OBSERVING THE SEEN AND UNSEEN: COMPUTER AND SOCIAL MEDIATION OF A COMPLEX BIOLOGICAL SYSTEM

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ABSTRACT
Working from a theoretical framework in which knowledge is socially constructed, this case study traces how computer and human interventions mediate one group of middle school students' observations of an aquatic ecosystem. Data sources included videotaped classroom observations as well as student artifacts, including worksheets and models of an aquarium system. Analysis suggests that the combination of both human and computer mediation is synergistic. The kinds of questions teachers and students ask during computer-supported inquiry scaffold students' observations of the computer simulations and support new connections between the seen (i.e., macro) and unseen (i.e., micro) levels of complex systems when students construct new models. These findings have implications for the design of computer-based tools and classroom instruction.

KEYWORDS
complex systems, modeling, scientific observation

INTRODUCTION

Observation is a complex practice that is fundamental to scientific activity and to all scientific disciplines (Daston, 2008; Norris, 1984). Far from simple, systematic observation necessitates noticing and representing theoretically relevant dimensions of phenomena, including phenomena that are visible and invisible to the unaided eye (Eberbach & Crowley, 2009). This is made even more challenging when learning to observe complex systems, which requires that learners notice the behavioral and functional connections between the macro and micro parts of a system (Assaraf & Orion, 2005; Chi, DeLeeuw, Chiu, & La Vancher, 1994; Feltovich, Coulson, & Spiro, 2001). Given these challenges, it may be useful to understand the instructional conditions under which students begin to notice and reason with observational evidence. Thus, we ask two research questions: (1) How can computer tools and social mediation support student observations of biological processes generally, and the macro and micro levels of complex systems specifically; and (2) What role do teachers' questions play in mediating student observation of complex systems? We add to the existing literature with our focus on learning to observe scientifically, which is rarely the focus of learning research (Ford, 2005; Smith & Reiser, 2005).

Computer-based learning tools provide exceptional opportunities for students to participate in authentic inquiry practices, such as observing, hypothesis testing, and constructing explanations (Lee & Songer, 2003). These tools typically depend upon the use of simulations that generate dynamic feedback (Wilensky & Reisman, 2006). Such simulations draw attention to system behaviors so that learners have repeated opportunities to observe the effect of one component on other system components. Additionally, computer-generated models provide learners with opportunities to generate, compare, and adjust representational tools in ways that support conceptual change (Lajoie, Lavigne, Guerrera, & Munsie, 2001; Roschelle, 1996).

Although computer-supported inquiry tools offer a critical means for learning about complex systems, such tools may prove to be a necessary but insufficient condition for learning (Hmelo-Silver, Liu, Gray, & Jordan, in review). In actual classroom practice, computer-supported inquiry is a demanding undertaking in which students need teachers to scaffold learning experiences if they are to engage in productive inquiry practices (Tabak, 2004). Working from a theoretical framework in which knowledge is socially constructed (Bransford, Brown, & Cocking, 1999; de Jong & Joolingen, 1998; Palincsar, 1998), we are interested in how computer tools and social interactions—teacher-to-student and student-to-student—support complex observations of complex biological systems. Because our research is exploratory, we use a case study approach to closely examine events as they unfold in order to identify critical episodes and potentially important trends (Yin, 2008). In this way, we trace how computer and human interventions mediate one group of middle school students' observations of the macro levels (i.e., those parts that are visible to the unaided eye, such as fish, water, fish food) and micro levels (i.e., those parts that require tools to observe, such as bacteria, biochemical processes) of an aquatic ecosystem.

METHODS

Study Context and Participants
This study is part of a larger program of design research that develops and investigates a suite of computer-based and instructional interventions that facilitate middle school students' understanding of complex natural systems. In this paper, we describe three episodes from a 7th grade classroom where students are learning about an aquarium system. These episodes are featured because each includes computer, teacher, and student mediation of complex observational activity. With 17 years of experience, Ms Garrison, is an experienced science educator who is both knowledgeable and enthusiastic about ecosystems. Her instructional style is to ask questions that guide students' problem-solving activities and that draw attention to critical structures, behaviors, and functions of phenomena. We focus on one of two groups nominated by the teacher and the group with the better quality video. Although we cannot speak to how representative this group is of the rest of the class, the group consisted of three girls who appeared comfortable using the computer tools and whose individual behavior suggested varying levels of knowledge and interest. Like other groups, these students shared a 12" Macbook computer, which they huddled around to view the screen and moved between them to enter information.

