Exploring Inquiry-based Problem-Solving Strategies in Game-based Learning Environments

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Abstract. Guided inquiry-based learning has been proposed as a promising approach to science education. Students are encouraged to gather information, use this information to iteratively formulate and test hypotheses, draw conclusions, and report their findings. However, students may not automatically follow this prescribed sequence of steps in open-ended learning environments. This paper examines the role of inquiry behaviors in an open-ended, game-based learning environment for middle grade microbiology. Results indicate that students' quantity of information-gathering behaviors has a greater impact on content learning gains than adherence to a particular sequence of problem-solving steps. We also observe that information gathering prior to hypothesis generation is correlated with improved initial hypotheses and problem-solving efficiency.

Keywords: Problem solving, Inquiry-based learning, Game-based learning

1 Introduction

Inquiry-based learning has been a focus of recent attention in both traditional classrooms [1,2] and intelligent tutoring systems [3,4,5], particularly in science education. There is evidence that inquiry-based learning may only be effective under particular conditions. Students typically need to have some background knowledge in order to learn new material in an inquiry-based setting [1, 2], and they may also require explicit guidance during inquiry-based learning in order to avoid floundering [1,2,5]. There is further evidence that providing guidance about appropriate inquiry behaviors can improve students' future inquiry skills [5].

A variety of approaches to inquiry-based learning have been explored in the intelligent tutoring systems community. For example, Woolf *et al*. have developed the inquiry environment *Rashi*, which supports inquiry skills in a variety of different domains including biology and geology [4]. Students use an inquiry notebook and hypothesis editor to record their observations, reason about findings and support or reject hypotheses. In the *Invention Lab*, students are encouraged to "invent" equations that explain the relationships between variables [3]. *River City* and *Crystal Island* both embed inquiry-based learning within interactive science mysteries in which students are encouraged to gather information about patient symptoms and diagnose a spreading disease in open-ended virtual environments [5,7].

adfa, p. 1, 2011.

A promising platform for promoting inquiry-based learning is digital game environments. Game-based learning environments have been used for a range of domains, including negotiation skills [8], foreign languages [9], and policy argumentation [6]. Devising effective methods for guiding inquiry-based learning in game environments requires an understanding of students' inquiry strategies in digital games. This paper examines students' inquiry behaviors within a game-based learning environment, as well as inquiry behaviors' relationships with problem solving and learning.

2 CRYSTAL ISLAND Learning Environment

Our work on problem-solving behaviors is situated in CRYSTAL ISLAND, a game-based learning environment for middle grade microbiology [7]. The premise of CRYSTAL ISLAND is that a mysterious illness is afflicting a research team stationed on a remote island. The student plays the role of a visitor who is drawn into a mission to save the research team from the outbreak. The student explores the research camp from a first-person viewpoint and manipulates virtual objects, converses with characters, and uses lab equipment and other resources to solve the mystery. The student is expected to gather information regarding patient symptoms and relevant diseases, form hypotheses based on her findings, use virtual lab equipment and a diagnosis worksheet to record their findings, and share her conclusion with the camp's nurse.

A range of in-game information gathering behaviors are available to students: they can converse with virtual characters about microbiology concepts; they can discuss symptoms and possible transmission sources with sick patients; and they can read virtual posters and books to narrow down which illnesses match the patients' symptoms. As students work towards solving the mystery, they have two primary mechanisms to specify and test their hypotheses. The first mechanism is a virtual laboratory instrument that enables students to test food objects to determine if they are contaminated with pathogens, mutagens or carcinogens. The second method is a diagnosis worksheet that serves as a graphic organizer for recording findings and hypothesized diagnoses. A camp nurse will review the diagnosis worksheet to determine its correctness and provide feedback. This paper examines two primary problem-solving tasks that are critical for solving the mystery: achieving a positive test with the laboratory instrument, and submitting a correct diagnosis worksheet to the camp nurse. In particular, this work investigates how different problem-solving strategies for these tasks relate to content learning gains and in-game problem solving performance.

3 Procedure

A study was conducted with 450 eighth grade students from two North Carolina middle schools. All of the students interacted with the CRYSTAL ISLAND environment. After removing instances of incomplete data, the final corpus included data from 400 students. Of these, there were 194 male and 206 female participants. The average age of the students was 13.5 years (SD = 0.62). At the time of the study, the students had not yet completed the microbiology curriculum in their classes.

Participants interacted with CRYSTAL ISLAND in their school classroom, although the study was not part of their regular classroom activities. During the week prior to using CRYSTAL ISLAND, students completed several personality questionnaires and a researcher-generated curriculum test consisting of 19 questions created by an interdisciplinary team of researchers assessing microbiology concepts covered in CRYSTAL ISLAND. During the study, participants were given approximately 55 minutes to work on solving the mystery. Immediately after solving the mystery, or after 55 minutes of interaction, students moved to a different room in order to complete several post-study questionnaires including the curriculum post-test.

In order to understand how students approach problem solving in the game, we consider four key milestones in CRYSTAL ISLAND's problem-solving process: *first laboratory test*, *positive laboratory test*, *first diagnosis worksheet check*, and *correct diagnosis worksheet check*. We are interested in identifying what in-game behaviors typically precede problem-solving milestone achieved by students, and what behaviors occur after completing milestones. Two hypotheses guide this investigation. It is hypothesized that students who spend more time gathering data and reviewing resources prior to their first laboratory test or diagnosis worksheet check will be more effective at solving the mystery (Hyp. 1) and have higher learning gains (Hyp. 2) than students who attempt the problem solving milestones without having gathered much background information. Data gathering behaviors in the context of CRYSTAL ISLAND include talking with characters, viewing posters, reading books, and taking notes.

4 Results

Of the 400 students in the corpus, 320 students were able to perform a positive lab test and 124 students were able to arrive at a correct diagnosis. In our investigation of laboratory test milestones and diagnosis worksheet milestones, we limit our analyses to these respective subsets of students.

4.1 Hypothesis 1 – More Effective Problem Solving

Pearson correlations were calculated to investigate the relationships between different information gathering behaviors and initial problem solving milestones. Metrics of effective problem solving include total number of attempts (i.e., tests conducted with the laboratory instrument or submissions of the diagnosis worksheet) and total time to achieve a successful result (i.e., time taken to perform a lab test that results positive or submit a complete and correct diagnosis worksheet).

Laboratory Tests. Prior to their first laboratory test, students read an average of 1.5 books in the game, looked at 3.9 posters, took 2.7 notes and talked to 3.7 unique virtual characters. On average, 7.3 minutes elapsed between students conducting their first lab test and conducting a positive test. During this time they ran an average of 5.2 total tests. A series of Pearson correlations revealed that students who talked to more unique characters took less time to achieve a successful test, $r(318) = -0.27$, $p < .001$

Table 1. Correlations of data-collection behaviors prior to first diagnosis check. * and ** indicate statistical significance at p < .05 and .01, respectively.

	Total Problem-Solving Time	*Total Number of Attempts*	*Correctness of First Submission*
Books	-0.35**	-0.29**	0.44**
Posters	-0.41**	-0.43**	0.47**
Notes	-0.22*	-0.19*	0.25*
Characters	-0.36**	-0.12	0.28*

and ran fewer total tests, $r(318) = -0.14$, $p = .012$. Similarly, students who viewed more posters took less time to achieve a successful test, $r(318) = -0.18$, $p = 0.002$ and ran fewer tests, $r(318) = -0.11$, $p = 0.05$. The number of books read and notes taken were not observed to be significantly correlated with the problem solving metrics.

Diagnosis Worksheet. Prior to their first diagnosis worksheet check, students read an average of 3.2 books, looked at 7.3 posters, took 3.1 notes and talked to 5.2 unique characters. Students took an average of 10.4 minutes to submit a correct diagnosis after their first attempt, and made an average of 3.5 attempts. Correlations revealed that prior information gathering was associated with more effective problem solving behaviors. Table 1 shows medium-strong correlations between many of the information gathering behaviors, problem-solving time, and number of worksheet checks.

Overall, Hypothesis 1 was supported. Increased data-collection behavior prior to problem-solving attempts was correlated with more effective problem solving. Students spent less time and made fewer total attempts than those who did not engage in information gathering behaviors prior to problem solving.

4.2 Hypothesis 2 – Better Learning Gains

Correlations were calculated between students' information gathering behaviors prior to their first laboratory test and first diagnosis check and normalized learning gains. However, there was no correlation between any of these metrics. The absence of an observed relationship prompted further investigation. When examining the relationships between student learning gains and total information gathering behaviors over the entire session, several significant correlations were observed. Conversations with characters, $r(398) = .26$, $p < .001$, looking at posters, $r(398) = .18$, $p < 0.001$, and reading books $r(398) = .18$, $p < .001$ were all positively correlated with normalized learning gains. This suggested that the total number of investigative actions was more associated with students' learning outcomes than when the behaviors were performed.

In order to further investigate this trend, we grouped students into early and late investigators based on the proportion of their information gathering behaviors that occurred prior to their first test or diagnosis check. T-tests between these groups yielded interesting findings. First, it appears that while early investigators are completing more information-gathering prior to problem solving, they are not completing more information gathering across the interaction (Figure 1). Specifically, prior to the

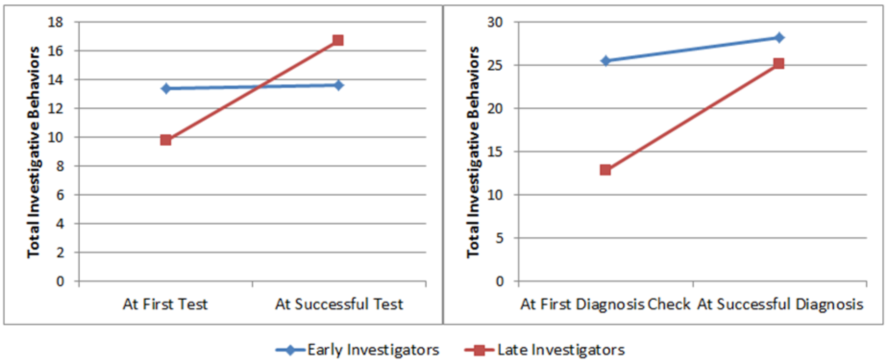

Fig. 1. Change in total investigative behaviors for early and late investigators

first test or first diagnosis check, early investigators have completed significantly ($p < 0.001$) more information gathering behaviors than late investigators. However, at the time of a successful test late investigators have actually completed significantly more information gathering behaviors than their peers, $t(318) = 3.23$, $p = 0.001$. Alternatively, there is no difference in total investigative behaviors between early and late investigators at the time of a successful diagnosis check.

Together these findings suggest that no support was observed for Hypothesis 2. Increased information gathering behaviors prior to problem solving does not lead to better learning gains. Instead, total investigative behaviors, and not their timing, is what is important for microbiology content learning. There is evidence that early and late investigators still engage in the same amount of total data-collection behaviors, which accounts for the lack of difference in learning gains between these two groups.

5 Discussion

These findings suggest that students who do not automatically employ effective problem-solving strategies in open-ended game-based learning environments, and problem-solving strategy-use can experience distinct impacts on in-game problem solving and content learning gains. A possible explanation for this study's findings is as follows: the curriculum test primarily assessed microbiology concepts, as opposed to science problem-solving strategies. Students who gathered background information throughout the session benefitted from increased exposure to microbiology content, and these benefits were revealed by the curriculum test. However, gathering information prior to formulating and testing hypotheses was evidence of problem-solving skill. This strategic knowledge was primarily assessed by in-game performance, and not the curriculum test. This explains why effective problem-solving strategy use did not necessarily yield improved performance on a curriculum post-test, but it was associated with improved in-game problem solving outcomes.

The results point toward several promising directions for future work. First, the observation that both early and late investigators perform a comparable number of total information-gathering behaviors raises questions about whether the late investigators learned how to improve their inquiry skills. In fact, there is evidence from other learning systems that repeated exposure to game-based inquiry environments may improve students' inquiry skills [5, 8]. Another important area for future work will be closely examining those students who were unable to complete CRYSTAL ISLAND's problem-solving milestones, and identifying which features separate them from students who were more successful. It will particularly important to determine what patterns of inquiry behaviors these students exhibit in order to devise intelligent scaffolding techniques to guide their problem solving.

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6 References

1. P. A. Kirschner, J. Sweller, and R. E. Clark, "Why Minimal Guidance during instruction does not work: An analysis of the Failure of Constructivist, Discovery, Problem-Based, Experiential, and Inquiry-Based Teaching," *Ed. Psychologist*, vol. 41, pp. 75-86, 2006.
2. L. Alfieri, P. Brooks, N. Aldrich, and H. Tenenbaum, "Does Discovery-Based Instruction Enhance Learning," *Journal of Education Psychology*, vol. 103, no. 1, pp. 1-18, 2011.
3. I. Roll, V. Aleven, and K. R. Koedinger, "The Invention Lab: Using a Hybrid of Model Tracing and Constraint-Based Modeling to Offer Intelligent Support in Inquiry Environments," in *Proc. of the 10th Intl Conf. on Intelligent Tutoring Systems*, 2010, pp. 115-124.
4. B. P. Woolf et al., "Critical Thinking Environments for Science Education," in *Proceedings of the 12th Intl Conference on Artificial Intelligence in Education*, 2005, pp. 515-522.
5. D. J. Ketelhut, "The impact of student self-efficacy on scientific inquiry skills: An exploratory investigation in 'River City', a multi-user virtual environment," *Journal of Science Education and Technology*, vol. 16, no. 1, pp. 99-111, 2007.
6. M. W. Easterday, V. Aleven, R. Scheines, and S. M. Carver, "Using Tutors to Improve Educational Games," in *Proceedings of the 15th International Conference on Artificial Intelligence in Education*, 2011, pp. 63-71.
7. J. P. Rowe, L. R. Shores, B. W. Mott, and J. C. Lester, "Integrating Learning, Problem Solving, and Engagement in Narrative-Centered Learning Environments," *International Journal of Artificial Intelligence in Education*, 2011.
8. J. Kim, R.W Hill, P. Durlach, C. Lane, E. Forbell, M. Core, S. Marsella, D. Pyanadath, and J. Hart, "BiLAT: A game-based environment for practicing negotiation in a cultural context," *Intl Journal of Artificial Intelligence in Education*, vol. 19, no. 3, pp. 289-308, 2009.
9. W. L. Johnson, "Serious Use of a Serious Game for Language Learning," *International Journal of Artificial Intelligence in Education*, vol. 20, no. 2, pp. 175-195, 2010.