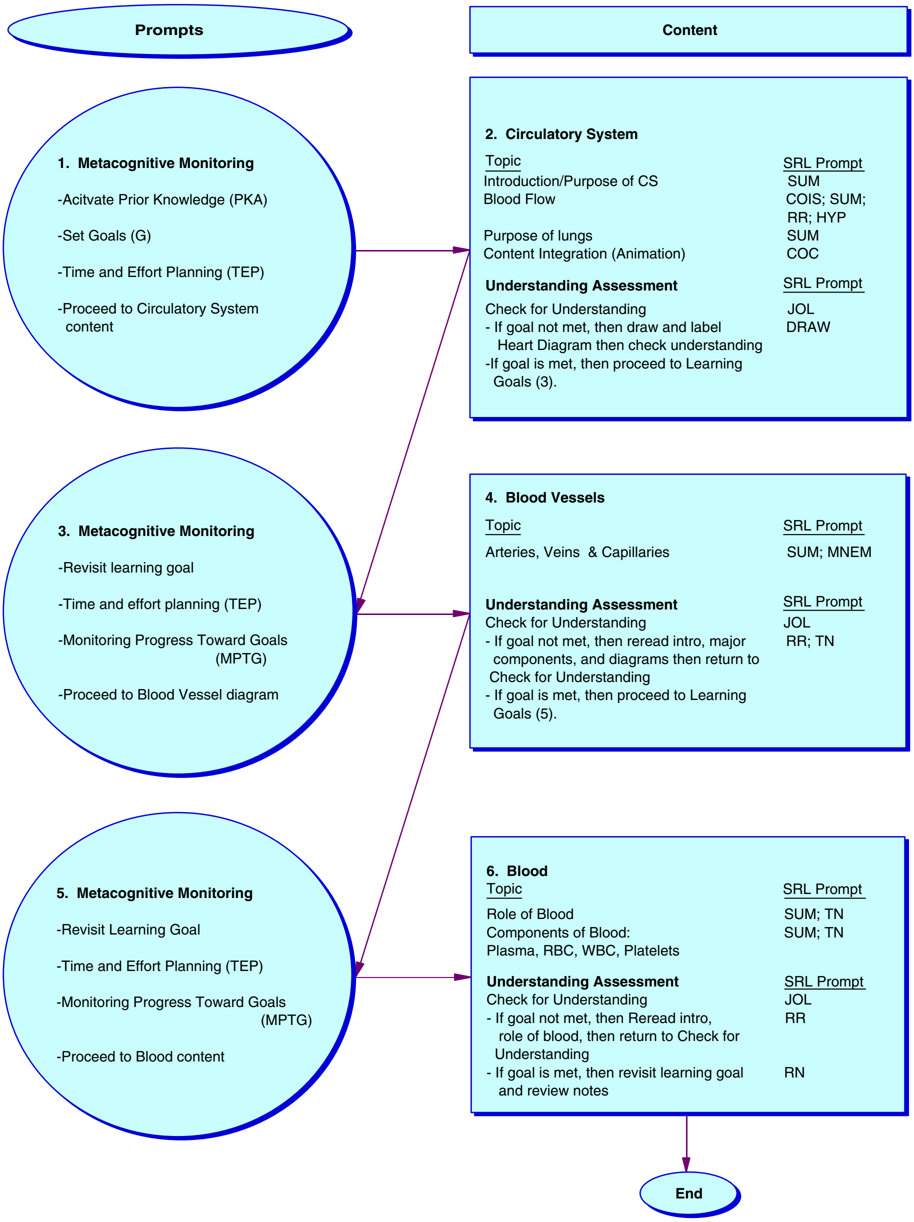

Fig. 1 Script for the externally-regulated learning (ERL) condition. *Note:* SUM = Summarizing; COIS = Coordinating Informational Sources; RR = Re-reading; HYP = Hypothesizing; COC = Control of Context; JOL = Judgment of Learning; DRAW = Drawing; MNEM = Using Mnemonic Device; TN = Taking Notes; RN = Reading Notes

(a) no understanding, (b) basic global concept, (c) basic global concept with purpose, (d) basic single loop model, (e) single loop with purpose, or (f) advanced single loop model. A participant with an "intermediate" understanding of the circulatory system wrote an essay containing all of the information in the “low” category plus any of the following key pieces of information: (g) single loop model with lungs or (h) advanced single loop model with lungs. Finally, a participant placed in the “high” mental model category wrote an essay that contained all of the information in the “intermediate” category plus any of the following: (i) double loop concept, (j) basic double loop model, (k) detailed double loop model, and (l) advanced double loop model. The key qualitative differences between these categories are the inclusion of the lungs as a component of the circulatory system (moving the participant from the “low” to the “intermediate” category) and the recognition of the circulatory system as having a double loop (moving the participant from the “intermediate” to the “high” category). See Appendix A for a complete description of the necessary features for each of the three mental model categories.