Computer Tools
The computer-learning environment included an integrated suite of three tools. First, RepTools hypermedia uses function-oriented questions (e.g., *why do fish breathe*) to guide students through domain content (Liu & Hmelo-Silver, 2009). Starting with these questions, students clicked through multiple screens to find information about the behaviors and structures of aquarium systems. Second, NetLogo simulations of an aquarium environment enable users to manipulate variables in order to observe their effect on a system's various levels (Wilensky & Reisman, 2006). Specific to this analysis, students used the Fish Spawn simulation (see Figure 1) to observe an aquarium's macro level and the Nitrification simulation (see Figure 2) to observe its micro level. Finally, students used the Aquarium Construction Tool (ACT) to create models that displayed the functional relationships between a system's structures (Vattam, Goel, Rugaber, Hmelo-Silver, & Jordan, 2009). Students entered information about an aquarium's system to create models that made their thinking visible.

Data and Analysis
Data sources consist of video-recordings of students and the teacher in the classroom, researcher field notes, and where relevant, student-generated models and worksheets. Video focused on what students appeared to observe on the computer screen, but also captured their interactions with each other, the teacher, and the computer. Because this is a preliminary analysis, we used an iterative deductive and inductive approach in which we initially viewed the video with certain expectations but were open to unanticipated phenomena and interactions (Derry et al, 2010; Powell, Francisco, & Maher, 2003). We explore student and teacher discourse, with a particular interest in the role of questions. In general, we

expected that asking questions would be an important strategy for learning to observe scientifically, but adjusted our expectations about the kinds of questions that appear to support the observation of relationships between an aquarium's structures, behaviors, and functions. Prior science education research suggests that use of *how* and *why* questions that focus on behavior and function are more scientifically valuable than simple *what* questions that focus on the identification of structural components (e.g., Abrams, Southerland, & Cummins, 2001). However, in this context, the use of *what* questions appeared to be an effective strategy for stimulating productive observations and complex reasoning.

RESULTS

Observing the Macro Level: "What are all those yellow things?"

Episode one occurs midway through the curriculum unit. In prior instruction, the teacher used whole class discussion and small group activity to introduce students to the parts, behaviors, and functions of an aquarium system and to familiarize students with the hypermedia and ACT programs. Ms Garrison begins this class by orienting students to the NetLogo Fish Spawn simulation (Figure 1), which is designed to explore relationships between the growth of the fish population, the amount of food, and the quality of the water. Ms Garrison orients students to the simulation screen, variables, data outputs (i.e., frequency boxes and graph), and the operating buttons. The simulation screen features fish that are pink (female) and blue (male), and large (adult) and small (spawn). The screen also includes abstract yellow squares, a design feature that the teacher exploits and that becomes central to our narrative.

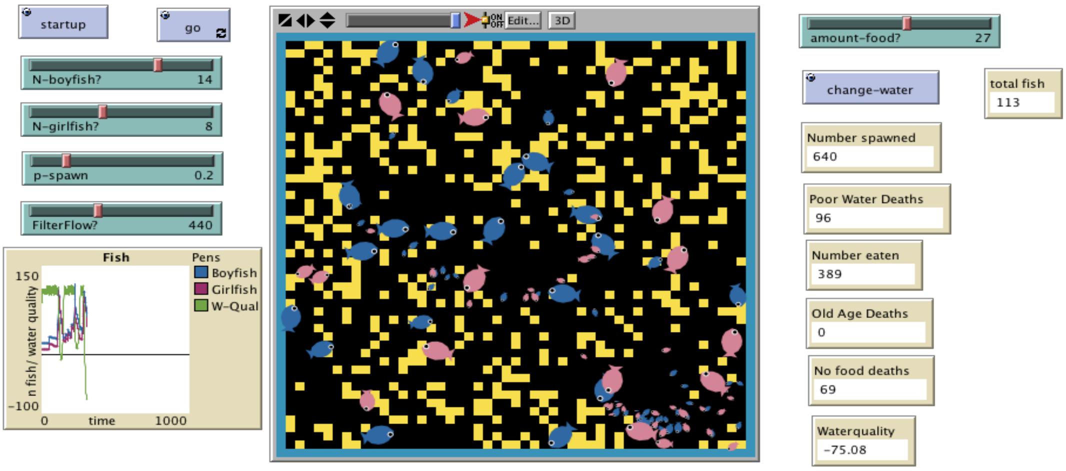

Figure 1. Screenshot of the Fish Spawn simulation

During the orientation, one student group—Mary, Shruti, and Erica—is already busy pushing buttons, changing variable amounts, and looking at the simulation screen. Shruti quietly asks, "What are all those yellow things?" Receiving no response, she repeats the question. This time Ms Garrison responds, "That's something you are going to find out." In fact, this question is also of special interest to the teacher. Not only does she include it in a worksheet she designed to accompany student activity, she also concludes the orientation by instructing each group to figure out, "What do the yellow squares represent?" In doing so, she effectively cues students about what is important to notice.

The quest to figure out the identity of the yellow squares drives many the interactions between students, the teacher, and the simulation. Students begin by playing with the simulation, randomly changing variables, and changing the speed of the simulation. They appear to focus on the simulation screen. After some time, Shruti notices that the fish appear to pass over the yellow squares at which point the yellow disappears from view. Noticing this pattern, she returns to her original question:
Shruti: They (*fish*) get a lot of food. Is the yellow the food?"

Ms G: Is what?
Shruti: yellow the food?
Erica: Is the yellow the eggs?
Ms G: No.
Shruti: Is it the food?
Ms G: No.
Mary: Then what is it? The algae?

Once the teacher moves to another group, the girls begin an iterative cycle in which they restart the simulation, view the simulation screen, note behavior, and make some guesses (e.g., waste? oxygen?), without making progress. But clearly, other students are having difficulty figuring out what the yellow squares are when Ms Garrison asks the class, "Has anyone figured out what the yellow patches are?" When another group announces that the yellow is food, Shruti protests, "Hey! That's what we said and you said wrong." The teacher replies, "That's a good guess," but indicates they need to do more investigation. The girls now turn their attention to the data output boxes and start randomly calling out numbers that appear. They notice emerging trends and begin comparing multiple outputs and inputs:
Shruti: The number (*of fish*) eaten keeps going up!
Erica: Now the total fish is 76.
Shruti: Who's eating the other fish?
Erica: 92! Oh! We just got more. 112!
Shruti: Why are so many fish getting eaten? It says poor water deaths.
Erica: 132!
Shruti: All the fish are dying from poor water too.
Mary: Poor water? We have good water! We changed it like a million times!
Shruti: No, I made the water quality 100—1,000% (*refers to water flow*)

The simulation screen is quickly filling with yellow squares when Erica observes, "none of the fish are dying from no food." Having previously noted that so many fish deaths are related to being eaten, the girls now notice that the fish are also dying from poor water quality. Shruti cannot figure out why fish are dying from poor water quality, even though when she has increased water flow. What else can cause the water to be—in Shruti's words—"so disgusting?"

Next, the girls attempt to improve the water quality and to figure out the identity of the yellow squares by repeatedly changing the water. Although they *look* at the screen, they have yet to coordinate the behaviors occurring in the simulation with the data output displays. Similarly, each girl makes independent observations without considering these collectively. For instance, Mary notices that "the yellow in ganging up in places where the fish aren't" without also noticing that the fish population is growing smaller and the water quality getting worse. No one consolidates these observations with their prior observations to suggest, for example, that large amounts of food could adversely affect water quality. The girls appear to tire of this activity and begin answering questions on the worksheet.

A few minutes pass when Shruti notices that the teacher's simulation (projected on a screen) has few yellow squares and no poor water deaths. Without discussing her actions, Shruti declares that she is going to "starve" the fish and reduces the food because she wants "the fish to die from food death." Looking at the simulation and the data outputs, Mary notices, "But the yellow goes away when there's less food. So, but she (*the teacher*) said it wasn't the food." So what we see here is that the girls are explicitly connecting the data outputs with the behavior of the yellow squares, which suggests that they now connect their explanations to observational evidence. Just then, Ms Garrison approaches the group and asks what they have decided about the yellow patches:
Shruti: Well, we figured out that when we put the food down more of it goes away. But we don't—you said it wasn't food. So I thought it was waste, but I don't know.
Ms G: Well that's what I was thinking too. Waste. Fish waste.

We should note at this point our narrative that Ms Garrison mistakenly identified the yellow squares to be fish waste, whereas the students correctly identified the yellow to be food. Mary and Shruti's comments make clear that they are struggling to reconcile their observations with what they perceive to be the teacher's authoritative explanation. So even when Shruti concedes the yellow must be waste, her statement, "but I don't know," remains non-committal. This hesitation is also evident as the girls begin to answer questions on the worksheet and each describes the fish spawn as "eating the yellow."

In what appears to be a last attempt to reconcile their observations with the teacher's explanation, Shruti reduces the food level on the simulation and the girls observe the screen. As the simulation is running, the teacher joins them and has reconsidered her earlier interpretation of the yellow squares:

Mary: We have no food.

Shruti: Of course we have no fish.

Ms G: …the yellow patches, I think they are the food. I was thinking they were the waste. But I think they're the food. But if you think about it, the waste would probably be similar. They don't show the waste apparently. But it would be a similar amount if they're eating that food. It's gonna be converted into waste.

Shruti: I thought it wasn't waste because when the baby fish went over it, it started disappearing.

Ms G: It did? Ok. So, good.

From the experiences in this episode, we can begin to appreciate how asking even a simple question about structure—*what are those yellow things*—can filter complexity and stimulate productive observations of a complex behaviors of a system. Admittedly, had the teacher not confused the yellow squares with fish waste, the students' pursuit of this particular question may not have continued for as long as it did. In the end, observing multiple relationships between the simulation's behavior and the data outputs was necessary for both teacher and students if they were to observe scientifically meaningful patterns and to identify the yellow squares. Along the way, students came to reason with their observations and to develop a new awareness that the importance of the quality of the water to an aquarium system, even if they have yet to understand what water quality means precisely.

Observing the Micro Level: "But where are the fish?"

Episode two begins with Ms Garrison and the whole class reflecting on why the fish were dying in the Fish Spawn simulation: "Could it be that there are some micro systems going on that are not shown that affect water quality? What might be going on chemically and not visible to the human eye beneath all that you see?" She then orients students to the Nitrification Cycle simulation (Figure 2), which is designed to explore the micro level processes of an aquarium system that transform nitrogen into different forms. With the exception of a plant form, the screen includes only abstract shapes and colors, which float chaotically around the simulation screen, and some of which grow into what the teacher describes as patches. She then distributes worksheets that include questions that primarily focus on the identities of the abstractions, the sources of data in the graph, and the biological and chemical relationships that affect a complex aquarium system.

During the orientation, Shruti, Mary, and Erica are already interacting with the simulation. Shruti increases the number of fish, pushes the start button, and the three girls view the screen, which is suddenly animated with bursts of different shapes and colors. Very soon, a message pops up and warns that the ammonia is too high in the system. Shruti restarts the cycle and a new message warns that the nitrite is too high and that fish will start dying. Shruti is pressing the change water button to reduce ammonia levels when Ms Garrison joins the group and suggests they slow the simulation "to see what's really happening." Consistent with the Fish Spawn simulation, asking questions about what something is leads to focused and repeated observations:

Shruti: What are the red dots?

Mary: I don't see any fish. [Pause = 4 seconds] Are the red dots the ammonia?

Ms G: Well um why did you say that?

Mary: Because the ammonia was going up and there was more red dots.

Ms G: Did you hear what Mary said? She noticed that as she saw red dots the ammonia level in the graph was going up. (*points to graph*)

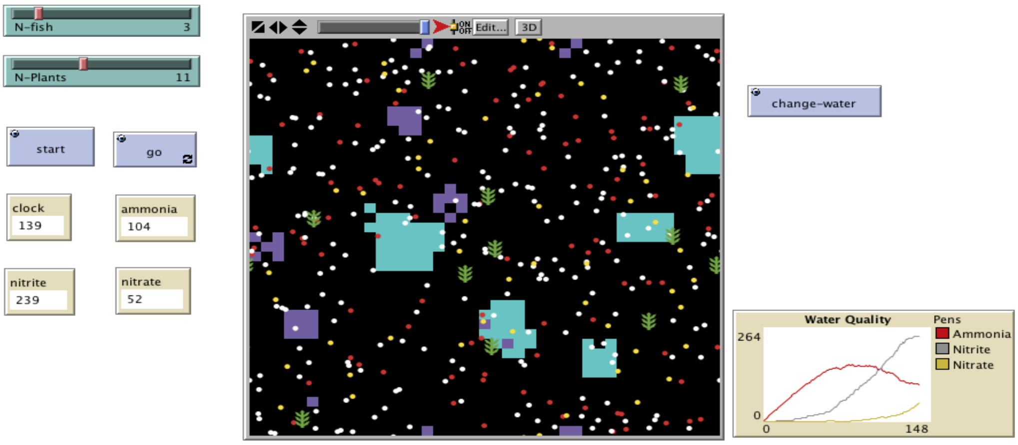

Figure 2. Screenshot of the Nitrification simulation

Thus begins a succession of observations, questions, and cues to sort out what is happening in the simulation. With the teacher's encouragement, the girls quickly coordinate the information on the graph and the data outputs with the behavior of the colored shapes that are populating the simulation. Within a few minutes, they notice that the ammonia and nitrite levels are now low and that "there is more nitrate than ammonia." A few moments more and the first purple and blue colors pop up onto the screen.

Shruti: But what's the purple and blue?
Ms G: Oh?
Mary: That's not on here. (*refers to graph*)

As Mary rightly notices, these colors are not labeled on the graph and she repeats Shruti's question. At the same time Shruti is searching the worksheet for critical clues and asks what the difference is between nitrite and nitrate. Rather than provide any answer, Ms Garrison directs them to the hypermedia. Shruti then opens the hypermedia, clicks through several screens before clicking on the question, "How does the nitrogen cycle work?" She then quietly reads before re-voicing the text:
Shruti: So fish poo and then they create ammonia. And then the bacteria turn into nitrite which is still kinda bad. And then the other bacteria put it into nitrate and then it helps the plants. I guess. And then the fish eat it, the plants. Ok.

Just as Shruti begins to understand this information, she and Mary simultaneously notice that there are no fish in the simulation:
Mary: Where are the fish?
Shruti: Yeah where are the fish? [Pause = 5 seconds] I think the fish are like either the blue or like the purple.
Erica: I see one red dot … Purple!
Shruti: Where are the fish though? [Pause = 4 seconds] The fish are creating ammonia so there has to be fish. I think they're the purple because otherwise it would be too many fish.

The teacher tells them the fish are assumed to be there "because we're looking at a more microscopic, smaller scale … the fish aren't even shown." Agreed that the blue patches and purple patches are something other than fish, the girls focus on figuring out the identity of the patches. However, coordinating observational practice with domain knowledge proves to be rather challenging:
Ms G: Now did you figure out what those patches are? Those colored patches.
Shruti: I have no idea.
Ms G: Hmmm?

Shruti: I have no idea—Maybe they're the bacteria?
Erica: Blue? Teal?
Shruti: Maybe they're the different types of bacteria?
Ms G: How could you figure that out?
Shruti: I don't know. (*laughs*)
Ms G: What if you started again and really looked at when those patches start to appear, the timing of the patches, then look at the other data (*points to screen*). What's happening when those chemicals start to build? How does the appearance of those patches um relate to the chemicals?

The teacher makes several moves that facilitate productive observations of the nitrification simulation of the nitrification cycle. Previously, she suggested slowing the simulation to see what is really happening and checking out content in the hypermedia to identify the colored patches. Now, she cues them to associate the timing of the appearance of the colored patches with difference in chemical levels (i.e., ammonia, nitrite, nitrate). The girls start a new cycle and closely observe the screen, waiting for the patches to appear:
Shruti: Ooh, here it comes! Bacteria appear when the red ammonia appears.
Erica: So that bacteria would be the first bacteria?
Shruti: Yeah.
Mary: So the blue is bacteria.
Erica: So the aqua patches.
Shruti: The blue is the first bacteria, probably. The blue is the first whatever bacteria.
Mary: First bacteria I think.
Shruti: That converts the ammonia into nitrite.
Erica: That's so funny!
Shruti: Because it shows up right when, right when the red…

At this point, Shruti, Erica, and Mary realize that the appearance of the first bacteria is associated with changes in the ammonia. Long before the purple patches begin to populate the simulation, the girls understand that the purple patches are the second bacteria and anticipate a spike in nitrate levels when they do appear on the screen.

Modeling Macro and Micro Level Connections: "Ammonia poops?"
Episode 3 occurs at the end of the curriculum unit as the students generate functional models of an aquarium system. The teacher first reviews the nitrification cycle and its impact on water quality, and then demonstrates how to use the ACT modeling tool to identify the system's structures and to describe relationships between them. As an example, the Ms Garrison asks students to list relationships between fish and water. The teacher's expectation is that by creating the models, "this will all come together and make more sense." Her final instruction is for students to discuss the relationships between the aquarium's parts and to use all that they have learned to update the ACT table and to create their ACT models.

Consistent with earlier episodes, the girls are already interacting with the computer during the orientation. Shruti assumes control of the computer and is busy updating the ACT table as Mary and Erica look on. She switches to the ACT model and moves the structures (e.g., air pump, filter, fish) around the screen, draws lines between structures, and writes brief comments describing relationships. After nearly 10 minutes working like this, Shruti mentions that they should add ammonia and nitrate. Switching back to the ACT table, she adds these to the structure column. So far very little talking has occurred between the girls, that is, until Shruti describes the behavior of *nitrobacter* (a kind of bacteria) to be *pooing*, a colloquial term to mean eliminating animal waste:
Erica: Pooing?
Shruti: That's how they get rid of their waste (*laughs*).
Erica: Ammonia poops?
Mary: Ammonia's in their poo.
Erica: Then why does it say pooing? That isn't how.

The three girls debate whether or not pooing accurately describes bacterial behavior. Because Mary and Shruti think that *nitrobacter* "live and eat ammonia," implying that they also eliminate waste, the issue is semantic and they suggest alternative words for *pooing*. However, Erica is unsure if pooing is how *nitrobacter* transform ammonia into nitrite. It soon becomes evident that no one can confidently explain whether bacteria are even living, much less how ammonia in fish waste becomes nitrite. This conversation is briefly interrupted by a class discussion, but before long Shruti (and now Erica) continue updating the ACT table and creating the model. Erica links *nitrosonomas* and nitrite and writes "turns itself in" between *nitrosonomas* and nitrite when Shruti interrupts:

Shruti: We need to delete this. (*points to text "turns itself into"*)

Erica: No, don't.

Shruti: Because of the blue bacteria (*refers to the representation of this bacteria in the simulation*), the blue bacteria do turn into nitrite. It doesn't turn itself into nitrite. The *nitrosonomas* turn ammonia into nitrite.

So, in response to Erica's initial question about whether ammonia poops, the girls appear to draw upon the hypermedia text and their earlier observations of the nitrification cycle (i.e., substituting *nitrobacter for nitrosonomas*). It is also possible that their decision to describe nitrosomonas as turning ammonia into nitrite also implies a subtle distinction between biological processes (pooing) and chemical processes ("turns into").

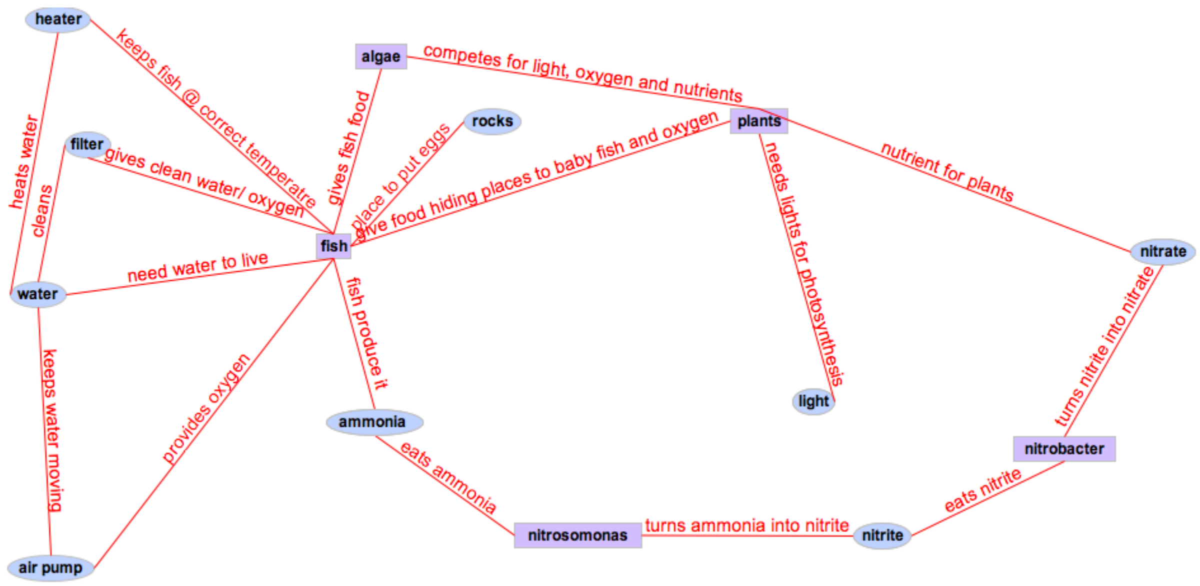

Figure 3. Students' final model of an aquarium system

After completing their models, each group presents its model to the whole class (see Figure 3). Shruti reports that the first thing to notice is that their model resembles a fish. She then explains that the fish has the most connections to everything in the system because, "The point of an aquarium is to keep the fish alive." Except to compliment "how pretty" the model looks, the other students make few comments other than to note that the model has no algae. Ms Garrison asks whether including algae is critical to the system working and leaves it to the girls to decide whether or not to include it. Their initial response is to change nothing. However, after being asked again if algae is important to the system, the three girls check with the hypermedia tool and noting that algae competes with plants for light and food and also provides food for fish, they decide to include algae in the model. These changes are included in the final model.

Although prominent in episodes one and two, asking questions plays a smaller role during the curriculum's modeling phase. With the exception of the conversation about how bacteria transform ammonia, most student talk is oriented to completing the modeling task. We think it may be significant that this singular question occurs at the intersection of the macro (fish) and micro (nitrogen transformation) levels of the system.

DISCUSSION

In this study, we explored how computer and human interactions facilitated one group of middle school students' observations of an aquarium system. Our analysis suggested that the combination of both computer and human mediation is synergistic (Puntambekar & Kolodner, 1998; Tabak, 2004). In other words, the combination of a computer learning environment and teacher mediation provided an integrated system of support for student learning. The kinds of questions used by the teacher during computer-supported inquiry played a key role in the kinds of questions students also asked and their ability to observe features and behaviors of phenomena in ways that begin to distinguish scientific from everyday practice (Eberbach & Crowley, 2009).

The centrality of asking questions in this context should be expected. After all, asking questions is fundamental to the practice of scientific observation (Mayr, 1997). Doing so filters complexity (Janovy, 2004) and stimulates iterative cycles of noticing of recurring patterns and asking new questions (Daston, 2008; Smith & Reiser, 2005). Although question asking is a powerful heuristic in scientific practice, asking simple questions about the identification of phenomena is not generally expected to stimulate complex scientific reasoning (e.g., Abu-Shumays & Leinhardt, 2002; King, 1994). However, during episodes one and two, we saw how asking "what is it" questions led students to iteratively observe phenomena, to purposefully notice recurring behavioral patterns that the simulation made visible, and to reason about complex relationships across the macro and micro levels of a system. We suspect that there are several possible explanations. First, the abstract nature of the yellow squares, purple patches, and so on necessitated that students closely observe their behavior in conjunction with using the graphs in order to identify the entities. Second, the teacher balanced identification questions with questions of a more conceptual nature. