

Supporting Self-Regulated Science Learning in

Narrative-Centered Learning Environments

James C. Lester, Bradford W. Mott, Jennifer L. Robison,

Jonathan P. Rowe, Lucy R. Shores

North Carolina State University

Abstract

Narrative-centered learning environments provide engaging, story-centric virtual spaces that afford opportunities for discreetly embedding pedagogical guidance for content knowledge and problem-solving skill acquisition. Students' abilities to self-regulate learning significantly impact performance in these environments and are critical for academic achievement and lifelong learning. This chapter explores the relationship between narrative-centered learning environments and self-regulation for science learning. Connections are drawn between the salient characteristics of narrative-centered learning environments and principles for promoting self-regulation in science education. These relationships are further explored through an examination of the CRYSTAL ISLAND learning environment. The chapter investigates the hypothesis that narrative-centered learning environments are particularly well suited for simultaneously promoting learning, engagement, and self-regulation. Empirical support is provided by a summary of findings from a series of studies conducted with over 300 middle school students.

Keywords: Narrative-centered learning environments, Self-regulated learning, Game-based learning

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Narrative-centered learning environments have become the subject of increasing attention in the intelligent tutoring systems community (Aylett, Louchart, Dias, Paiva, & Vala, 2005; McQuiggan, Rowe, Lee, & Lester, 2008b; Johnson & Valente, 2008).

Narrative-centered learning environments are a class of educational games that contextualize educational content and problem solving with interactive story scenarios. By combining salient features of stories (rich settings, believable characters, and compelling plots) with key elements of digital game environments (agency, rewards, and multimedia feedback), narrative-centered learning environments show significant promise for increasing student motivation, supporting meaning making, and guiding complex problem solving. Narrative-centered learning environments tap into students' innate facilities for crafting and understanding stories (Bruner, 1990), and they encourage students to become active participants in ongoing narratives. By integrating technologies from intelligent tutoring systems, embodied conversational agents, and serious games into story-centric virtual environments, narrative-centered learning environments offer the promise of adaptive, situated learning experiences that are highly interactive and engaging for students. Narrative-centered learning environments have been studied in a range of domains, including anti-bullying education (Aylett, et al., 2005), language learning (Johnson & Valente, 2008), and science education (Ketelhut, Dede, Clarke, 2010; McQuiggan, et al., 2008b).

Narrative-centered learning environments offer the potential to not only enhance students' content knowledge, but also aid in problem solving and self-regulation. Self-

regulated learning refers to students' ability to generate, monitor and control their cognitive, metacognitive, and motivational processes (Zimmerman, 1990). Self-regulation is particularly important in scientific inquiry where learning is guided by students' curiosity and motivation for acquiring knowledge through the application of efficient strategies (Graesser, McNamara, & VanLehn, 2005). Although narrative-centered learning environments can be designed for a broad range of subject matters, this chapter focuses on specific approaches to self-regulated learning in science education. Schraw, Crippen, and Hartley (2006) identify six pedagogical strategies that have been empirically shown to increase student self-regulation in science, including inquiry-based learning, collaboration, strategy instruction, construction of mental models, technology use, and the role of epistemological beliefs. Each of these strategies can be implemented within the motivating contexts of narrative-centered learning environments.

This chapter explores the benefits of narrative-centered learning environments for student self-regulated learning in science. Connections between pedagogical strategies for self-regulated learning in science and interactive narrative environments are drawn through an examination of CRYSTAL ISLAND, a narrative-centered learning environment for middle-school microbiology. Empirical support is provided by a summary of results drawn from several studies with CRYSTAL ISLAND investigating learning outcomes, engagement, and problem-solving activities.

Self-Regulation in Narrative-Centered Learning Environments

Narrative-centered learning environments offer significant promise for promoting guided discovery learning by leveraging the motivational characteristics of narrative and interactive game environments and providing a compelling context for developing and

applying problem-solving skills. However, students' ability to pursue pedagogical and narrative goals is central to narrative-centered learning environments' efficacy, particularly in open-ended environments that feature inquiry-based scenarios and multiple problem-solving paths. As a consequence, self-regulation is often critical for students interacting with narrative-centered learning environments.