The fourth and fifth authors scored the students’ pretest and posttest mental models by assigning the value associated with the mental models described in Appendix A. For example, a student who began by stating that blood circulates and the purpose of blood is to transport oxygen and nutrients would be assigned a low mental model. If that same student on the posttest also described the heart as a pump, mentioned blood vessel transport, described the purpose of the circulatory system, and mentioned the role of the lungs in blood circulation, he or she would be assigned an intermediate mental model. The values for each student’s pretest and posttest mental model were recorded and used in a subsequent analysis to determine the shift in their conceptual understanding (see inter-rater agreement below).

Due to the qualitative nature of the mental models used to measure learners’ understanding of the circulatory system (for pretest and posttest), we analyzed whether the distributions of students with low, intermediate, and high mental models differed by condition. That is, we examined whether there was a statistically significant relation between condition and the distribution of participants’ mental models at pretest and posttest. Our hypotheses were that there would be no such relation at pretest, given that the students had little to no prior knowledge of the circulatory system. At posttest, however, we hypothesized that students in the ERL would learn more, and therefore that condition would have more students in the intermediate and high categories than the SRL condition, as evidenced by a statistically significant association between condition and mental model category.

Matching and labeling tasks

The second and fourth authors scored both tasks by giving each student either a 1 (for a correct match between a concept and its corresponding definition or for each correctly labeled component of the heart) or a 0 (for an incorrect match between a concept and definition or for each incorrect label) on his/her pretest and posttest (matching, range 0–13; labeling, 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.

Blood flow diagram

The second and fifth authors scored the flow diagram by giving each student a 1 (for correct placement of a provided term) or a 0 (for incorrect placement of a provided term; range 0–8). The correct progression of the provided terms for the flow is: (a) right atrium, (b) right ventricle, (c) arteries/capillaries/veins or lungs, (d) lungs or arteries/capillaries/veins, (e) left atrium, (f) left ventricle, (g) arteries/capillaries/veins or body, and (h) body or arteries/capillaries/veins. The scores for each student's pretest and posttest on the matching task, heart diagram, and flow diagram were tabulated separately and used in subsequent analyses.

Participants' verbalizations and regulatory behavior

The raw data collected from this study consisted of 5,120 min (85.3 h) of audio and video tape recordings from 128 participants, who gave extensive verbalizations while they learned about the circulatory system. During the first phase of data analysis, a graduate student transcribed the think-aloud protocols from the audio tapes and created a text file for each participant. This phase of the data analysis yielded a corpus of 2,530 single-spaced pages (M = 19.77 pages per participant) with a total of 625,708 words (M = 4,888 words per participant). These data were used to code the participants' SRL behavior.

We used Azevedo and colleagues' coding scheme to analyze the participants' regulatory behavior during learning with hypermedia (see Azevedo and Cromley 2004; Azevedo et al. 2004a, b, 2005). This coding scheme is based on several recent models of SRL (Butler and Winne 1995; Corno and Mandinach 1983; Pintrich 2000; Winne 2001; Winne and Hadwin 1998; Zimmerman 2000). It includes key elements of Winne's (2001) and Pintrich's (2000) view of self-regulation as a four-phase process, and extends these key elements to capture a total of 33 different self-regulatory variables used by learners to regulate their learning of complex science topics with hypermedia (see Azevedo et al. 2004; see Appendix B). Briefly, the coding scheme includes the following variables—(a) *Planning activities* including planning, goal setting, activating prior knowledge, and recycling goal in working memory; (b) *Monitoring activities* including FOK, JOL, monitoring progress towards goals, content evaluation, identifying the adequacy of information, evaluating the content as the answer to a goal, self-questioning, and monitoring the use of strategies; (c) *Learning strategies* including hypothesizing, coordinating informational sources, inferences, mnemonics, drawing, summarizing, goal-directed search, skipping content, 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, expecting 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 model also includes codes for the tutor's regulatory behavior, except for help-seeking behavior and self-questioning, which were only verbalized by learners (see Appendix B).

In Appendix B we present descriptions of and examples from the think-aloud protocols of the planning, monitoring, strategy use, task difficulty and demands, and interest variables used for coding the learners' and tutors' regulatory behavior. We used Azevedo and colleagues' SRL model to re-segment the data from the previous data analysis phase. This phase of the data analysis yielded 19,870 segments (M = 155.23 per participant), each assigned a corresponding SRL variable. The fifth author was trained to use the coding scheme and coded all of the transcriptions by assigning an SRL variable to each coded segment.

Inter-rater agreement

Inter-rater agreement was established by training the fourth and fifth authors to use the description of the mental models developed by Azevedo and colleagues (Azevedo and

Cromley 2004; Azevedo et al. 2004a, b, 2005). They independently coded all selected protocols (pre- and posttest essays of the circulatory system from each participant). There was agreement on 246 out of a total of 256 student descriptions, yielding an inter-rater agreement of .96. Inter-rater agreement was also established for the coding of the learners' regulatory behavior by comparing the individual coding of several authors with that of the fifth author. The second author independently re-coded 14,768 protocol segments (74%). There was agreement on 14,604 out of 14,768 segments yielding an inter-rater agreement of .98. Inconsistencies were resolved through discussion between the two raters.

Results

Research Question 1: do different scaffolding conditions influence learners' ability to shift to more sophisticated mental models of the circulatory system?

Given the qualitative nature of our mental model coding scheme, we utilized chi-square procedures to examine whether there was a relationship between condition and mental model category at both pretest and posttest. We expected no statistically significant difference in the distribution of students within mental model category between conditions at pretest, and this hypothesis was supported (χ^2 [2, N = 128], p = .527, n.s.). At posttest, however, we hypothesized that there would be a statistically significant relation between condition and distribution of students' mental model, and this hypothesis was also supported (χ^2 [2, N = 128] = 7.760, p = .022; Cramer's V = .246). Table 1 shows that at pretest a majority of students in each condition were classified as having a "low" mental model, with a relatively proportionate number of students having "intermediate" or "high" mental models in each condition. At posttest, however, the distribution of mental models for the SRL condition had changed very little from pretest, whereas the distribution for the ERL condition changed dramatically. Specifically, in the ERL condition 31 students had a mental model of "high" at posttest, compared to only 6 having had such a designation at pretest. On the other hand, in the SRL condition, only 17 students had a model of "high" at posttest, compared to 7 at pretest. Given the lack of differences in the distributions across conditions at pretest, we maintain that it was participation in the ERL condition that led to this statistically significant association at posttest.

Table 1 Frequency and percentage of the participants' qualitative mental model categories by condition

Condition	Low	Intermediate	High
Pretest			
SRL	44 (68%)	14 (22%)	7 (10%)
ERL	40 (63%)	17 (27%)	6 (10%)
Posttest			
SRL	34 (52%)	14 (21%)	17 (27%)
ERL	25 (40%)	7 (11%)	31 (49%)

Note: SRL = Self-regulated learning; ERL = Externally-regulated learning

Research Question 2: do different scaffolding conditions lead students to gain significantly more declarative knowledge of the circulatory system?

To analyze changes in scores on the matching, labeling tasks, and flow diagram tasks, we used a 2 (condition: SRL, ERL) X 2 (time: pretest, posttest) mixed design. For these analyses, condition was a between-groups factor and time was a within-subjects factor. Mauchly's test showed that the assumption of sphericity was retained, thus univariate repeated measures ANOVA was used, as it is generally more powerful than multivariate techniques (Hair et al. 1998).

Matching task

A 2 × 2 repeated measures ANOVA on the pretest and posttest data showed a significant main effect of time (F [1, 126] = 127.78, MSE = 253.72, $p < .05$, $\eta^{2\,=}$ .49), and a significant interaction between condition and time (F [1, 126] = 11.08, MSE = 253.85, $p < .05$, $\eta^{2\,=}$ .09). Despite the significant interaction in the omnibus test, follow-up independent sample t tests found no significant differences between the conditions at pretest, t (126) = 1.506, $p > .05$, or posttest, t (126) = –1.905, $p > .05$. The results indicate that participants in both conditions improved their scores on the matching task from pretest to posttest (see Table 2).

Labeling task

A 2 × 2 repeated measures ANOVA on the pretest and posttest data showed a significant main effect of time (F [1, 126] = 268.90, MSE = 264.87, $p < .05$, $\eta^{2\,=}$ .68), and a significant interaction between condition and time (F [1, 126] = 16.37, MSE = 264.87, $p < .05$, $\eta^{2\,=}$ .12). Independent sample t tests found no significant difference between the conditions at pretest, t (126) = .920, $p > .05$, but there were differences at posttest, t (126) = –3.120, $p < .05$, η^2 = .09. The results indicate that the ERL condition led to a greater improvement in participants' labeling of the heart diagram, from pretest to posttest (see Table 2).

Flow diagram

A 2 × 2 repeated measures ANOVA on the pretest and posttest data showed a significant main effect of time (F [1, 126] = 35.23, MSE = 247.12, $p < .05$, $\eta^{2\,=}$ .22), and a significant

Table 2 Means (and standard deviations) for the pretest and posttest learning measures by conditions

	Self-regulated learning (SRL) (n = 65)		Externally-regulated learning (ERL) (n = 63)	
	Pretest M (SD)	Posttest M (SD)	Pretest M (SD)	Posttest M (SD)
Matching (%)	45.47 (27.86)	61.50 (29.89)	38.35 (25.60)	67.28 (29.78)
Labeling (%)	6.04 (10.73)	32.46 (24.03)	4.42 (9.11)	45.76 (24.26)
Flow (%)	3.62 (5.63)	9.45 (17.88)	4.52 (8.59)	22.17 (31.12)

Note: Range for all three measures is 0–100%

interaction between condition and time (F [1, 126] = 9.28, MSE = 247.12, $p < .05$, η^{2} = .07). Independent sample t tests found no significant conditions at pretest, t (126) = –.710, $p < .05$, but there were differences at posttest, t (126) = –2.848, $p < .05$, $\eta^2 = .06$. The results indicate that the ERL condition led to a greater improvement in participants' ability to list the order of body structures to demonstrate the correct order of blood flow through the body, from pretest to posttest (see Table 2).

Research Question 3: how do different scaffolding conditions influence learners' ability to regulate their learning?

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 adolescents' use of SRL variables across the two conditions.[1] We examined how participants regulated their learning of the circulatory system by calculating how often they used each of the variables related to the five main SRL categories of *planning, monitoring, strategy use*, and *handling task difficult and demands, and interest*. The raw counts coded across the participants in the SRL condition and those of the participants and tutor in the ERL condition are provided in Table 3. The raw counts for each coded category and the number of participants using each SRL variable above the median proportion across conditions and the results of the chi-square tests are presented in Table 4. We minimized the potential for Type I error by dividing ∝ = .05 by 33 to account for the number of chi-square analyses conducted on the SRL data (experiment-wise α = .002 based on the Bonferroni technique).

Planning

Chi-square analyses revealed significant differences in the number of participants who used one of the four planning variables above the median proportion across the two conditions. Overall, a significantly larger number of participants in the ERL condition planned their learning by *activating their prior knowledge* (see Table 4).

Monitoring

Chi-square analyses revealed significant differences in the number of participants who used four of the seven variables related to monitoring above the median proportion across the two conditions. A significantly larger number of participants in the ERL condition monitored their learning by using *feeling of knowing* (FOK), *judgment of learning* (JOL), and

[1] We conducted a series of chi-square tests to examine how learners' use of self-regulatory variables differed across conditions. We first converted the raw counts to percentages for each person's use of each strategy. We then conducted a median split across all conditions for the proportion of use for each variable. We were then able to identify, for each variable, which participants used that variable at a proportion above or below the median. For example, participant 1029 used *feeling of knowing* (FOK) 3 times out of 87 utterances, or 3% of her moves. Across all participants, the median proportion for FOK was 14%, placing participant 1029 below the median proportion for FOK. By contrast, participant 1050 used FOK 20 times out of 95 moves, or 21% of her moves, placing her above the median proportion for FOK. We then conducted a 2 × 2 chi-square analysis for each self-regulatory variable to determine whether the distribution of participants above and below the median across the treatments was significantly different from the null.

Table 3 Frequency of coded student and tutor verbalizations during learning, by condition

Variable	Self-regulated learning (SRL)	Externally-regulated learning (ERL)	
	Total coded raw frequencies for student codes (based on 65 students)	Total coded raw frequencies for student codes (based on 63 students)	Total coded raw frequencies for tutor codes (across 63 tutoring sessions)
Planning			
Prior knowledge activation	132	1,098	2,258
Planning	10	20	91
Sub-goals	132	118	277
Recycle goal in working memory	30	18	12
Monitoring			
Content evaluation	141	46	240
Self-questioning	85	19	0
Judgment of learning (JOL)	167	621	12
Feeling of knowing (FOK)	318	1,111	1,584
Monitoring progress toward goals	47	112	218
Monitor use of strategies	13	15	53
Identify adequacy of information	95	113	512
Strategy use			
Selecting new informational source	134	42	5
Re-reading	368	120	61
Goal-directed search	40	5	15
Free search	41	8	0
Memorization	31	12	5
Taking notes	372	171	215
Hypothesizing	7	77	112
Coordinating informational sources	77	287	407
Draw	57	196	243
Mnemonics	1	16	53
Inferences	52	130	111
Summarization	358	567	736
Read notes	37	82	38
Read new paragraph	10	6	340
Find location in environment	21	30	32
Knowledge elaboration	60	55	31
Task difficulty and demands			
Control of context	571	75	377
Time and effort planning	45	13	141
Help seeking behavior	41	503	0
Expect adequacy of information	65	38	165
Task difficulty	62	19	95
Interest			
Interest statement	129	71	48

Table 4 Number and (percentage) of adolescents using self-regulated learning processes above the median proportion, by condition

Variable	Self-regulated (SRL) (n = 65)	External-regulated learning (ERL) (n = 63)	χ^2	p
Planning				
Prior knowledge activation	7 (11%)	**56 (89%)**	78.114	<.001
Planning	8 (12%)	17 (27%)	4.385	.036
Sub-goals	36 (55%)	28 (44%)	1.532	.216
Recycle goal in working memory	14 (22%)	14 (22%)	.009	.925
Monitoring				
Content evaluation	**47 (72%)**	17 (27%)	26.288	<.001
Judgment of learning (JOL)	13 (20%)	**51 (81%)**	47.543	<.001
Feeling of knowing (FOK)	16 (25%)	**48 (76%)**	34.040	<.001
Monitoring progress toward goals	21 (32%)	**41 (65%)**	13.757	<.001
Monitor use of strategies	11 (17%)	13 (21%)	.289	.591
Identify adequacy of information	31 (48%)	**33 (52%)**	.281	.596
Self-questioning	21 (32%)	9 (14%)	5.791	.016
Strategy use				
Selecting new informational source	**47 (72%)**	17 (27%)	26.288	<.001
Re-reading	**43 (66%)**	21 (33%)	13.785	<.001
Hypothesizing	5 (8%)	**40 (63%)**	43.696	<.001
Coordinating informational sources	18 (28%)	**46 (73%)**	26.288	<.001
Draw	18 (28%)	**46 (73%)**	26.288	<.001
Mnemonics	1 (2%)	12 (19%)	10.749	.001
Goal-directed search	16 (25%)	4 (6%)	8.097	.004
Free search	17 (26%)	5 (8%)	7.459	.006
Memorization	15 (23%)	5 (8%)	5.563	.018
Taking notes	**39 (60%)**	25 (40%)	5.283	.022
Inferences	24 (37%)	**40 (63%)**	9.033	.003
Summarization	26 (40%)	**38 (60%)**	5.283	.022
Read notes	14 (22%)	23 (37%)	3.488	.062
Read new paragraph	6 (9%)	4 (6%)	.369	.544
Find location in environment	17 (26%)	19 (30%)	.254	.614
Knowledge elaboration	23 (35%)	22 (35%)	.003	.956
Task difficulty and demands				
Control of context	**56 (86%)**	8 (13%)	69.048	<.001
Time and effort planning	26 (40%)	6 (10%)	15.848	<.001
Help seeking behavior	13 (20%)	**51 (81%)**	47.543	<.001
Expect adequacy of information	31 (48%)	25 (40%)	.834	.361
Task difficulty	26 (40%)	16 (25%)	3.095	.079
Interest				
Interest statement	31 (48%)	27 (43%)	.302	.583

Note: Degrees of freedom = 1 and n = 128 for all analyses

Note: The bold type indicates the variable was used above the median frequency by more than 50% of learners *monitoring their progress toward goals*. In contrast, participants in the SRL condition monitored their learning mainly by *evaluating the content* of the hypermedia environment (see Table 4).

Strategies

Chi-square analyses revealed significant differences in the number of participants who used six of the 16 strategies above the median proportion across the two conditions. A significantly larger number of participants in the ERL condition used *hypothesizing, coordinating of information sources, drawing*, and *mnemonics* to learn about the circulatory system. In contrast, a larger number of participants in the SRL condition learned by *selecting new informational sources* and *re-reading* (see Table 4).

Task difficulty and demands

Chi-square analyses revealed significant differences in the number of participants who used three of the five SRL variables related to task difficulty and demands above the median proportion across the two conditions. A significantly greater number of participants in the ERL condition handled task difficulties by *seeking help* from the tutor. In contrast, a significant number of participants in the SRL condition dealt with task difficulty and demands by *controlling the context* and *time and effort planning* (see Table 4).

Interest

A chi-square analysis revealed no significant difference in the number of participants who reported interest across the two scaffolding conditions (see Table 4).

Discussion

Our results, including product and process data, illustrate that hypermedia can be used to enhance learners' understanding of challenging science topics if they are provided with a human tutor who can externally facilitate the regulation of their learning. Providing adolescents with a human tutor whose role is to facilitate the use of key self-regulatory processes designed to foster learning of a science topic led to statistically significant increases in their understanding of the circulatory system. Verbal protocols provide evidence that learners who had access to the human tutor deployed the key SRL processes and mechanisms that have been found to lead to significant shifts in the distribution of mental model categories and learning gains on other declarative knowledge measures (e.g., prior knowledge activation).

With regard to the first research question, the results of this study showed that there were no statistically significant differences in the distribution of mental model categories across conditions at pretest. Yet, at posttest, there was a statistically significant association between mental model category distribution and condition. Specifically, 60% of the participants in the ERL condition had a mental model of intermediate or high, versus only 48% in the SRL condition. In terms of the high mental model category, the results were even more dramatic, with 49% of the ERL participants in this category versus only 27% of the SRL participants. Given that only 10% of participants in each condition had high mental models at pretest, we conclude that providing students with an external agent that prompts them to deploy key self-regulatory processes leads to greater qualitative shifts in understanding. This finding is consistent with previous research which indicates that learners who are provided with adaptive scaffolding in the form of an external regulating agent show significant learning gains in a variety of domains and tasks such as science (e.g., Azevedo et al. 2004b, 2005; Chi et al. 1994). More importantly, this finding contributes to the literature on learning with hypermedia by demonstrating that externally-regulated learning provided by a human tutor, aimed at facilitating a students' ability to regulate their learning, is associated with superior performance gains during learning with hypermedia.

In our study, a significant number of students in the SRL condition demonstrated either very little or no qualitative shift in their mental model of the circulatory system. Our results indicate that allowing adolescents with low prior knowledge to regulate their learning in the absence of an external regulating agent will lead to inferior shifts in conceptual understanding. This finding is consistent with the majority of studies on non-linear, random-access hypermedia environments with a high degree of learner control (e.g., Azevedo and Cromley 2004; Azevedo et al. 2004a; Greene and Land 2000; Hill and Hannafin, 1997).

As for the students' performance on the matching, labeling, and blood flow tasks, our results are similar to previous studies conducted in the general area of learning with hypermedia (e.g., Azevedo et al. 2004b; Shapiro 1999). All students in the current study gained some declarative knowledge, as measured by the matching task. This finding has been consistently replicated in other hypermedia studies (e.g., Azevedo et al. 2005; Shapiro 2000). We hypothesized that all students, regardless of age and instructional support provided either by the hypermedia environment or by an external regulating human agent, would gain some declarative knowledge when learning with hypermedia. As for the labeling and flow tasks, students in the ERL condition significantly outperformed students in the SRL condition, with small effect sizes. In addition to the small effect sizes, our results also illustrate that while the students in both conditions demonstrated significant gains from pretest to posttest, they still did not do particularly well on the posttest (i.e., did not reach 50% for both tasks). This finding illustrates potential differences between the adolescents in our study and the performance of college students in the majority of our other studies (e.g., Azevedo et al. 2005). We propose that students in the ERL condition learned significantly more on these two tasks because much of the tutoring script, and therefore the tutor's role, was designed to have students learn about specific aspects of the heart and the circulatory system (see script in Fig. 1). Furthermore, the tutor prompted specific regulatory processes (consistent with the previous description), which may have also contributed to the significant learning gains seen in the ERL condition. For example, in step 2 of the script (see Fig. 1) students were prompted by the tutor to coordinate representations of information, summarize, re-read, and hypothesize.

With regard to the third research question, our extensive think-aloud protocols indicate that not only did the learners in the ERL condition show significant qualitative shifts in their conceptual understanding and also show significant gains in several measures of declarative knowledge, but they more frequently deployed the SRL processes prompted by the human tutor, facilitating their own regulatory behavior with hypermedia. The verbal protocol data provides support for our hypothesis that students in the ERL condition deployed key self-regulatory process during learning, based on the amount of external regulating offered by the human tutor. The verbal protocols provide process data to indicate that students in the ERL condition used the SRL processes, and the chi-square analyses together with the product data show that the use of these processes led to significant increases in their understanding of the science topic. Students in the ERL condition regulated their learning by activating their prior knowledge, metacognitively monitoring their cognitive system (JOL, FOK), monitoring their progress towards goals, deploying several effective learning strategies (hypothesizing, coordinating informational sources, drawing, using mnemonics), and engaging in help-seeking behavior.

For the most part, these findings are consistent with previous research using trace methodologies to examine the deployment of self-regulatory processes used by learners *during* learning with hypermedia (Azevedo and Cromley 2004; Azevedo et al. 2004a, b, 2005). It also addresses current theoretical and methodological concerns among SRL researchers that more research is required to understand the inter-relatedness and dynamics of the cognitive, motivational/affective, behavioral, and contextual variables deployed *during* the cyclical and iterative phases of planning, monitoring, control, and reflection (Azevedo 2002, 2005; Winne et al. 2002; Winne and Perry 2000). This study contributes to our understanding by highlighting qualitative differences in *what* self-regulatory processes are deployed by learners of different ages, and *how* they are differentially deployed.

Learners in the SRL condition attempted to regulate their learning by monitoring the content of the hypermedia system relative to their goals, and by using a combination of effective and ineffective strategies to learn about the circulatory system (e.g., memorizing and engaging in free search). They handled task difficulties and demands by focusing on features of the hypermedia environment to enhance the reading and viewing of information and making intentional efforts to control their learning. While these findings are consistent with the results of recent SRL studies on learning with hypermedia (e.g., Azevedo et al. 2005), they also demonstrate that adolescents regulate their learning with hypermedia differently than college students (e.g., see Azevedo and Cromley 2004). For instance, there is evidence that college students are more capable of regulating their own learning than are adolescents (see Pintrich and Zusho 2002). Future research should continue to focus on the developmental differences in students' self-regulated learning of challenging science topics with hypermedia. This study provided evidence that in the absence of an external regulating human agent, adolescents may not decide to plan their learning or monitor their learning, use effective strategies, and generate interest to sustain the learning activity. This is a critical educational issue that needs to be empirically examined given the widespread use of hypermedia-based learning environments in schools. As such, assessing the educational value of hypermedia represents an important step in understanding *how* students use these environments to learn about challenging topics (Azevedo 2002, 2005; Hmelo-Silver and Azevedo 2006; Jacobson and Wilensky 2006; Lajoie and Azevedo 2006). In sum, future research in this area has the potential to advance our current understanding of human tutors as external regulating agents who can facilitate students' understanding of challenging and complex science topics. This knowledge can then be used to inform the design of adaptive hypermedia systems.

Limitations

The conclusions drawn from this study are limited by the participants' age, low prior knowledge, and the nature of the hypermedia environment. It is possible that older students with a certain amount of prior knowledge would have benefited differentially from our conditions; these questions should be explored in future research. It should be noted that the commercially-based software used in this study did not include all of the representations of information ideally needed to learn about the topic. We further note that even though an experimenter was present in both conditions, the results for the ERL condition may have been due to some aspect of social desirability due to the additional presence of the human tutor and the complex nature of the ERL condition. Both the product and process data in the ERL condition are a reflection of the metacognitive prompts and individualized instruction provided by the tutor.

Implications for the design of adaptive hypermedia learning environments

Our results show that adolescents experience certain difficulties when regulating their own learning about a complex science topic with hypermedia. By contrast, externally-facilitated self-regulated learning provided by a human tutor is significantly related to a higher proportion of students experiencing qualitative shifts in their mental models of complex topics such as these. Furthermore, our findings can inform the design of scaffolding for specific SRL variables to foster students' self-regulated learning with hypermedia. Based on the four SRL categories of *planning, monitoring, strategy use*, and *task difficulties and demands*, we propose design guidelines for how specific SRL variables can be addressed to foster students' self-regulated learning with hypermedia.

For the category of *planning*, our results suggest that prior knowledge activation is a key SRL process that a hypermedia environment should scaffold. To foster prior knowledge activation, the students could be asked to recall everything they can about the topic being learned, prior to beginning the learning task. Furthermore, they could view annotations of the nodes that have already been navigated (Brusilovsky 2001). Our results indicate that several *monitoring activities* such as feeling of knowing (FOK), judgment of learning (JOL), and monitoring progress towards goals, are particularly crucial to learning. To foster JOL, a prompt could be inserted to have the students periodically rate their understanding on a Likert-type scale. FOK could be fostered by asking the students to connect what they are about to learn (based on their selection of new content) to what they have already learned. A planning net could be presented at different intervals throughout the learning to aid in off-loading the students' monitoring of progress toward goals.

There are numerous effective *strategies* that could be scaffolded in a hypermedia environment, including coordinating informational sources, drawing, mnemonics, and making inferences. A major challenge with hypermedia is its inability to detect, trace, and model effective strategies and ineffective strategies (Brusilovsky 2004). Prompts and feedback could be designed to encourage effective strategies and discourage students from using ineffective strategies. For example, scaffolding the use of mnemonics, and drawing could be fostered via prompting when a diagram and text with relevant information are being viewed by the learner. By being prompted to use an embedded drawing tool, students can be encouraged to construct and externalize their current understanding of some aspect of the topic.

Within the category of *task difficulty and demands*, help-seeking is clearly linked to higher learning outcomes and should be scaffolded within a hypermedia environment. One challenge is to design an environment that can provide help for different aspects of the learning task. For example, a student could select from among the following (from a long list of items phrased as sentences) from a help feature—information about whether the current content is relevant for the current goal, explanation of some complex biological mechanism, and directions for how to coordinate multiple informational sources, etc. (Azevedo 2005; Jacobson in press).

It is important to note that these design guidelines we have proposed, which we believe would facilitate students' use of key self-regulatory processes, are different from those that have typically been recommended for the design of adaptive hypermedia systems. Some guidelines have typically focused on adaptive presentations of information (or content-level presentations) and adaptive navigation (or link-level adaptation) (Park and Lee 2004). However, they have not simultaneously focused on adaptive facilitation of students' self-regulated learning.

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Appendix A

Necessary features for each type of mental model (based on Azevedo and Cromley 2004)

Low mental model category

a. No understanding

b. Basic global concepts
- blood circulates

c. Global concepts with purpose
- blood circulates
- describes "purpose"—oxygen/nutrient transport

d. Single loop—basic
- blood circulates
- heart as pump
- vessels (arteries/veins) transport

e. Single loop with purpose
- blood circulates
- heart as pump
- vessels (arteries/veins) transport
- describe "purpose"—oxygen/nutrient transport

f. 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

g. 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

h. 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

i. 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

j. Double loop—basic
- blood circulates
- heart as pump
- vessels (arteries/veins) transport
- describe “purpose”—oxygen/nutrient transport
- describes loop: heart–body-heart-lungs-heart

k. 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

l. Double loop—advanced
- 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
- mentions one of the following: electrical system, transport functions of blood, details of blood cell

Appendix B

Classes, descriptions and examples of the variables used to code students' regulatory behavior (based on Azevedo and Cromley 2004)

Variable	Description[a]	Student example
Planning		
Planning	A plan involves coordinating the selection of operators. Its execution involves making behavior conditional on the state of the problem and a hierarchy of goals and sub-goals	"First I'll look around to see the structure of environment and then I'll go to specific sections of the circulatory system"
Goals	Consist either of operations that are possible, postponed, or intended, or of states that are expected to be obtained. Goals can be identified because they have no reference to already-existing states	"I'm looking for something that's going to discuss how things move through the system"
Prior knowledge activation	Searching memory for relevant prior knowledge either before beginning performance of a task or during task performance	"It's hard for me to understand, but I vaguely remember learning about the role of blood in high school"
Recycle goal in working memory	Restating the goal (e.g., question or parts of a question) in working memory	"...describe the location and function of the major valves in the heart"
Monitoring		
Judgment of learning	Learner becomes aware that they don't know or understand everything they read	"I don't know this stuff, it's difficult for me"
Feeling of knowing	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	"... let me read this again since I'm starting to get it..."
Self-questioning	Posing a question and re-reading to improve understanding of the content	[Learner spends time reading text] and then states "what do I know from this?" and reviews the same content
Content evaluation	Monitoring content relative to goals	"I'm reading through the info but it's not specific enough for what I'm looking for"
Identify adequacy of information	Assessing the usefulness and/or adequacy of the content (reading, watching, etc.)	"...structures of the heart...here we go..."
Monitor progress toward goals	Assessing whether previously-set goal has been met.	"Those were our goals, we accomplished them"
Monitor use of strategies	Participant comments on how useful a strategy was	"Yeah, drawing it really helped me understand how blood flow throughout the heart"

Appendix B continued

Variable	Description[a]	Student example
Strategy use		
Selecting a new informational source	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.	[Learner reads about location valves] then switches to watching the video to see their location
Coordinating informational sources	Coordinating multiple representations, e.g., drawing and notes.	"I'm going to put that [text] with the diagram"
Read new paragraph	The selection and use of a paragraph different from the one the student was reading.	"OK, now on to pulmonary"
Review notes	Reviewing learner's notes.	"Carry blood away. Arteries—away"
Memorization	Learner tries to memorize text, diagram, etc.	"I'm going to try to memorize this picture"
Free search	Searching the hypermedia environment without specifying a specific plan or goal	"I'm going to the top of the page to see what is there"
Goal-directed search	Searching the hypermedia environment after specifying a specific plan or goal	Learner types in blood circulation in the search feature
Summarization	Summarizing what was just read, inspected, or heard in the hypermedia environment	"This says that white blood cells are involved in destroying foreign bodies"
Taking notes	Copying text from the hypermedia environment	"I'm going to write that under heart"
Draw	Making a drawing or diagram to assist in learning	"...I'm trying to imitate the diagram as best as possible"
Re-reading	Re-reading or revisiting a section of the hypermedia environment	"I'm reading this again."
Inferences	Making inferences based on what was read, seen, or heard in the hypermedia environment	...[Learner sees the diagram of the heart] and states "so the blood....through the ...then goes from the atrium to the ventricle... and then..."
Hypothesizing	Asking questions that go beyond what was read, seen or heard	"I wonder why just having smooth walls in the vessels prevent blood clots from forming...I wish they explained that..."
Knowledge elaboration	Elaborating on what was just read, seen, or heard with prior knowledge	[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"
Mnemonic	Using a verbal or visual memory technique to remember content	"Arteries—A for away"

Appendix B continued

Variable	Description[a]	Student example
Find location in environment	Statement about where in environment learner had been reading	"That's where we were"
Task difficulty and demands		
Time and effort planning	Attempts to intentionally control behavior	"I'm skipping over that section since 45 minutes is too short to get into all the details"
Help seeking behavior	Learner seeks assistance regarding either the adequateness of their answer or their instructional behavior	"Do you want me to give you a more detailed answer?"
Task difficulty	Learner indicates one of the following: (1) the task is either easy or difficult, (2) the questions are either simple or difficult, (3) using the hypermedia environment is more difficult than using a book	"This is harder than reading a book"
Control of context	Using features of the hypermedia environment to enhance the reading and viewing of information	[Learner double-clicks on the heart diagram to get a close-up of the structures]
Expectation of adequacy of Information	Expecting that a certain type of representation will prove adequate given the current goal	"...the video will probably give me the info I need to answer this question"
Motivation		
Interest statement	Learner has a certain level of interest in the task or in the content domain of the task	"Interesting", "This stuff is interesting"

[a] All codes refer to what was recorded in the verbal protocols (i.e., read, seen, or heard by the participant in the environment and/or during discussions)

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