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Constructing knowledge in the context of BioWorld

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Abstract. BioWorld is a computer learning environment designed for high school biology students. BioWorld complements the biology curriculum by providing a hospital simulation where students can apply what they have learned about body systems to problems where they can reason about diseases. Students work collaboratively at collecting evidence to confirm or refute their hypotheses as they attempt to solve BioWorld cases. The present study examined students' use of BioWorld to solve problems related to the digestive system. Analyses of student actions and verbal dialogue were conducted to pinpoint the types of features within BioWorld that were most conducive to learning and scientific reasoning. An exploratory analysis of the types of assistance provided to students by a teacher, researcher, and BioWorld alone was conducted to examine how scaffolding influenced student actions.

Keywords: computer-based learning environments, argumentation, scientific reasoning, high school biology, problem based learning, coaching

Introduction

The decline in student performance and enrollment in science courses (American Association for the Advancement of Science [AAAS], 1989; Cadigan, 1993) have raised concerns about the manner in which science is taught and learned (AAAS, in prep; National Science Teachers Association, 1996). The primacy of rote learning has been called into question and alternative forms of learning that involve hands-on experience, collaborative problem solving, and inquiry are now being explored (Linn, 1992; McCade, 1995; National Research Council, 1995; Roth et al., 1996; Tobin et al., 1990). Recently, innovative learning environments have been designed to promote scientific inquiry in order to achieve a closer correspondence between classroom learning and real-world applications of science (Collins, 1997; National Academy of Sciences, 1994; Resnick, 1987). Problem-based learning (PBL) is an example of how this alignment can be accomplished. Students are presented with 'real-life' problems that require defining the problem, creating hypotheses, gathering and analyzing data, and evaluating or justifying solutions collaboratively (Barrows, 1986; Barrows & Myers, in prep; Gallagher et al., 1995). Decision making in a variety of life situations involves engaging in such thinking processes. PBL environments can facilitate the transfer of schooled knowledge and skills to real-life contexts (Hoffman & Ritchie, 1997; Resnick, 1987).

Authentic problems of the PBL kind provide meaningful, challenging, and rich learning experiences that (a) foster the development of students' reasoning abilities (Johnson & Lawson, 1998; Kuhn et al., 1997; Metz, 1995 1997), (b) enable students to explore the nature of experimentation (Schauble et al., 1995), (c) reflect everyday practices and tools of the scientific community (Roth & McGinn, 1997), and (d) foster a community of learners (Brown, 1997; Polman & Pea, 1997). The challenge in employing realistic problems is that they are more demanding cognitively than conventional science tasks (Koschmann et al., 1994), they are more open-ended, complex, and they require sustained periods of investigation (Haury, 1993; Schauble et al., 1995) and engagement (Kuhn et al., 1997). Problem solving in this context is demanding because (a) there may be more than one way to solve the problem, (b) the nature of the problem unfolds over time, and (c) decisions must be made in the absence of definitive knowledge and there may never be certainty about having made the right decision (Koschmann et al., 1994). At issue is how to foster meaningful learning while also preserving the integrity of complex problems; i.e., not reducing the complexity to routine procedures and rote learning. One way to accomplish this objective is to scaffold learning and support cognitive activities.

Barron et al. (1998) reviewed the success of both problem and project-based learning. They suggest that PBL provides more scaffolding for learners and that project-based learning environments could benefit from following specific design principles, such as (a) defining learner appropriate goals to ensure deeper understanding; (b) providing scaffolds that support both student and teacher learning, i.e., sets of 'contrasting cases'; (c) providing frequent opportunities for self assessment; and (d) creating social organizations that promote participation and a sense of agency.

Scaffolding learning

Teachers can facilitate learning by guiding rather than directing students' learning. Appropriate use of prompts to encourage further exploration of scientific ideas, knowing when to provide and withdraw assistance (i.e., fading; Collins et al., 1989), and encouraging intellectual risk-taking by making relevant tools and resources accessible are some of the ways in which teachers can scaffold learning. This process can be facilitated through the use of technology. Computers are interactive technologies that can support cognition and expand the mind (Jonassen, 1996; Jonassen & Reeves, 1996; Kommers et al., 1992; Lajoie & Derry, 1993; Pea, 1985; Salomon et al., 1991) by helping students during thinking, problem solving, and learning. Technologies (e.g., multimedia) can assist learners by providing (a) multiple modalities for representing real-world problems; (b) adequate information, advice, and feedback when and where needed; (c) opportunities to solve and reason about problems while applying scientific knowledge, and; (d) on-line resources that reduce memory load and increase the time for in-depth thinking. The use of technology can also help teachers adopt a more facilitative role in the classroom. The development of environments that support learning is an ongoing effort. However, more research is needed to provide insights into when and how to scaffold learning in scientific learning contexts (de Jong & van Joolingen, 1998). There are studies that suggest that learning styles should be taken into account regarding the use of scaffolding. Some individuals prefer to 'discover' while others prefer to be 'guided' to the appropriate information. Shute (1993) found that it could be counter-productive to place individuals with a discovery-oriented learning style into a guided computer-based learning environment.

Scaffolding is key to the development of high-level science performance on ill-structured problems that reflect everyday scientific practice. Students' learning and cognitive abilities need to be supported with appropriate resources and tools. Technologies, such as multimedia, can facilitate this process. Computer supported cognitive tools can provide contextualized assistance in order to scaffold learning. The present study examines the effectiveness of various features within BioWorld, a computer-based learning environment, that are intended to support the acquisition of scientific reasoning skills in high school students. BioWorld integrates a variety of cognitive tools (Jonassen & Reeves, 1996; Lajoie, in press; Lajoie & Derry, 1993; Pea, 1985; Perkins, 1985; Salomon et al., 1991) to assist students in the acquisition of knowledge pertinent to conducting scientific investigations about diseases. One question that intrigues us is whether or not a computer-based learning environment such as BioWorld can provide the necessary scaffolding to support learning or whether additional assistance is needed. Before describing the study, a condensed review of the literature on scientific reasoning and argumentation is provided as BioWorld supports the development of these skills. This review is followed by a description of the BioWorld environment, an outline of the methodology, preliminary answers to the research questions posed in the study, and conclusions.

Scientific reasoning and argumentation in inquiry settings

Broadly defined, reasoning involves the ability to think and to make logical and rational decisions. Numerous types of reasoning have been identified and researched. However, two forms of reasoning, formal and informal, are particularly relevant to the present study. Formal and informal reasoning (Galotti, 1989) reflect the distinction between well- and ill-structured problems, respectively (Koschmann et al., 1994; Lesgold, 1988). Formal reasoning involves solving problems whereby all relevant information is specified in advance and where only one suitable response exists. Informal reasoning is a goal-dependent process that involves generating and/or evaluating evidence relating to a claim or conclusion (Means & Voss, 1996). This form of reasoning relates specifically to everyday contexts where not all premises are stated and multiple solution paths exist. It is elicited when information is less accessible or when problems are more open-ended, debatable, or complex (Galotti, 1989; Means & Voss, 1996). Scientific reasoning has traditionally been characterized as formal, while argumentation is more consistent with informal reasoning. The main difference between scientific and informal reasoning lies in the focus of research. Scientific reasoning is examined in contexts designed to promote such thinking. In the case of informal reasoning, lay people's thinking is examined in everyday contexts to identify what is scientific about their thinking (Kuhn, 1997). According to Kuhn (1991, 1997), reasoning in everyday situations is reflected in argument.

Scientific reasoning is often evaluated in terms of the quality of student arguments. Argumentation involves formulating theories or hypotheses, gathering evidence and assessing the reliability of the evidence that is accumulated in order to arrive at a reasoned judgment or conclusion based on the evidence. Evidence is defined as information that serves to confirm or disconfirm hypotheses (Hemple, 1961). Toulmin (1958) describes argumentation as a process of making assertions or claims and providing support and justification for these claims using accumulated data, facts and evidence. Argumentation also involves conceiving of alternative or opposing hypotheses and resolving conflicts between competing hypotheses by weighing and analyzing accumulated evidence. It is this skillful coordination of theory and evidence that is believed to be the most central premise underlying scientific thinking and that relates scientific reasoning to informal reasoning or argumentation (Kuhn, 1989, 1991, 1997). Since scientific practice typically involves collaboration (Okada & Simon, 1997), the structure of reasoning in this context extends premises and conclusions to challenges, answers to challenges (in the form of doubts, questions, or exclamations), and concessions (Resnick et al., 1993). Scientific dialogue or conversation is therefore an important indicator of reasoning and argumentation (Resnick et al., 1993).

Research examining scientific reasoning has often been driven by a debate as to whether or not children can reason like scientists (Kuhn, 1997; Metz, 1997). Children's evaluation skills have been found to be both consistent and discordant with those of adults and scientists (Amsel & Brock, 1996; Klahr et al., 1993). For example, children are able to evaluate hypotheses on the basis of contingency data even though they exhibit inferential biases and confusions. In addition, although children are poor hypothetico-deductivists, they seem to be competent inductivists or abductivists (Amsel & Brock, 1996). In short, despite their characterization as inefficient scientists, children display early competencies in scientific investigation that provide the basis for further development (Kuhn, 1997). Other researchers, however, argue that there are no principled differences between elementary school children and scientists (Sodian, 1997). Contrary to Kuhn et al. (1988) and Kuhn (1989), Leach (1997) and Sodian (1997) found that children (7 to 9 year olds) were able to treat theory and evidence as separate entities even if not in a rational way. In essence, children differ in the degree to which they are proficient as scientists. For instance, some can evaluate their evidence more appropriately than others (Amsel & Brock, 1996).

Description of the learning environment and its support mechanisms

BioWorld (Lajoie, 1993; Lajoie et al., 1995) is a curriculum support tool, developed based on a PBL approach, that assists students in developing an understanding of biological terminology and the ability to reason scientifically about diseases. Declarative knowledge of diseases is put into practice by solving a realistic problem; i.e., diagnosing a disease in a simulated hospital environment. The intent is not to make physicians out of students, but rather, to provide opportunities for them to reason scientifically about data that is available in a simulated setting. In typical biology classrooms, students acquire declarative knowledge about diseases, how they are transmitted, how different diseases affect different parts of the body, and how the body has different defense systems to guard against certain diseases. Although, the nature of experimentation is better understood through sustained periods of real investigation than on discrete tasks (Schauble et al., 1995), students are rarely provided with such opportunities.

BioWorld promotes scientific inquiry and allows for the development of explanations and model-based reasoning. Rather than tutor students on various types of diseases and how they are transmitted and diagnosed, BioWorld engages students in the scientific reasoning process in various stages. First, students must hypothesize about a disease a patient might have based on a problem case and indicate their level of confidence in that hypothesis. To do this, a hypothesis menu was designed to support the process of

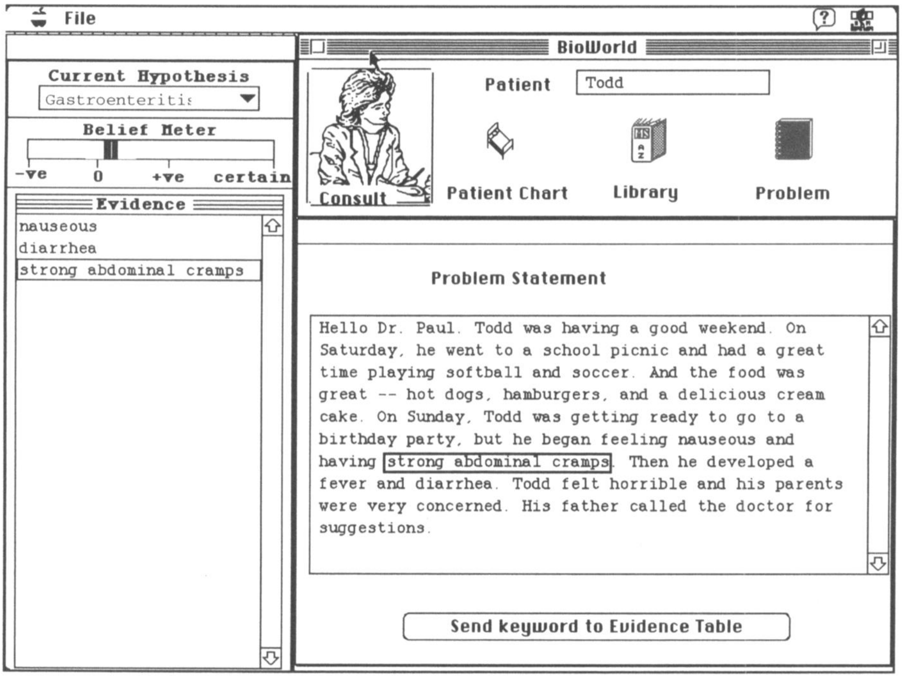

Figure 1. BioWorld patient scenario and evidence palette.

hypothesis generation (Shute & Glaser, 1990) by listing the various body systems and the types of diseases that develop in each of these systems. Through an argumentation process, students form a diagnostic hypothesis and collect evidence to either confirm or disconfirm their current diagnosis. As they do so, they can adjust a *belief meter* to indicate how comfortable they are with a stated diagnosis based on the collected evidence (see Figure 1). The role of confidence and evaluation of evidence is important, particularly given recent research suggesting that evidentially irrelevant data make children more uncertain (Amsel & Brock, 1996). Children do not seem to dismiss irrelevancies as readily as adults. As such, it is important to determine whether or not students distinguish between relevant and irrelevant data, and how this relates to their confidence in the course of problem solving.

A second way in which BioWorld engages students in scientific reasoning is by requiring the collection of data in order to evaluate hypotheses. Information for diagnosing a disease can be obtained from a variety of resources contained within BioWorld. For instance, as shown in Figure 1, diagnostic information is provided in a problem scenario that describes a patient's symptoms (both relevant and irrelevant). Medical information can be obtained from an on-line library of biological terms, diagnostic tests, and symptoms.

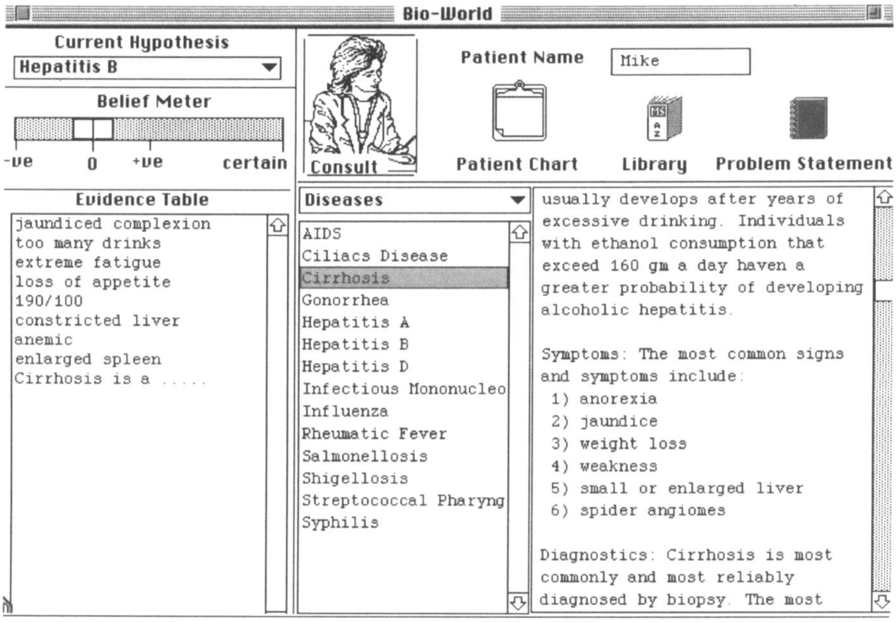

Figure 2. Disease library.

Experimental data can be acquired by performing diagnostic tests provided in the patient chart resource tool (see Figures 2 and 3). These resources (i.e., problem scenario, on-line library, and patient chart) provide students with information with which to construct arguments. A mechanism for making these arguments visible to students, so that they can begin to monitor their own scientific thinking, is the *evidence palette*.[1] This palette serves a similar function to argumentation tools provided in other environments (see Linton, 1995; Suthers et al., 1995). BioWorld's evidence palette is similar to the hypothesis scratchpad (de Jong & van Joolingen, 1998; van Joolingen & de Jong, 1997, 1991) that stores hypotheses in a list form which learners can inspect at any point. The scratchpad was originally designed as a support tool for scientific discovery learning (van Joolingen & de Jong, 1991). In BioWorld, actions such as selecting evidence, and conducting library searches or tests are displayed in the evidence palette dynamically. Formulating hypotheses and building justifications require students to engage in top-down reasoning, i.e., set goals and subgoals, justify goals with supporting facts, and keep track of all of this information (Anderson, 1983). Moreover, while pursuing evidence to confirm diagnostic hypotheses, contradictory evidence may be found, which may reduce confidence in a stated diagnosis or lead to an entirely new hypothesis. Making actions and results visible in the evidence palette facilitates reasoning by supporting memory.

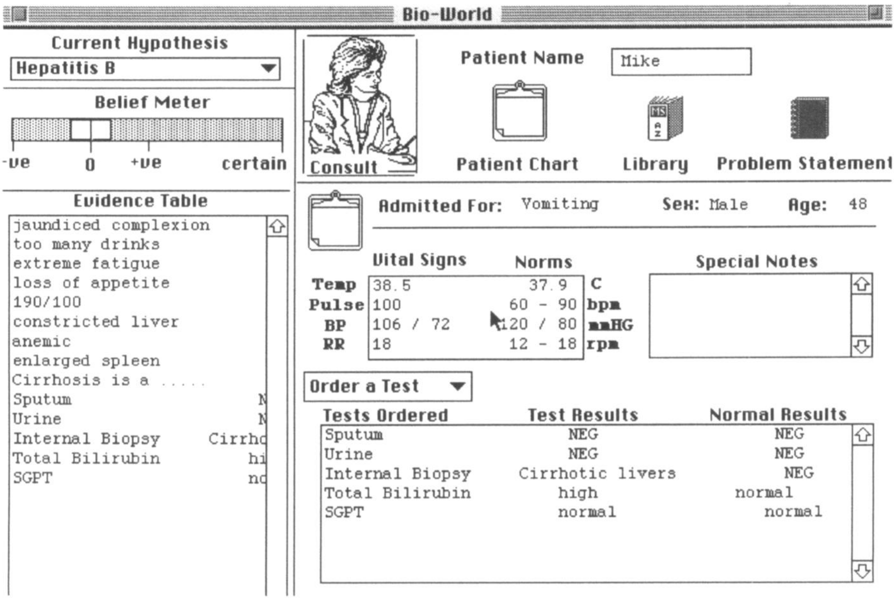

Figure 3. Conducting diagnostic tests.

In addition to supporting memory, the belief meter and evidence palette scaffold metacognitive processes. *Metacognition* can be defined as an individual's cognitions about his or her own cognition (Bruning et al., 1995; Flavell, 1979; Nelson, 1999). Metacognitive theory focuses on an individual's awareness and executive management of their thinking, self-evaluation and the management of cognitive development and learning, knowledge and executive abilities that develop through experience, and constructive and strategic thinking (Hacker, 1998). Researchers widely recommend that metacognitive skill should be fostered in educational settings (Dunlosky, 1998; Mayer, 1998; Schraw, 1998; Sternberg, 1998; Winne, 1997; Wolters & Pintrich, 1998). Recommended instructional activities include matching encoding strategies to the type of material to be learned, engaging learners in deep processing, engaging students in elaboration, encouraging metacognitive awareness, and emphasizing instruction on metacognitive strategy use (Bruning et al., 1995).

BioWorld engages users in particular types of metacognitive processing, namely the externalization and evaluation of their reasoning. Users engage, sort, and categorize the evidence they use to make a diagnosis, and compare it to the evidence used by an expert. Metacognitive activities are incorporated in BioWorld's design because they are widely regarded as beneficial for learning. Both the belief meter and evidence palette support metacognition by providing reflection tools for learners that encourage them to assess their overall problem solving process rather than focus on a single action. Through the use of the evidence palette, learners check prior plans and actions in terms of how systematic they have been in reviewing the evidence available to them. Computers support reflective thinking when they enable users to develop new knowledge by adding new representations, modifying old ones, and comparing them (Norman, 1983).

By supporting memory and metacognition, BioWorld fosters argumentation skills. These skills are also required in the evaluation of evidence, which is the final way in which BioWorld engages students in scientific reasoning. Relevant and irrelevant information must be distinguished on the basis of competing hypotheses and changes in hypotheses result in shifts in confidence levels. An *argumentation palette* enables students to organize evidence to build a justification for their diagnostic conclusions once a patient's disease is correctly identified (see Figure 4). Students' final argument is then compared to an expert argument (see Figure 5) where feedback is provided in the form of a sequenced list of relevant information needed to solve the problem. Expert arguments were provided by physicians and teachers who helped establish benchmarks of competent performance for each BioWorld problem. A narrated recap of how a physician solved the problem is also provided. This type of feedback allows students to reflect on their argument in comparison to an expert's argument.

Support mechanisms, learning, and confidence

Three research questions are examined in this study: (a) which features within BioWorld are most conducive to learning? (b) what is the relationship between confidence and knowledge acquisition as reflected in the final argument? and (c) do teachers (content experts somewhat familiar with BioWorld) and researchers (BioWorld experts with some content knowledge) differ in their assistance and do such differences influence student learning and performance? Moreover, do groups without human assistance in using BioWorld perform differently than those receiving additional scaffolding from a teacher or researcher?

The features (i.e., patient scenario, on-line library, patient chart, evidence palette, and argumentation palette) embedded within BioWorld provide users with different learning opportunities. The patient scenario provides students with information that can be used as evidence to support a diagnosis. Students' initial problem representation can be determined by examining the nature of the symptoms students select as relevant based on their selected hypothesis. The on-line library supports the acquisition of declarative knowledge by providing access to information about diseases, medical terms, and

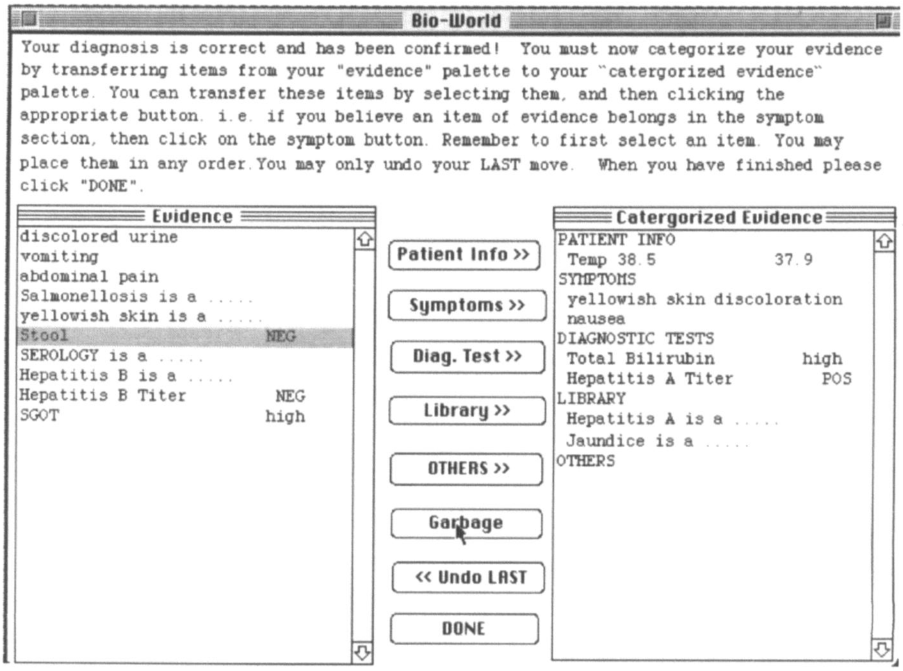

Figure 4. Categorizing evidence.

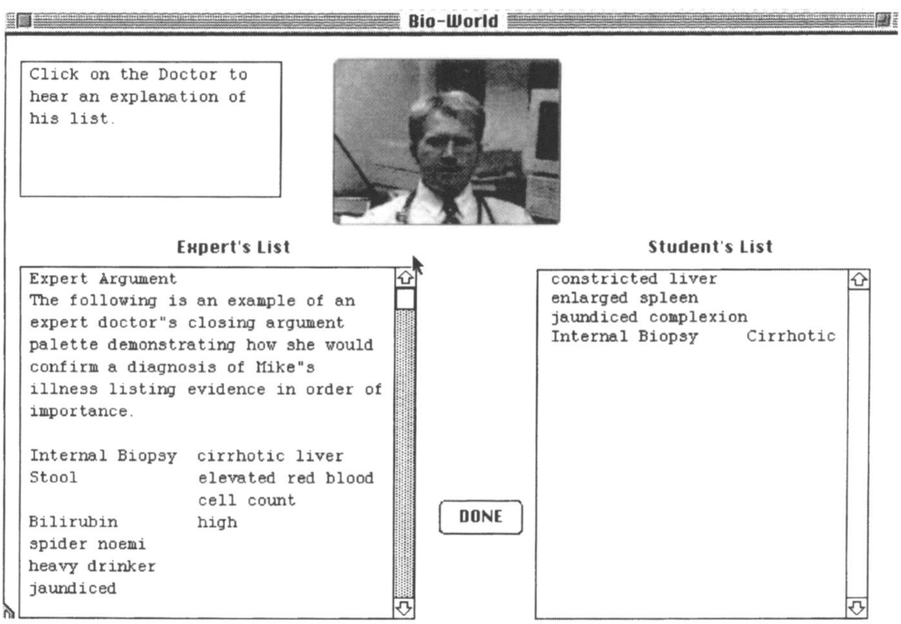

Figure 5. Comparing student argument to an expert argument.

diagnostic tests. The patient chart supports procedural skill by allowing students to order diagnostic tests that can confirm or disconfirm their hypothesis. Knowing how to conduct the appropriate diagnostic tests is a procedural skill.[2] The evidence palette stores information those students collect in the patient scenario, library and patient chart. In addition to demonstrating to learners and researchers what is viewed as important evidence, the palette serves to identify how student problem representations change as a result of information gathered. The argumentation palette supports the posting of a scientific argument. We predict that students will become more expert-like in their use of information within each BioWorld feature.

The second research question involves examining the relationship between confidence and the final argument. As mentioned previously, children's decision making appears to be sensitive to irrelevant data (Amsel & Brock, 1996). Our assumption is that students' confidence in their decision making would increase as they become more capable of differentiating between relevant and irrelevant information. Ascertaining the role of confidence in the context of BioWorld (as indicated by the belief meter), where groups of students discern relevant from irrelevant evidence as they refine their hypotheses is important. We predict that there will be a significant increase in confidence levels from the time that students make an initial hypothesis to the final hypothesis.

The final research question is exploratory and specifically addresses the type of scaffolding that human tutors may provide in this context and whether such scaffolding leads to more learning opportunities with BioWorld than without such tutoring. These preliminary data were collected to see whether or not a full-scale study of this question would be warranted. In this pilot we compared 3 conditions, a teacher (content expert with experience using BioWorld), a graduate student researcher (BioWorld expert with some content knowledge), and BioWorld-alone. We did not predict differences in learning outcomes but in learning processes.

We anticipated that students in the teacher condition would receive a more conceptual form of scaffolding that was linked to their classroom activities, whereas the other human tutor would provide a more procedural form of scaffolding, i.e., how to find information in the on-line library. We expected BioWorld to provide the necessary scaffolding to support learning but we wanted to explore whether or not additional assistance from teachers or researchers is necessary to support problem solving. Our intent was to explore any differences that might emerge naturally, rather than to implement a specific intervention. As such, the teacher and researcher were not given instruction on how to assist students, they were simply told to provide help when needed. We anticipated that philosopical differences, knowledge, and experience would lead to different types of scaffolding. Philosophical differences were anticipated in that the teacher had a traditional approach to instruction, transmitting knowledge. The researcher, on the other hand, was influenced by a constructivist approach advocating student-directed learning. Moreover, the teacher was expected to have more pedagogical and content knowledge in biology, whereas the researcher was expected to have more BioWorld specific content and procedural knowledge about how to solve these problems.

The importance of feedback, be it human or computer generated (Azevedo & Bernard, 1995; Frederiksen et al., 1995; Graesser & Person, 1994; Lepper et al., 1993; Merrill et al., 1992, 1995), has proven effective given the right circumstances. Coaching in inquiry classrooms designed to build communities of learning (Polman & Pea, 1997) and explanations in general (whether generated by a peer or a teacher) have been found to facilitate reasoning (Okada & Simon, 1997). An exploration of how such tutors differ in the types of feedback they provide and how such feedback influences students' reasoning is important for informing future decisions regarding the use and development of BioWorld.

Methodology

Participants

A total of 40 grade 9 Biology students from an all girls private school in a metropolitan city participated in this study. This was a convenience sample in that the teacher had worked with us before and the school provided access to a fully equipped computer laboratory in which we could conduct our research with entire classrooms. The classroom teacher has been an active participant in the BioWorld project for several years. She volunteered to use BioWorld in two of her grade 9 biology classes, which she stated were of comparable ability level. This grade level is appropriate for investigating reasoning due to the variety of new scientific reasoning skills that develop and consolidate at the same time (Schauble et al., 1995). The teacher allowed students to choose their own partners for collaborative work, resulting in 20 groups in all. The entire sample was used for the first two research questions, whereas a subset of this sample was examined for the final research question. The sample was reduced for the third question since the teacher and researcher could only coach one group per classroom. Data from 6 groups were consequently examined; 3 groups from each classroom, resulting in 2 teacher-guided groups, 2 graduate student investigator-guided groups, and 2 BioWorld-only groups. The teacher selected these 6 groups as being equivalent in terms of their previous grades and ability to articulate their understanding. The teacher was an experienced biology teacher who has used BioWorld in her classrooms. The graduate student was part of the BioWorld design team who had experience in both the content knowledge and the types of reasoning possible within BioWorld, but whose knowledge of general biology was limited. The groups without human coaches relied on each other to reason through problems and they also had access to an on-line consult button that provided general hints that they could use to help them solve the problem.

The design

Two types of data were examined to answer each research question: computer and verbal data. Computer actions were dynamically collected by and stored in BioWorld at the completion of each problem. The dependent variables included frequency of symptoms collected, library entries made after making a diagnosis, evidence collected, diagnostic tests ordered, diagnostic accuracy, and the evidence contained in the first and final arguments. More specifically, each dependent variable was computed by BioWorld. For instance, each time a student selected symptoms from the patient scenario as evidence to be posted in the evidence palette, BioWorld would keep a record of when and where the symptom was collected. Likewise, records of when, where, what, and how many library entries were made for each problem were collected. The total amount of evidence collected during problem solving was also calculated (i.e., symptoms, diagnostic test entries, library information). The number of diagnostic tests was computed based on student entries in the patient chart. Diagnostic accuracy was based on whether or not the problems were solved. Final arguments were computed based on evidence listed in the argumentation palette.

For the first research question, student actions were compared to benchmarks of performance that were determined by teachers[3] and physicians as indicators of competence in scientific reasoning (see Lajoie et al., 1995). These competencies are established by recording the types of evidence these experts collect in the context of BioWorld to confirm a diagnostic hypothesis. Such evidence is gathered by identifying central information in the patient medical history, locating information in the library that is specific to the hypothesis or ordering diagnostic tests after inspecting the patient chart. Students are monitored in terms of how much evidence they collect that is relative to benchmarks that are established for each feature (see dependent variables). Proportion of overlap of student actions with a predetermined benchmark (i.e., based on the types of plans and actions experts would take in specific problems) was computed for each of the variables in question. An "interpretation approach" (Chi, 1997) was used in which computer data supplemented the verbal data in order to facilitate interpretation. More specifically, the verbal data provided information regarding the reasoning underlying computer actions.

In addition to these features, we were interested in student self-assessments as they related to learning. The focus for this second question was on students' confidence in their hypothesis development. A one-way RM ANOVA was used to examine changes in confidence from initial to final hypothesis. The third research question was whether or not different types of assistance would result in different patterns of use and learning outcomes. A MANOVA with condition (3) as between-subjects design was used with the same dependent measures as above (frequency of symptoms collected, library entries made after making a diagnosis, evidence collected, diagnostic tests ordered, diagnostic accuracy, and the evidence contained in the first and final arguments).

Procedure

The biology teacher worked with the researchers to select a set of digestion diseases that would fit her curriculum. Based on the teacher's suggestions, we created four patient scenario problems (i.e., ciliacs, shigellosis, hepatitis A, and cirrhosis) for groups to solve over a three-day period, each problem taking between 20–45 minutes resulting in 1–1.5 problems solved per class period (45 minutes). Multiple problems were developed since one episode is insufficient for valid assessment of learning, particularly in group settings (Williams, 1997). These problems were counterbalanced to avoid contamination from neighboring groups and to balance for potential problem difficulty. Verbal dialogues were audio/video taped and BioWorld recorded group actions as groups posted their evidence and completed the final argument after solving the problem. The teacher and one researcher were each available for assistance to one group in each class.

Results

The class variable was not of theoretical interest but was included in the design to control for possible differences. Given the small sample size, it was not possible to include the class variable along with the other independent variables of interest in a single analysis. Therefore, a one-way MANOVA with class as the between-subjects factor was performed to investigate whether or not there was a main effect of class on the dependent measures. An alpha level of .10 was adopted to compensate for the small sample size. Multivariate or univariate differences were not found for the class variable, therefore the data were collapsed across class for all subsequent analyses.

Group vs. expert use of BioWorld features

A pearson correlational analysis was performed to examine the effect of BioWorld features in terms of the relationship between group and expert actions. This analysis revealed a significant correlation between proportion of expert symptoms collected during problem representation and overall evidence collected that was expert-like (r = 0.59, p = 0.002). The declarative knowledge acquired in the library was positively correlated with the proportion of expert-like diagnostic tests ordered (r = 0.42, p = 0.04). Hence, declarative and procedural knowledge as defined in this study were correlated. Furthermore, those who scored high on collecting expert evidence also scored highly on expert-like diagnostic tests ordered (r = 49, p = 0.02). These findings suggest that (a) initial problem representation, as identified by symptoms that students select as relevant to their current hypothesis, is related to the amount of expert-like evidence collected overall, (b) information collected in the library is related to whether or not appropriate diagnostic tests are taken, (c) the ability to select relevant from irrelevant information is indicated by the proportion of expert-like evidence collected as it relates to total number of symptoms entered, and (d) final arguments were examined in terms of expert-like evidence selected.

Student dialogues during interactions support the computer trace data in that groups do use information from the disease library to form and revise their hypotheses about a patient's disease, as indicated by the following dialogue:

S1: What are you doing? [in hypothesis field]
S2: Going to another one. [another hypothesis]
S1: No, I don't think ... Oh my God. Why don't we look it up. Don't go. Okay keep it there. We'll look up another one. [points to the library]
S2: Okay, infectious mononucleosis.
S1: No, that's mononucleosis! That's mono. No, it's not that.
S2: Okay, headache, vomiting, fever. Fine. [points to evidence that the patient has these symptoms that are listed in the library]
S1: No, don't press ok! [on the belief meter]
It's already there.
S2: Okay, streptococcus.
S1: Okay, I think that's strep throat Student2. [points to library]
Go down.

Subsequently, good students, such as these, confirm their hypotheses by conducting the diagnostic tests associated with particular diseases. The dialogue below gives an example of test-taking strategies.

S1: It's normal. No wait ... I'm saying we're done.
S2: We'll do another one. Let's just do another one.
S1: Okay, okay.
S2: This one's unbelievable!
S1: Microbiology. Microbiology. Ok.
S2: Sputum, Sputum ... Go to sputum.
S1: Sputum? What's sputum? [giggling]
S2: Negative you moron! Look, we actually got something weird. What's that?
S1: I don't know. Total (bilirubin) Ok, so which one, in terms of highest ... ?
S2: It's ciliacs. Was it that?
S1: Yeah. Do you want to go back just to make sure?

At this point in the problem space students were conducting diagnostic tests that could confirm or disconfirm the hypothesis that the patient had mononucleosis or ciliacs disease. Even when one of the tests confirmed that the disease was ciliacs, students still went back to the library to check their interpretation of the test results. These verbal data correspond with the computer trace data, confirming that information collected in the library corresponded with appropriate test-taking strategies and expert evidence collected overall.

A more powerful representation of students' reasoning strategies is displayed in Figure 6, where a group was solving a shigellosis case. Students were provided with the problem representation found in Figure 7. The students first suggested that the disease was related to digestion and asserted that it was not ciliacs. Although one student suggested that it was a respiratory problem, the group returned to digestion and selected peptic ulcer as their hypothesis. They went to the library to gather more information about peptic ulcer but found no support for this hypothesis and moved on to explore the descriptions for gonorrhea and influenza. After making little progress they returned to the problem representation and collected 4 symptoms as evidence (diarrhea, vomiting, blood in the stool, and fever). They then posted shigellosis as their next hypothesis and conducted an AIDS test. This test-taking strategy was considered random since AIDS has no visible connection to shigellosis. After reviewing the evidence, the students decided that they needed to visit the library to see which tests would confirm or disconfirm that their patient had shigellosis. The following dialogue reveals the groups' reasoning and argumentation style.

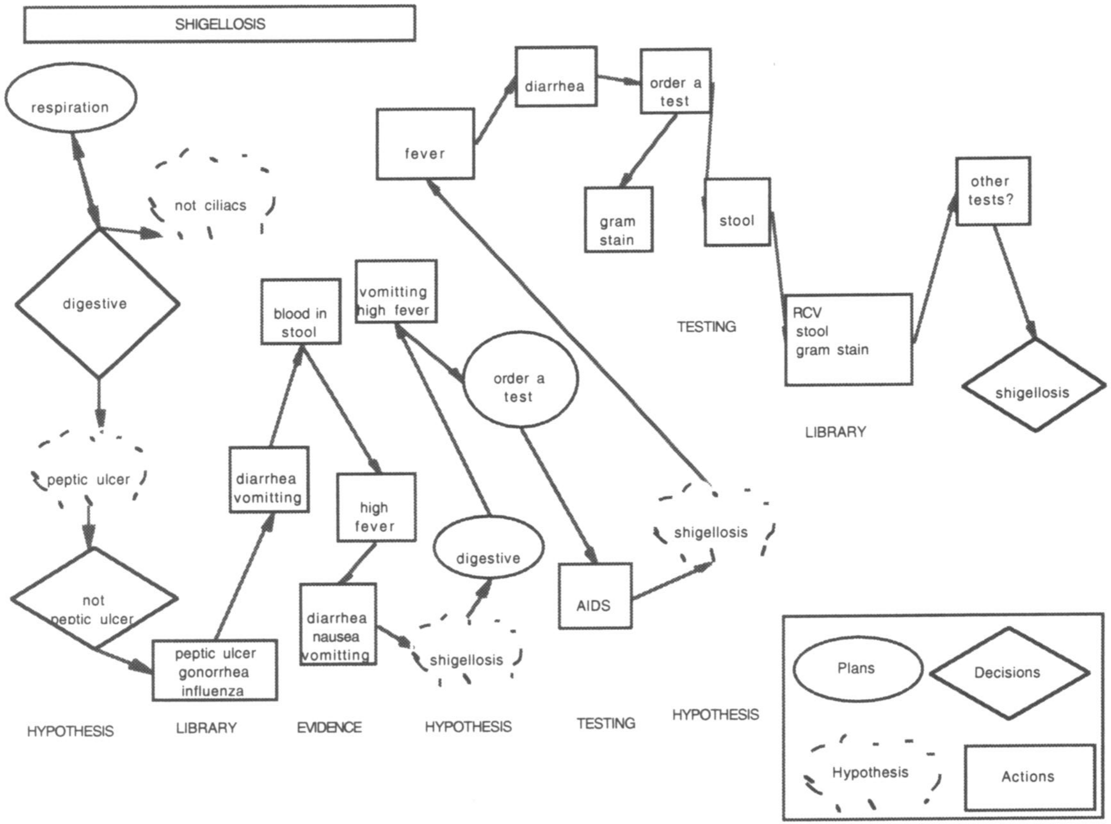

Figure 6. Solution trace for solving a shigellosis problem.

Problem Statement

Marie, a 4 month old infant has recently been exhibiting **fever** and **fussiness**. Her mom has given her tempra to reduce the fever and thought Marie was getting a cold. Within two days of showing the fever, Marie began to have severe **diarrhea** and **vomiting**. Her mom noticed small traces of **blood** in her diapers when changing her and thought she had better start washing her hands from now on after cleaning her diapers. After 4 days, Marie still did not seem to have a cold but was still suffering from a high fever. Her mom became very worried about her condition and decided to take her to their doctor. The doctor asked her mom if there was any possiblity that Marie may have somehow gotten near her soiled diapers or put her dirty hand from touching a diaper in her mouth. What illness do you think Marie has?

Expert Path

Gram's stain - gram-negative rod
Bacteria
Stool - Positive
Severe Diarrhea
Fussiness
Fever

Figure 7. Problem representation and expert path for shigellosis.

TESTS (Procedural Knowledge)

S15: Wait, wait, wait. Go back up. Okay, ummm ... what other tests could we do?
S16: What do you want me to do?
S15: Go back up. Stop. Sorry. What test do we take?
S16: We've done two already! We've just ... we've done two already.
S15: I know but they ... they weren't the right ones.
S16: No, they were good. She said ...
S15: (inaudible)
S16: We can still ...
S15: WBC. Okay wait.

HYPOTHESIS/CLOSING ARGUMENT

S15: Go back to the problem statement. (a couple of seconds elapse) How do we move it to certain? (silence for several seconds)

S16: Woo! (computer programs informs them that their diagnosis was correct)

EVIDENCE TABLE (Categorizing Evidence)

S15: Ah, we should have finished it, I'm sorry.

S16: Oh the symptoms ...
(alot of noise and experimenter also telling students that they can consult an expert through consult button)

S16: We should ... 'Cause that's not a symptom. I mean ... blood in the ah ... in the diaper.

S15: What? This is ...

S16: Yeah, but that's not a symptom.

S15: It is.

S16: No, it's not.

S15: Blood is in the stool.

S16: No! Vomiting and severe diarrhea is all a symptom but it's just that the person has blood in the diaper.

S15: Are you sure?

S16: (can't hear what she said)

S15: I don't think so.

S15: Yeah.

S16: Uh uh ... (i.e., no)

S15: Yeah. Yeah. Yeah.

S16: (mumbles)

S15: But not all human (something) diseases are going to have traces of blood in the diaper.

S15: Yes, but that's just one of the symptoms!

S16: I don't think so.

S15: Yes it is!

S16: Look, okay. Traces of blood yeah, but not in the diaper.

S16: (mumbles)

S15: I'm telling you!

S16: Go to the library ...

The last part of the dialogue reveals the amount of in-depth argumentation that occurred at the end of the problem when the students determined which evidence belonged in which category and whether or not it was important for solving the problem.

Relationship between confidence and argumentation and diagnostic accuracy

The computer data were also used to examine the relationship between confidence and diagnostic accuracy. Belief meter entries indicated how confident students were at the time of their first diagnosis (belief $M = -1.01$, $SD = 1.94$) and last diagnosis (belief $M = 14.08$, $SD = 6.36$). The belief meter values ranged from -6 to $+18$. Based on these values we found that students significantly increased their confidence about their diagnosis at the time of their final argument (one-way RM ANOVA, $F(1,19) = 51.042$, $p = 0.00$). These findings replicated our earlier work (Lajoie, 1993; Lajoie et al., 1996). Furthermore, confidence was tied to final diagnostic accuracy ($r = 0.51$, $p = 0.022$) but not to first hypothesis ($r = 0.232$, $p = 0.325$). As accuracy increased, confidence increased.

Exploration of coaching styles

A MANOVA was conducted to investigate the condition (3) effects of instruction on all dependent measures of interest. Again, an alpha level of 0.10 was adopted to compensate for the small sample size. No significant differences were found. A qualitative analysis of the verbal data from the two coached conditions demonstrated that a cognitive apprenticeship approach (Collins, Brown & Newman, 1989) to instruction was used by both teacher and graduate student. Both coaches started out being directive, modeling for the students what to look for in the context of a BioWorld problem, and later fading such directives. However, the types of directives between the two coaches differed.

Teacher guided. The teacher explicitly instructed and constantly guided students (e.g., reminding them to read all of the problem statement, telling them to go to specific parts of the library). In this sense, students in the teacher-guided condition were less responsible for their own learning. Although the teacher was an active participant of the group, pursuing answers to BioWorld questions, she still took a traditional role by telling students what to do and what to think about. The teacher directed students to consider what they learned in class by saying, "Remember when we talked about the digestive system in class. We talked about peptic ulcers related to the digestive system." Furthermore, the teacher frequently used concrete examples to link patient cases in BioWorld to real-life situations, thus helping students to understand what they were required to do. In the following example, the teacher links the BioWorld case to what a physician might do in that circumstance.

T: Let's look through this!
What is one of the most important things when you diagnose?
What do we have to do? We got to pick out symptoms right?
S8: Yeah. If you, if you go to the doctor and say what if he asks well ... (interrupts) Ok. Sorry.
T: Hi, I'm here. Fix me!
He says "Well, like how old are you?
Where have you been?
Like, do you have any hereditary (?) problems?"
S8: (adds) Personal history.
T: Okay.
He sees history but also ... What are you feeling like?
He needs to know that!
He needs to know what you feel like in order to diagnose.
So, let's look for yours. Okay.
S8: (looks at problem statement)

The teacher constantly pointed out the most salient information to students, reminding them what was important. In other words, the teacher served as a metacognitive aid, by prompting students by questions such as, what is one of the most important things to do when you make a diagnosis? Do you think it is important? These types of questions helped students by confining the problem space, helping them to efficiently arrive at a solution, and preventing them from going too far off track. The dialogue below is an example of the teacher's (T) interaction with one group (S1 and S2) regarding the types of diagnostic tests the group should perform and what the results mean.

T: Okay, so what kind of tests are we going to do?
S1: Serotypical?
T: Okay ... well let's go back to our testing ... patient chart
S2: Patient chart ... what tests are we going to order?
T: What are we going to look up?
S1: Serology
S2: I think it said something else
T: Okay, look at urinanlysis ... do we need to take a urine sample?
S2: No, it said Bilirubin
T: Neurobiology
S2: Internal biopsy ...
What about lactose intolerant?
T: Okay, ciliacs negative
S2: What do we have though?
T: You need to have positive ... so he doesn't have this

The above example clearly demonstrates how the teacher's explicit guidance led to student actions.

The graduate student as coach. The graduate student (GS) directed the biology students as well, but tended to use different amounts and types of scaffolding based on the groups' needs. For instance, with one group, the GS was similar to the teacher in that he directly told the group to perform a specific test but he gave explanations as to why such a test would rule out a diagnosis. The GS did help explain test results after they were conducted in terms of how they helped to rule out a diagnosis. The next dialogue illustrates an interaction between the GS with a group of students (S3 and S4). Notice that there is more explanation about why one would want to perform a diagnostic test and more discussion about what the results of such tests mean.

GS: But what do you think they (doctors) would do though at this point? 'Cause it could be salmonella.
I know that if you had salmonella you would also have diarrhea, vomiting, and fever.
So, what would a doctor do to rule out one diagnosis and prove another other? He'd probably run some kind of test right?

S3: Yeah.

GS: What do you think might say positive for shagala or shigellosis?

S4: Hmmm?

GS: What particular test might give you positive for shigellosis?
A microbiology test? or hematology test?

S3: Well, blood.

GS: Or if you checked their urine?

S3: Stool. Their stool.

GS: Yeah check stool. That's a good idea. Oh. So we got umm ...

S4: Positive, normal, negative.

GS: So, what does that mean? Interpret that result.

S4: That it's positive for stool.

GS: Shigalla.

S4: Yeah.

GS: He's positive for shigellosis.
So, what does that say about your diagnosis?

S4: That possibly it could be right.

GS: No, that you, that it

S3: is right

S4: is right.

GS: That you found shigellosis in this gentleman's stool.

With another group the GS was not as direct. Instead of telling students what to do the GS asked questions that compelled students to make inferences about what steps would lead to solutions. For example, he would use statements such as the following.

GS: That's good.
Give it some thought
Use your logic that you have at this point without any information.

S13: Hmm ... I know what one of these things is. (a couple of seconds elapse)
(to experimenter) Just guess anything?

GS: Just guess anything at this point.
What we're going to do after this is go and find information to support or deny the one you guessed at
You got shigellosis, that's probably a good idea.

Instead of telling students to perform a specific diagnostic test the GS tended to instruct students to support their diagnosis with evidence. These sorts of questions encouraged self-reflection and risk-taking. With this group the GS was less directive than with the previous group, demonstrating that he was flexible in the types of scaffolding he provided based on the individuals' needs.

BioWorld-alone group. Students in this condition worked independently without the help of a teacher or GS as coach. At the same time, they could select the on-line consult button for assistance from BioWorld for general hints on how to proceed in the context of where they were in the problem solving sequence. However, they did not use the consult button for any of the problems. Initially, this group spent time on insignificant details, such as choosing a name for themselves and wondering what they were supposed to do next. In the other 2 conditions, these issues were quickly resolved since the teacher and GS intervened. In the alone condition, students were dependent on the library to provide them with additional information and to clarify misconceptions, whereas in the other conditions students simply asked their coach, saving them the step of looking up information in the library. The benefit of working alone with BioWorld is that students generated their own hypotheses, and followed up on their own problem solving strategies. Often they would pursue differential hypotheses in that they collected information on more than one hypothesis at a time. In the teacher and GS conditions students were sometimes thwarted from following through on hypotheses since they were perceived as unlikely possibilities. The following example from a teacher group demonstrates that students are not always given opportunities to learn from their own mistakes.

S8: What about cirrhosis?
T: No that is with the liver ... remember the alcohol ... he has no drinking problem

In a second example the graduate student does the same thing.

S: What's cirrhosis?
GS: I don't think a baby would have cirrhosis because it's usually related to alcohol.

These 2 examples clearly demonstrate how to prevent students from going down incorrect paths. However, there may be times that such explorations allow students to build their own conceptual understandings of the problem case and help them identify what forms of evidence confirm or disconfirm their diagnoses.

Summary

The exploratory information on human tutoring conditions compared to BioWorld alone is preliminary; however they can provide direction for more empirical studies of the effects of coaching on learning in this type of problem-based computer learning environment. Although, both human tutors demonstrated a loose connection to a cognitive apprenticeship model of instruction, where they scaffolded learners by modeling and fading assistance, they differed in the style of scaffolding. The teacher was more directive in the types of scaffolding she gave to her groups, whereas the GS chose different types of scaffolding based on his groups. In one group, he was similar to the teacher in that he was very directive. With another group he was much more tacit in the types of assistance he gave, by being more didactic rather then telling students what to look up. In the latter case, students were encouraged to be more self-reflective and systematic in the information they collected regarding their hypotheses. In the BioWorld-alone group, students did not select the on-line computer consultant. Rather, they consulted each other for what they should do next, and collected a great deal of information in the library to acquire knowledge about the disease. Although there were no condition effects (all 3 conditions solved problems in BioWorld) differences in the way students acquired such knowledge are possible. In addition, there may be better ways for students to learn, with human scaffolding or without. These issues need to be followed up in future studies using BioWorld with larger samples.

Conclusions

BioWorld teaches students about the processes of scientific reasoning within a problem-based learning context, and demonstrates that students can learn about diseases efficiently. In fact, 90% of the students who participated in this study solved the problems. This percentage is quite high considering that problem solving about diseases was a new experience for these students. Students who learned to reason scientifically with BioWorld did so in an efficient manner, taking less time, and needing fewer actions than students who did not make an accurate diagnosis. This finding indicates that the type of search strategies used by successful students were different than less successful students.

More in-depth examinations of the computer-trace data in parallel with the verbal data reveals that various features within BioWorld afford more opportunities for reasoning than other features. A strong relationship was found between how students interpreted the initial problem representation as presented in the patient case scenario, and in the amount of expert-like evidence they collected overall. This finding supports the literature on problem solving suggesting that individuals differ in their ability based on how they initially represented the problem (Mayer, 1983). The on-line library had a strong impact on students as indicated by the fact that those who made frequent visits to the library took more expert-like diagnostic tests. This finding supports Anderson's (1983, 1993) learning model, where declarative and procedural knowledge are interwoven, with declarative preceding procedural knowledge. Finally, the fact that students could differentiate between relevant and irrelevant information was determined by the proportion of expert-like evidence collected throughout BioWorld, another dimension of emerging proficiency (Chi et al., 1988).

The idea of face-to-face communication is not new and the reported advantages of small group activities include greater learning, improved productivity, more time on task, higher motivation, and an increased sense of competence (Johnson & Johnson, 1989; Rysavy & Sales, 1991; Sharan, 1980; Slavin, 1990a, 1990b). Ideally, collaborative group work provides opportunities for exposure to multiple points of view, thereby allowing learners to consider issues that would not have been salient had they been working independently (Shute et al., in press). The argumentation and reasoning patterns collected with BioWorld support the research on collaborative learning in that sophisticated patterns of scientific reasoning were found in small group learning situations. However, more research is needed to see how groups reason across various problems within BioWorld to see how reasoning evolves with practice and with different diseases. Barron et al. (1998) suggest that using contrasting cases facilitates transfer of learning since students analyze the differences between examples. BioWorld encourages transfer since it presents multiple contrasting cases within body systems and encourages students to reflect on the relevant categories of information. BioWorld's explicit argumentation palette directs students to both categorize the evidence that they have posted as well as prioritize its importance.

It is evident that BioWorld students can make an assertion (or hypothesis) and support it by collecting appropriate data, supporting Kuhn's (1997) assumption that students can demonstrate early competence in scientific investigation. However, it is too early to make generalizations. It is highly probable that problem or case difficulty influences problem-solving strategies as well. By having students construct and communicate their thoughts verbally, the hope is that group problem-solving activities will encourage learners to explain, justify, and negotiate meanings.

A strong relationship between student confidence and knowledge acquisition was found which replicated our earlier studies with BioWorld. As students acquired knowledge dynamically within the environment their confidence about their diagnoses increased. Confidence is a true indicator of students' diagnostic accuracy. This is an encouraging result since the learners' ability and confidence are bound together in a healthy manner, meaning that students have revealed self-efficacy as opposed to learned helplessness. In other words, students who are accurate believe that they are accurate. In some studies, students could be accurate but not believe in their abilities (Dweck, 1986). Short and Weissberg-Benchell (1989) coined the term "triple alliance for learning," and provide a theoretical framework that weds metacognition, cognitive strategies, and motivation to performance outcomes (see Snow, 1989 for an alternative position). This alliance is provided for within BioWorld since metacognition is scaffolded through the argumentation and evidence palettes and motivation is dynamically monitored in terms of student confidence. Motivation theories indicate that success and failure episodes in learning will affect whether students approach or avoid specific learning situations in the future (Lajoie, 1991). Students self-assess their understanding about the disease process in their voicing of their confidence levels about their hypotheses. Students' confidence increases as they gain knowledge about the disease while solving problems within BioWorld. This finding supports the assumption that cognition and motivation are wedded (Lepper et al., 1993).

In examining different types of instructional conditions, coaching vs. no coaching, we found differences in tutoring strategies between a teacher and a GS. Interestingly enough, there were no differences in student success based on whether they had human tutoring or were working with a standalone computer with their peers. BioWorld provides a mechanism for student-directed learning where minimal assistance is needed. However, instructional condition did have some effects on learning processes. The dialogues revealed that the teacher differed from the GS in that she directed students to look up specific information in the library, whereas the investigator asked questions where students would have to infer where to look up information. In the non-coached condition, students seem to become expert-like in their use of BioWorld without assistance from others. In fact, working together with peers in a problem-based learning environment, such as this, may be sufficient scaffolding to support the acquisition of scientific reasoning skills. However, there is still much to be explored in terms of the nature of human tutoring, and how it promotes scientific discourse, reasoning and learning in these types of learning environments. Once we understand how different forms of scaffolding promote learning, then better forms of scaffolding could be included within these computer-based learning environments.

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Notes

1. Much of the work on the evidence and argumentation palettes in BioWorld can be attributed to Jim Greer's contribution to the BioWorld project while on Sabbatical Leave at McGill.
2. By declarative and procedural knowledge we refer to the well-established distinction made by Anderson (1983, 1993).
3. Not the teacher who participated in the teacher condition.
4. The second author, Nancy Lavigne, is currently a Post-Doctoral Fellow at the Learning Research and Development Centre, University of Pittsburgh.

References

American Association for the Advancement of Science (1989). *Project 2061: Science for all Americans*. D.C.: AAAS Publications.

American Association for the Advancement of Science (in prep). *Resources for scientific literacy: Curriculum materials*. (American Association for the Advancement of Science Project No. 2061).

Amsel, E. & Brock, S. (1996). The development of evidence evaluation skills. *Cognitive Development* 11: 523–550.

Anderson, J.R. (1983). *The Architecture of Cognition*. Cambridge, MA: Harvard University Press.

Anderson, J.R. (1993). *Rules of the Mind*. Hillsdale, NJ: Erlbaum.

Azevedo, R. & Bernard, R.M. (1995). A meta-analysis of the effect of feedback in computer-based instruction. *Journal of Educational Computing Research* 13(2): 109–125.

Barron, B.J.S., Schwartz, D.L. Vye, N.J., Moore, A., Petrosino, A., Zech, L., Bransford, J.D. & The Cognition and Technology Group at Vanderbilt (1998). Doing with understanding: Lessons from research on problem and project-based learning. *The Journal of the Learning Sciences* 7(3&4): 271–311.

Barrows, H.S. (1986). A taxonomy of problem-based learning methods. *Medical Education* 20: 481–486.

Barrows, H.S. & Myers, A.C. (in prep.). Problem-based learning: A total approach to education. In H. Barrows & A. Kelson, eds, *Problem-Based Learning*.

Brown, A.L. (1997). Transforming schools into communities of thinking and learning about serious matters. *American Psychologist* 52(4): 399–413.

Bruning, R.H., Schraw, G.J. & Ronning, R.R. (1995). *Cognitive Psychology and Instruction*. Englewood Cliffs, NJ: Merrill.

Cadigan, J.J. (1993). The making of a scientist or engineer. In R. Ruopp, S. Gal, B. Drayton & M. Pfister, eds, *LabNet: Toward a Community of Practice*, pp. 200–204. Hillsdale, NJ: Erlbaum.

Chi, M.T.H. (1997). Quantifying qualitative analyses of verbal data: A practical guide. *The Journal of the Learning Sciences* 6(3): 271–315.

Chi, M.T.H., Glaser, R. & Farr, M. (1988). *The Nature of Expertise*. Hillsdale, NJ: Erlbaum.

Collins, A. (1997). National science educational standards: Looking backward and forward. *The Elementary School Journal* 97(4): 299–313.

Collins, A., Brown, J.S. & Newman, S.E. (1989). Cognitive apprenticeship: Teaching the craft of reading, writing, and mathematics, In L.B. Resnick, ed., *Knowing, Learning, and Instruction: Essays in Honor of Robert Glaser*, pp. 453–494. Hillsdale, NJ: Erlbaum.

de Jong, T. & van Joolingen, W. R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research* 68(2): 179–201.

Dunlosky, J. (1998). Epilogue: Linking metacognitive theory to education. In D.J. Hacker, J. Dunlosky & A.C. Graesser, eds, *Metacognition in Educational Theory and Practice*, pp. 367–381. Mahwah, NJ: Erlbaum.

Dweck, C. (1986). Motivational processes affecting learning. *American Psychologist* 41: 1040–1048.

Flavell, J.H. (1979). Metacognition and cognitive monitoring: A new area of cognitive-developmental inquiry. *American Psychologist* 34: 906–911.

Frederiksen, C.H., Roy, M. & Bedard, D. (1995). Discourse processing in situated learning: Learning through tutorial dialogue in a complex domain. In J.D. Moore & J.F. Lehman, eds, *Proceedings of the Seventeenth Annual Conference of the Cognitive Science Society*, pp. 643–647. Mahwah, NJ: Erlbaum.

Gallagher, S.A., Stepien, W.J., Sher, B.T. & Workman, D. (1995). Implementing problem-based learning in science classrooms. *School Science and Mathematics* 95: 136–146.

Galotti, K.M. (1989). Approaches to informal and everyday reasoning. *Psychological Bulletin* 105(3): 331–351.

Graesser, A. & Person, N. (1994). Question asking during tutoring. *American Educational Research Journal* 31(1): 104–137.

Hacker, D.J. (1998). Definitions and empirical foundations. In D.J. Hacker, J. Dunlosky & A.C. Graesser, eds, *Metacognition in Educational Theory and Practice*, pp. 1–23. Mahwah, NJ: Erlbaum.

Haury, D.L. (1993). *Teaching Science Through Inquiry*. Columbus, OH: Clearinghouse for Science, Mathematics, and Environmental Education (ERIC Reproduction Document No. ED 359 048).

Hemple, C. (1961). *Philosophy of Natural Sciences*. Englewood Cliffs, NJ: Prentice-Hall.

Hoffman, B. & Ritchie, D. (1997). Using multimedia to overcome the problems with problem-based learning. *Instructional Science* 25: 97–115.

Johnson, D.W. & Johnson, R.T. (1989). *Cooperation and Competition: Theory and Research*. Edina, MN: Interaction Book Company.

Johnson, M.A. & Lawson, A.E. (1998). What are the relative effects of reasoning ability and prior knowledge on biology achievement in expository and inquiry classes? *Journal of Research in Science Teaching* 35(1): 89–103.

Jonassen, D.H. (1996). *Computers in the Classroom: Mindtools for Critical Thinking*. Columbus, OH: Prentice Hall.

Jonassen, D.H. & Reeves, T.C. (1996). Learning with technology: Using computers as cognitive tools. In D.H. Jonassen, ed., *Handbook of Research for Educational Communications and Technology*, pp. 693–719. NY: Macmillan.

Klahr, D., Fay, A.L. & Dunbar, K. (1993). Heuristics for scientific experimentation: A developmental study. *Cognitive Psychology* 25: 111–146.

Kommers, P., Jonassen, D.H. & Mayes T., eds (1992). *Cognitive Tools for Learning*. Berlin: Springer.

Koschmann, T.D., Myers, A.C., Feltovich, P.J. & Barrows, H.S. (1994). Using technology to assist in realizing effective learning and instruction: A principled approach to the use of computers in collaborative learning. *The Journal of the Learning Sciences* 3(3): 227–264.

Kuhn, D., Amsel, E. & O'Loughlin, M. (1988). *The Development of Scientific Thinking Skills*. San Diego, CA: Academic Press.

Kuhn, D. (1989). Children and adults as intuitive scientists. *Psychological Review* 36(4): 674–689.

Kuhn, D. (1991). *The Skills of Argument*. Cambridge, MA: Cambridge University Press.

Kuhn, D. (1997). Constraints or guideposts? Developmental psychology and science education. *Review of Educational Research* 67(1): 141–150.

Kuhn, D., Shaw, V. & Felton, M. (1997). Effects of dyadic interaction on argumentative reasoning. *Cognition and Instruction* 15(3): 287–315.

Lajoie, S.P. (1991). Reality testing for cognitive strategy research. *Educational Researcher* 20(3): 30–33.

Lajoie, S.P. (1993). Computer environments as cognitive tools for enhancing learning. In S.P. Lajoie & S.J. Derry, eds, *Computers as Cognitive Tools*, pp. 261–288. Hillsdale, NJ: Erlbaum.

Lajoie, S.P., ed. (in press). *Computers as Cognitive Tools II: No More Walls: Theory Change, Paradigm Shifts and Their Influence on the Use of Computers for Instructional Purposes.* Mahwah, NJ: Erlbaum.

Lajoie, S.P. & Derry, S.J., eds. (1993). *Computers as Cognitive Tools*. Hillsdale, NJ: Erlbaum.

Lajoie, S.P., Greer, J.E., Munsie, S.D., Wilkie, T.V., Guerrera. C. & Aleong, P. (1995). Establishing an argumentation environment to foster scientific reasoning with Bio-World. In D. Jonassen & G. McCalla, eds, *Proceedings of the International Conference on Computers in Education*, pp. 89–96. Charlottesville VA: Association for the Advancement of Computing in Education.

Lajoie, S.P., Munsie, S.D. & Lavigne, N.C. (1996, April). Examining the relationship between evidence and argumentation in Bio-World. *Presented at the annual meeting of the American Educational Research Association*. New York, NY.

Leach, J. (1997, March). Students' understanding of the coordination of theory and evidence in science. *Paper Presented at the Annual Meeting of the American Educational Research Association*. Chicago, IL.

Lepper, M.R., Woolverton, M., Mumme, D.L. & Gutner, J. (1993). Motivational techniques of expert human tutors: Lessons for the design of computer-based tutors. In S.P. Lajoie & S.J. Derry, eds, *Computers as Cognitive Tools*, pp. 75–106. Hillsdale, NJ: Erlbaum.

Lesgold, A. (1988). Problem solving. In R. Sternberg & E. Smith, eds, *The Psychology of Human Thought*, pp. 188–21. NY: Cambridge University Press.

Linn, M.C. (1992). Science education: Building on the research base. *Journal of Research in Science Teaching* 29: 821–840.

Linton, F. (1995). Intellectual skills and cognitive strategies: Can one method tutor both? In J. Greer, ed., *Proceedings of the World Conference on Artificial Intelligence and Education*, pp. 445–452. Washington, DC: Association for the Advancement of Computing in Education.

Mayer, R. (1983). *Thinking, Problem Solving and Cognition*. NY: W. H. Freeman and Company.

Mayer, R. (1998). Cognitive, metacognitive, and motivational aspects of problem solving. *Instructional Science* 26: 40–63.

McCade, J. (1995). Educational reform and technology education. *The Technology Teacher* 54: 31–39.

Means, M.L. & Voss, J.F. (1996). Who reasons well? Two studies of informal reasoning among children of different grade, ability, and knowledge levels. *Cognition and Instruction* 14(2): 139–178.

Merrill, D., Reiser, B., Merrill, S. & Landes, S. (1995). Tutoring: Guided learning by doing. *Cognition and Instruction* 13(3): 315–372.

Merrill, D., Reiser, B., Ranney, M. & Trafton, J.G. (1992). Effective tutoring techniques: A comparison of human tutors and Intelligent Tutoring Systems. *The Journal for the Learning Sciences* 2(3): 277–305.

Metz, K.E. (1995). Reassessment of developmental constraints on children's science instruction. *Review of Educational Research* 65: 93–127.

Metz, K.E. (1997). On the complex relation between cognitive developmental research and children's science curricula. *Review of Educational Research* 67(1): 151–163.

National Academy of Sciences (1994). *National Science Education Standards*. Washington, DC: National Academy Press.

National Research Council (1995). *National Science Education Standards*. Washington, DC: National Academy Press.

National Science Teachers Association (1996). *Pathways to Science Education Standards*. Arlington, VA: Author.

Nelson, T.O. (1999). Cognition versus metacognition. In R.J. Sternberg, ed., *The Nature of Cognition*, pp. 625–641. Cambridge, MA: MIT Press.

Norman, D.A. (1983). Some observations on mental models. In D. Gentner and A.L. Stevens, eds, *Mental Models*, pp. 7–14. Hillsdale, NJ: Erlbaum.

Okada, T. & Simon, H.A. (1997). Collaborative discovery in a scientific domain. *Cognitive Science* 21(2): 109–146.

Pea, R.D. (1985). Beyond amplification: Using the computer to reorganize mental functioning. *Educational Psychologist*,20: 167–182.

Perkins, D.N. (1985). The fingertip effect: How information processing technology shapes thinking. *Educational Researcher* 14: 11–17.

Polman, J. & Pea, R.D. (1997, March). Transformative communication in project science learning discourse. *Paper Presented at the Annual Meeting of the Educational Research Association*. Chicago, IL.

Resnick, L.B. (1987). Learning in school and out. *Educational Researcher* 16: 13–20.

Resnick, L.B., Salmon, M., Zeitz, C.M., Wathen, S.H. & Holowchak, M. (1993). Reasoning in conversation. *Cognition and Instruction* 11(3&4): 347–364.

Roth, W.-M. & McGinn, M.K. (1997). Graphing: Cognitive ability or practice? *Science Education* 81(1): 91–106.

Roth, W.M., McGinn, M.K. & Bowen, B.M. (1996). Applications of science and technology studies: Effecting change in science education. *Science Technology and Human Values* 21: 454–484.

Rysavy, D.M. & Sales, G.C. (1991). Cooperative learning in computer-based instruction. *Educational Technology Research amd Development* 39(2): 70–79.

Salomon, G., Perkins, D.N. & Globerson, T. (1991). Partners in cognition: Extending human intelligence with intelligent technologies. *Educational Researcher* 20: 10–16.

Schauble, L., Glaser, R., Duschl, R.A., Schulze, S. & John, J. (1995). Students' understanding of the objectives and procedures of experimentation in the science classroom. *The Journal of the Learning Sciences* 4(2): 131–166.

Schoenfeld, A.H. (1999). Looking toward the 21st century: Challenges of educational theory and practice. *Educational Researcher* 28(7): 4–14.

Schraw, G. (1998). Promoting general metacognitive awareness. *Instructional Science* 26: 113–125.

Sharan, S. (1980). Cooperative learning in small groups: Recent methods and effects on achievement, attitudes, and ethnic relations. *Review of Educational Research* 50: 241–271.

Short, E.J. & Weissberg-Benchell, J.A. (1989). The triple alliance for learning: Cognition, metacognition, and motivation. In C.B. McCormick, G. E. Miller, M. Pressley, eds, *Cognitive Strategy Research*, pp. 33–63. NY: Springer-Verlag.

Shute, V.J. (1993). A comparison of learning environments: All that glitters. In S.P. Lajoie & S.J. Derry, eds, *Computers as Cognitive Tools*, pp. 47–74. Hillsdale, NJ: Erlbaum.

Shute, V.J. & Glaser, R. (1990). A large-scale evaluation of an intelligent discovery world: Smithtown. *Interactive Learning Environments* 1: 51–77.

Shute, V.J., Lajoie, S.P. & Gluck, K. (in press). Individual and group approaches to training. In S. Tobias & H. O'Neill, eds, *Handbook on Training*. Washington, DC: American Psychological Association.

Slavin, R.E. (1990a). *Cooperative Learning: Theory, Research, and Practice*. Englewood Cliffs, NJ: Prentice Hall.

Slavin, R.E. (1990b). Research on cooperative learning: Consensus and controversy. *Educational Leadership* (December 1989/January 1990) 47: 52–54.

Sodian, B. (1997, March). Young children's ability to test their own causal beliefs. *Paper Presented at the Annual Meeting of the American Educational Research Association*. Chicago, IL.

Snow, R.E. (1989). Toward assessment of cognitive and conative structures in learning. *Educational Researcher* 18(9): 8–14.

Sternberg, R. (1998). Metacognition, abilities, and developing expertise: What makes an expert student? *Instructional Science* 26: 127–140.

Suthers, D., Weiner, A., Connolly, J. & Paolucci, M. (1995). Belvedere: Engaging students in critical discussion of science and public policy issues. In J. Greer, ed., *Proceedings of the World Conference on Artificial Intelligence and Education*, pp. 266–273. Washington, DC: Association for the Advancement of Computing in Education.

Tobin, K., Kahle, J.B. & Fraser, B.J., eds (1990). *Windows into Science Classrooms: Problems Associated with Higher-Level Cognitive Learning*. Philadelphia, PA: The Falmer Press.

Toulmin, S.E. (1958). *The Uses of Argument*. Cambridge University Press.

van Joolingen, W.R. & de Jong, T. (1997). An extended dual search space model of scientific discovery learning. *Instructional Science* 25: 307–346.

van Joolingen, W.R. & de Jong, T. (1991). Supporting hypothesis generation by learners exploring an interactive computer simulation. *Instructional Science* 20: 359–404.

Williams, J. (1997, March). Scientific dialogue as evidence of learning. *Paper Presented at the Annual Meeting of the American Educational Research Association*. Chicago, IL.

Winne, P.H. (1997). Experimenting to bootstrap self-regulated learning. *Journal of Educational Psychology* 89(3): 397–410.

Wolters, C.A. & Pintrich, P.R. (1998). Contextual differences in student motivation and self-regulated learning in mathematics, English, and social studies classrooms. *Instructional Science* 26: 27–47.