Self-Regulated Learning

Research suggests that individuals who are able to self-regulate their learning processes in intentional and reflective ways are more likely to achieve academic success (Butler, Cartier, Schnellert, & Gagnon, 2006). The term *self-regulated learning* can be used to describe learning that is guided by metacognition, strategic action, and motivated behavior (Zimmerman, 1990). Pintrich (2000) notes that although multiple models of self-regulated learning exist, most share four main assumptions: (1) learners actively construct knowledge during the learning process, (2) learners actively control, monitor, and regulate aspects of their learning environment, as well as facets of their own cognition, behavior, and motivation, (3) learning is goal-driven, and (4) goals are compared to standards or criteria in order to monitor progress and adapt facets of cognition, behavior, and motivation.

Self-regulation is particularly important in domains that emphasize inquiry. Inquiry activities typically permit multiple lines of investigation, feature both implicit and explicit goals, and require knowledge construction and critical thinking skills (Anderson, 2002). In order to effectively navigate inquiry scenarios, students must be able to identify and synthesize relevant background knowledge, iteratively formulate hypotheses and hypothesis-testing plans, and critically assess and augment their investigation

strategies based on prior findings and current problem-solving contexts. Self-efficacy and motivation is important for students to sustain effort across hypothesis-testing-revision cycles and to adjust problem-solving strategies when necessary. Students who are self-regulated learners are likely to have many of the same skills needed to optimally benefit from inquiry-based learning methods.

Unfortunately, students often require explicit instruction in order to effectively self-regulate their learning, and may not develop these skills on their own. Boekaerts and Niemvirta (2000) note that teachers, and not students themselves, tend to have the responsibility of conveying information and procedures, monitor performance, provide feedback, and motivate learning. This assignment of responsibilities hinders the development of self-regulation by making learning the responsibility of the teacher rather than the student. It has been shown that although most teachers agree that one of the primary goals of education is to develop intrinsically motivated, self-regulated learners (Paris, Lipson, & Wixson, 1994), few students receive instruction in self-regulated learning in school and few have opportunities to regulate their own learning (Randi & Corno, 2000).

Scaffolding Self-Regulated Learning in Intelligent Tutoring Systems

Over the past several years, the education community has begun to investigate the role that learning technologies can play in detecting, scaffolding, and teaching effective self-regulatory processes. These attempts differ widely in the types of metacognitive phenomena with which they are concerned, the complexity of the environments used to support self-regulation, and the amount of support given to students to develop these skills. For example, work on the MetaTutor intelligent tutoring system has examined the

role of self-regulatory strategies in hypertext science learning environments

(Witherspoon, Azevedo, & D’Mello, 2008). This work has shown that providing students with prompts from a human tutor on appropriate types of self-regulatory strategies such as goal setting, plan development and summarizing learned materials can improve students’ use of these strategies. In particular, their findings indicate that students who are able to offload their self-regulatory processes use more diverse sets of strategies than students who have not been given the same instruction. Alternatively, the Betty’s Brain system implements *teachable agents*, where students instruct a virtual character from their own knowledge (Leelawong & Biswas, 2008). Students are then able to run queries on the knowledge of their virtual pupil and uncover errors in their own concepts and problem-solving approaches. This type of system encourages self-regulatory processes without providing explicit instruction about them, although providing additional scaffolding can lead to further benefits.

Other work has focused on specific student behaviors related to self-regulatory processes. Aleven, Roll, and Koedinger (2004) examined how students use help-giving features of tutorial learning environments. They argue that there are appropriate uses of help-seeking behavior (e.g., during a problem-solving impasse) and also a variety of poor strategies of help seeking (e.g., using help instead of trying themselves, or never seeking help even when it is needed). With the emergence of help-providing systems, understanding the types of “help-seeking” bugs that students engage in is important for designing educational technologies that not only teach content but also teach effective learning strategies. In similar work, Litman and Forbes-Riley (2009) examined how well students are able to monitor their own learning and judge their own correctness during

natural-language tutorial sessions. They used measures of uncertainty and correctness to develop a unified concept of accuracy, and showed that the more accurate students are in their judgments of knowing, the more likely they are to learn.

Narrative-Centered Learning Environments

Narrative-centered learning environments offer several natural affordances for enhancing students' learning experiences and promoting self-regulatory processes. Stories draw audiences into plots and settings, thereby introducing engaging opportunities for situated learning. Fantasy contexts in educational games have also been shown to provide motivational benefits (Parker & Lepper, 1992). Although it is important to remain mindful of potential disadvantages such as seductive details (Harp & Mayer, 1998), a carefully targeted narrative experience has the potential to be pedagogically compelling.

Recent work on narrative-centered learning environments has leveraged a range of techniques for providing effective, engaging learning experiences. Multi-user virtual environments such as Quest Atlantis (Barab, Scott, Siyahhan, Goldstone, Ingram-Goble, Zuiker, & Warren, 2009) and River City (Ketelhut, Dede, & Clarke, 2010) use rich narrative settings to contextualize inquiry-based science learning scenarios with prominent social and ethical dimensions. BiLAT (Kim, et al., 2009) and the Tactical Language and Culture Training System (TLCTS) (Johnson & Valente, 2008) emphasize story-driven interactions with virtual characters to provide instruction on cross-cultural negotiation and foreign language learning, respectively.

Empirical studies have begun to yield promising results that support the potential of narrative-centered learning environments in the classroom. For example, Ketelhut,

Dede, and Clarke (2010) compared several large-scale implementations of River City to a *paper-based control* condition that taught equivalent content and skills. The study found that students who used River City experienced improved content learning gains, increased evidence of thoughtful scientific inquiry, and increased interest in science careers, although the findings failed to be reproduced across all implementations and assessment strategies. Students' diversity and quantity of data gathering behaviors also increased as they used River City over multiple sessions. Barab et al. (2009) compared the Taiga Park module of Quest Atlantis to an *expository text* equivalent (i.e., an electronic textbook), as well as a *simple framing* condition (i.e., the scenario was situated with a 3rd person storyline, but the story was not interactive). Students who used Taiga Park outperformed the expository text condition on proximal post-test items. Students who used Taiga Park in dyads were also observed to outperform the expository text condition on distal post-test items. However, comparisons with the simple framing condition were equivocal; the dyad Taiga Park group outperformed the simple framing group on an open-ended transfer task, but there were no differences between groups on standardized post-test items. While evaluation methodologies are still the subject of ongoing research, River City and Quest Atlantis have yielded promising initial benchmarks for the expected efficacy of narrative-centered learning environments.

Related work has examined how artificial intelligence can be used to generate engaging interactive story experiences that are pedagogically effective and tailored to individual students' interactions. FearNot! uses affectively-driven autonomous agents to generate dramatic, educational vignettes about bullying (Aylett et al., 2005). TLCTS uses a range of artificial intelligence techniques for speech recognition, dialogue modeling,

and virtual human behavior across a suite of story-centric, serious games designed for language and culture learning (Johnson & Valente, 2008). BiLAT uses rule-based intelligent tutoring facilities that deliver individualized guidance in the form of hints and feedback, as well as structured after-action reviews (Kim, et al., 2009). Extending intelligent tutoring systems to support self-regulated learning during narrative-centered learning experiences is a promising direction for this line of research. However, systematic investigation of narrative-centered learning environment features that best promote self-regulated learning processes is still in its infancy.

Leveraging Narrative Environments for Self-Regulated Learning

As noted above, Schraw, Crippen, and Hartley (2006) identify six areas of focus for improving self-regulated learning in science education: inquiry-based learning, collaboration, strategy instruction, construction of mental models, technology use, and epistemological beliefs. Narrative-centered learning environments present opportunities for discreetly implementing each of these strategies in motivating and effective ways. Incorporating these strategies may also provide students with important problem-solving guidance that simultaneously enhances student self-efficacy and engagement in the sciences.

Inquiry-Based Learning

Interactive narratives naturally support several key aspects of inquiry-based learning. For example, audiences interact with narrative in a way that resembles the steps of inquiry-based learning. Generally, narratives contain sequences of causally related events that contribute to an overarching plot, and most individuals appear to have inherent schemata for these structures (Bruner, 1990). Audiences naturally draw

inferences about the narratives they encounter (Gerrig, 1993). As the plot of a narrative develops, audiences instinctively form hypotheses about possible future events. These hypotheses are actively tested as the story continues, and they are either supported or contradicted as the plot is revealed. Thus, each situation must be reevaluated in light of new information, and alternate hypotheses must be formulated.

The continuous cycle of forming and evaluating expectations has the benefit of keeping readers motivated and engaged. Furthermore, events such as unexpected twists, humorous or empathetic characters, and fantasy are generally introduced to encourage reader engagement. This narrative inference process aligns well with the hypothesis generation-testing-revision cycles of inquiry-based learning, creating opportunities for the two processes to complement one another in effective and engaging manners. Of course, the alignment between narrative inference and inquiry-based learning depends upon tight integration between narrative content and science content. Tight integration between narrative and curriculum is one of the key features of narrative-centered learning environments. This integration is one of the primary characteristics distinguishing narrative-centered learning environments from other types of educational games with stories that are tangential to their primary instructional objectives. In the case of science learning, tight integration means that the inferences necessary for reasoning about the narrative are the same inferences necessary for scientific thinking.

Narrative-centered learning environments also support active participation in stories as students adopt the roles of characters. Students in narrative-centered learning environments carry out problem-solving actions in a manner similar to that of authentic inquiry. In authentic inquiry, students generate research questions and guide themselves

through the problem-solving process (Anderson, 2002); however, in the case of narrative-centered learning environments, students' problem-solving activities can also be guided within the structure of the narrative. For example, in a medical mystery scenario, by establishing which actions serve as the narrative's desired resolution (e.g., determining the identity of a mysterious disease), the student is implicitly scaffolded to set an overall goal: it is the student with guidance from the narrative, rather than guidance from the instructor, who determines what actions to take in order to accomplish the task at hand (the desired plot resolution). Narrative-centered learning environments also offer means for supporting hypothesis formation and testing. Each action taken by a student (e.g., running a virtual lab experiment, gathering background information) is taken because the student believes it will bring her closer to the solution, based on her current understanding or hypothesis. Evidence that an action does not lead to the goal solution may indicate a flawed hypothesis, forcing the student to reconsider her hypotheses and problem-solving plans.

Collaboration

Given the importance of characters for engaging narratives, collaboration within narrative-centered learning environments is a natural technique for supporting self-regulated learning. Schraw, Crippen, and Hartley (2006) identify four distinct ways in which collaboration directly enhances SRL instruction: modeling partner behaviors, planning and evaluating discussion, utilizing the academic strengths of each student, and promoting classroom equity (Schraw, Crippen, & Hartley 2006).

A promising feature of narrative-centered learning environments is introducing a companion agent, a character that works closely with the student and can prompt

discussion, reflection, and assistance in natural and subtle ways. Companion agents can assume the role of an apprentice, peer, or mentor to the student character. As an apprentice, the companion agent can ask the student to interpret and explain data gathered in the course of problem solving and to convey to the agent how this new information contributes to achieving the narrative's resolution. This method of forming explanations and teaching material to others has been shown to have beneficial effects on understanding and self-regulated learning (Chi, de Leeuw, Chiu, & LaVancher, 1994; Leelawong & Biswas 2008).

A companion agent can serve as a peer by asking questions such as, "What should we do next?" in order to prompt student planning, monitoring, and self-reflection, which are three key metacognitive strategies. Companion agents subtly inform the student of oversights or discourage conceptual overconfidence while maintaining the student's sense of agency and responsibility. A companion agent that serves as a mentor to the student interacts in a similar fashion by modeling important behaviors and guiding the student through the environment. Because companion agents are personified as characters within a story, their presence yields a noninvasive mechanism for metacognitive prompting, which can also be used to collect metacognitive data about the student. Techniques for devising companion agents capable of delivering metacognitive prompts that are appropriate for a given narrative context and SRL phase is an open research question.

Strategy Instruction

A growing body of research suggests that explicit instruction in self-regulated learning strategies promotes academic achievement (Schunk & Zimmerman 1998).

Specifically, these skills include effective problem-solving and critical-thinking skills (Schraw, Crippen, & Hartley 2006). Utilizing engaging features of narratives, such as character interactions, can transition strategy instruction from explicit procedural steps provided by an instructor to an integral component of a compelling narrative.

Within the context of a narrative, a student can be assigned a specific role in conjunction with a target task. Particular skills appropriate for that role can be practiced in ways motivated by the narrative, rather than through direct instruction. For example, a student could be assigned the role of a scientist or examiner whose occupational requirements discreetly scaffold problem-solving processes, such as recording notes for reporting back to an authority figure, representing information in a physical model, or evaluating the relevance of information for a particular a task. Rather than providing explicit instruction to students to perform specific steps, the student's learning is scaffolded in a manner that has been engagingly incorporated into the story environment.

Additionally, critical thinking skills can be incorporated into narrative plots. As Schraw, Crippen and Hartely (2006) observe, essential critical thinking skills are “identifying relevant information, constructing arguments, testing the credibility of information and hypotheses, and forming plausible conclusions” while consistently monitoring these activities (p. 124). Identifying relevant information and testing the credibility of information and hypotheses can be achieved through prompted reflection, which encourages students to formulate questions about a given task and extract the most important information. Characters can explicitly ask students questions throughout the learning interaction that encourages reflection on how information was attained and why it is vital for accomplishing the task at hand. Moreover, expert characters, as well as

virtual posters and books in the environment, can be utilized to help the student practice how to decide what information is the most important when an abundance of information sources are available.

With respect to constructing arguments and forming plausible conclusions, students can benefit from interactions with other virtual characters in the narrative. These characters can be designed to probe students and suggest other sub-goals to pursue. If a student finds these suggestions inadequate, he or she can be prompted to explain to the character why the advice will not be followed. As the student provides this explanation, a narrative-centered learning environment can dynamically probe the student until an adequate argument has been formulated. After the student provides an explanation for a desired learning goal, the system has an opportunity to detect what information the student understands, and what information the student should elaborate or further investigate.

Mental Models and Conceptual Change

Mental models are cognitive aids that enable students to mentally represent and reason about complex processes. Narrative-centered learning environments, and virtual environments in general, can contribute to novel mental model construction and conceptual change. The graphical technology of narrative-centered learning environments allows animated, 3D representations of scientific processes to aid in student conceptual understanding. Moreover, since the structure of narrative builds upon sequences of events, models can be continuously created and refined as more information is gathered and events occur.

Student Personal Beliefs

Student epistemological beliefs and self-efficacy play an important role in self-regulation because of their effect on students' perceived personal abilities and motivation (Schraw, Crippen, & Hartley 2006). Students with high levels of science self-efficacy have been shown to be more motivated and more likely to undertake and persist on difficult tasks. It is plausible that virtual characters could be designed to provide appropriate feedback on student performance and enhance student self-efficacy during narrative-centered learning experiences. Further, as peer modeling has been shown to increase self-efficacy (Schunk & Hanson 1985), virtual characters can be used to model desirable behaviors.

Students who hold the epistemological belief that academic ability is not static, and can be improved with effort, are more likely to be motivated when working on intellectually challenging tasks (Schommer, 1990). Virtual characters can be utilized to model and discuss desired epistemological beliefs. For instance, findings contradicting the student's initial beliefs can occur as the plot progresses; an agent in the environment can help the student to understand that these contradictions are natural and common. Character interactions are a natural element of narrative, and leveraging multimodal conversations with virtual characters is a promising vehicle for impacting student self-efficacy and epistemological beliefs.



Figure 1. CRYSTAL ISLAND narrative-centered learning environments.

An Implemented Narrative-Centered Learning Environment

Now in its fourth major iteration, CRYSTAL ISLAND is a narrative-centered learning environment built on Valve Software's Source™ engine, the 3D game platform developed for the popular Half-Life 2 series of games. The curriculum underlying CRYSTAL ISLAND's mystery narrative is derived from the North Carolina state standard course of study for eighth-grade microbiology. Students play the role of the protagonist, Alex, who is attempting to discover the identity and source of an infectious disease plaguing a research station. Figure 1 displays a screenshot from CRYSTAL ISLAND, in which the student learns about the infectious disease through a conversation with a virtual character.

CRYSTAL ISLAND's narrative takes place in a small research camp situated on a recently discovered tropical island. As students explore the camp, they investigate the island's spreading illness by forming questions, generating hypotheses, collecting data, and testing hypotheses. Throughout their investigations, students interact with non-player characters offering clues and relevant microbiology facts via multimodal "dialogues" delivered by characters through student menu choices and characters' spoken language. The dialogues' content is supplemented with virtual books, posters, and other resources encountered in several of the camp's locations. As students gather information about the spreading illness, they have access to a personal digital assistant to take and review notes, consult a microbiology field manual, communicate with characters, and report progress in solving the mystery. To solve the mystery, students complete a *diagnosis worksheet* to manage their working hypotheses and record findings about patients' symptoms and medical history, as well as any findings from tests conducted in the camp's laboratory. Once a student enters a hypothesized diagnosis, cause of illness, and treatment plan into the diagnosis worksheet, the findings are submitted to the camp nurse for review and possible revision.

To illustrate how CRYSTAL ISLAND implements instructional strategies for self-regulated science learning, consider the following scenario. The student has been exploring the CRYSTAL ISLAND virtual environment and has been tasked by the camp nurse with researching the island's mysterious spreading illness. The student begins by consulting with the island's residents, as well as by reading nearby posters and books that discuss various microbiology concepts. Some of the island's characters help to identify objects and symptoms that are relevant to the scenario, while others provide pertinent

microbiology information. However, not all of the camp's team members provide relevant information, so the student must critically evaluate the information she obtains. As the student gathers clues and progresses through the narrative, she begins to develop, test, and revise hypotheses about possible explanations for the disease (*inquiry-based learning*). This inquiry process emerges naturally in the course of solving the science mystery, and to organize her thoughts the student records her inferences about the symptoms and candidate causes of the outbreak in a diagnosis worksheet. The worksheet enables her to encode a simplified version of her mental model of the disease's spread (*mental models*). The student shares her diagnosis worksheet with the camp nurse, and they collaboratively review evidence that the student has collected, as well as the worksheet's proposed diagnosis, but discover a flaw (*collaboration*). The nurse, who serves as a virtual mentor to guide the student through the inquiry process, encourages the student to reflect on her current findings. The student and the nurse then discuss possible directions for establishing a revised hypothesis (*strategy instruction*). The student decides to test several partially consumed food items that the sick members recently ate, and after conducting a battery of tests in the laboratory, she discovers that a container of unpasteurized milk in the dining hall is contaminated with bacteria. By combining this discovery with information about the sick characters' symptoms, the student concludes that the team members' illness stems from an *E. coli* infection. The student reports her findings back to the camp nurse, and together they discuss a plan for treatment of the sick team members.

Findings

Over the past few years, CRYSTAL ISLAND has been the subject of several studies

conducted with North Carolina middle school students to investigate factors related to self-regulated learning including learning gains, problem-solving, engagement, and off-task behavior (McQuiggan, et al., 2008b; McQuiggan, Goth, Ha, Rowe, & Lester, 2008a; Rowe, Shores, Mott, & Lester, 2010a; Rowe, Shores, Mott, & Lester, 2010b). Three categories of instruments have been used to collect data about student learning processes during interactions with CRYSTAL ISLAND: (1) direct prompts and self-report requests embedded within the virtual environment, (2) pre-intervention and post-intervention tests and subjective surveys, and (3) trace data logs of students' in-game actions. Embedded prompts and self-reports have asked students to report on their current goals, goal-achievement progress, confidence in their content knowledge, and reflections about the problem-solving strategies employed. Pre- and post-intervention measures have assessed students' content knowledge, knowledge transfer, goal achievement orientation, self-efficacy, game-playing experience, personality, situational interest, and presence. Student trace data logs have recorded students' problem-solving actions, on-task and off-task behaviors, goals, affective states, and help-seeking behaviors. These investigations have yielded several areas of empirical support for the promise of narrative-centered learning environments to promote engaging science learning and self-regulatory processes.

An experiment involving an early version of CRYSTAL ISLAND investigated the impact of story content on student learning in narrative-centered learning environments (McQuiggan, et al., 2008b). The study compared two versions of CRYSTAL ISLAND—a full-narrative version featuring a poisoning scenario and rich character inter-relationships, and a minimal narrative-version featuring only story details necessary to support the problem-solving scenario—against a more traditional instructional approach, a narrated

slideshow that conveyed the same curricular material. The results showed that students in the CRYSTAL ISLAND conditions exhibited learning gains, but that those gains were less than those produced by traditional instructional approaches. However, the motivational benefits of narrative-centered learning, particularly with regard to self-efficacy, presence, and interest, were substantial. Students reported the highest levels of presence in the full-narrative condition, a finding that bears important implications for motivation.

A follow-up study using an updated version of CRYSTAL ISLAND found improved learning gains compared to the prior study (Rowe, Shores, Mott, & Lester, 2010a). Furthermore, it was found that several factors hypothesized to be related to student engagement (e.g., presence, in-game performance, and situational interest) were significantly associated with improved learning outcomes, independent of students' background knowledge and game-playing experience. These results contrast with the initial study's findings that placed learning and engagement variables at odds with one another. The updated version of CRYSTAL ISLAND incorporated a number of changes believed to contribute to the improved learning outcomes. The changes included the following: multimodal spoken character dialogues, an expanded diagnosis worksheet, a streamlined narrative (lacking the poisoning scenario and non-essential character relationships), tighter coupling between the narrative and microbiology curriculum, simplified controls, a revised laboratory testing device, a new sub-activity in which students labeled parts of cells, and an updated look-and-feel of the island. The findings indicate that story and gameplay features can be crafted such that engagement in the interactive narrative scenario can contribute to learning outcomes, rather than detract from learning.

Several analyses have been conducted to investigate students' problem-solving processes during interactions with CRYSTAL ISLAND. One version of CRYSTAL ISLAND maintained an in-game score to assess students' progress and efficiency in completing the science mystery. Score incorporated time taken to accomplish important narrative goals, students' ability to demonstrate microbiology content knowledge, and evidence of careful hypothesis formulation. Scores were decreased after any attempt to "game the system" by repeatedly submitting incorrect diagnoses to the camp nurse or guessing on content knowledge quizzes. A comparison of students who achieved high scores during gameplay versus low-scoring students found striking differences in their learning outcomes, self-efficacy for science, and gameplay profiles (Rowe, Shores, Mott, & Lester, 2010b). High-scoring students scored significantly higher on a post-experiment content test, were significantly more self-efficacious for science, and performed more information gathering and offloading behaviors during gameplay, such as reading virtual books and accurately completing their diagnosis worksheets. Low-scoring students tended to spend more time engaged in dialogues with non-player characters and conducted more tests in the laboratory, including unnecessary tests. These findings may be symptomatic of low-scoring students being less effective at devising and following successful problem-solving and self-regulatory strategies in CRYSTAL ISLAND, as evidenced by inefficient inquiry behaviors and decreased diagnosis worksheet performance. Examples of inefficient inquiry behaviors include randomly guessing the mystery's solution, conducting an excessive number of redundant or irrelevant laboratory tests, and taking excessive amounts of time to complete the narrative's sub-goals.

An examination of students' note-taking behaviors during interactions with CRYSTAL ISLAND revealed that students who took notes about their hypotheses performed better on a post-experiment content test (McQuiggan, et al., 2008a). This observation reinforces inquiry-based learning findings suggesting the importance of scaffolding students' hypothesis generation activities. The study also found significant gender effects on note-taking, with females taking significantly more notes than males. Goal orientation and efficacy for self-regulated learning were also significantly correlated with note-taking behavior.

Findings from a study with CRYSTAL ISLAND indicated that gender and game-playing experience significantly impact variables related to student engagement, such as presence (Rowe, Shores, Mott, & Lester, 2010b). It was found that male students reported being more present than female students during interactions with CRYSTAL ISLAND, and that experienced gamers tended to be more present than less-experienced gamers. An analysis of student off-task behavior within the virtual environment (i.e., students' attendance to non-essential environmental features) also found negative associations with science achievement; students with lower scores on pre-experiment and post-experiment content tests tended to perform more off-task behaviors than their higher-scoring counterparts (Rowe, McQuiggan, Robison, & Lester, 2009). Male students were also found to perform significantly more off-task behaviors. It was unclear to what extent these off-task behaviors consisted of students' disengaging from the learning activity versus engaging in behaviors that were inconsistent with effective problem-solving tactics. It may be that these off-task behaviors are symptomatic of inadequate self-regulatory processes, but additional investigation is necessary to confirm this hypothesis.

While the rich details of virtual environments may draw some students away from learning-focused activities, they play a critical role in establishing a compelling narrative and virtual environment. Rather than remove such elements in the hope of avoiding off-task behaviors, a more promising approach is to devise adaptive scaffolding techniques that help students regulate their learning and return to productive problem-solving behaviors. Despite these open questions, the finding that students' gender and game-playing experience impact factors associated with student engagement is important for informing future research about the design of narrative-centered learning environments that seek to promote engagement as part of supporting self-regulated learning.

Discussion and Challenges

Findings indicate that narrative-centered learning environments can be effective platforms for inquiry-based learning that synergistically integrate learning and engagement in problem-solving scenarios. Although the potential for introducing seductive details is an important issue, the potential for narrative-centered learning environments to create engaging practice opportunities for self-regulatory skills and discreetly embed scaffolding for self-regulatory processes is a compelling potential benefit. Analyses of students' problem-solving performances in an implemented narrative-centered learning environment have revealed significant variations in self-regulatory skills, as evidenced by variations in problem-solving tactics, note-taking behaviors, learning and engagement outcomes, and off-task behaviors. Continued development of an empirical account of students' self-regulation in narrative-centered learning environments, and the efficacy of different techniques for subtly scaffolding

self-regulatory processes, is an important direction for further investigation and will inform the design of future narrative environments.

Despite the considerable potential of narrative-centered learning environments to provide engaging inquiry support facilities for students, designing effective narrative-centered learning environments to enhance students' self-regulatory skills poses several challenges. First, narrative-centered learning environments' ability to deliver individualized and adaptive scaffolding for self-regulated behaviors is strongly dependent upon accurate assessments of the student's current knowledge and abilities. However, it can prove difficult to access information about students' self-regulatory processes due to their internal nature. While detailed records of students' behaviors during interactions with narrative-centered learning environments offer a window into students' self-regulatory skills, further investigation is needed to develop automated methods for dynamically diagnosing self-regulation skills in a manner that is not disruptive to learning.

Second, developing effective narrative-centered learning environments is currently highly resource-intensive. New authoring systems are needed to accelerate the development of narrative-centered learning environments, and professional development materials need to be created so that teachers can effectively integrate these new technologies into their classrooms.

Conclusions

Narrative-centered learning environments provide inquiry-based learning interactions through rich, immersive story worlds that charge students with effectively utilizing content knowledge and problem-solving skills to achieve plot resolutions.

Success during interactions with narrative-centered learning environments is often dependent upon the degree to which students are self-regulated; it is the students, not instructors, that ultimately guide instruction by setting learning goals, monitoring goal progression, implementing strategies, and maintaining motivation. Narrative-centered learning environments offer the potential to supplement self-regulated learning processes by discreetly embedding such instruction within narrative structures. Self-regulatory instruction can then be provided through the narrative itself rather than through explicit prompts. While there are challenges to subtly integrating self-regulatory support, advances in intelligent tutoring systems and intelligent interactive narrative technologies hold significant promise for adaptive, real-time self-regulated learning scaffolding and assessment.

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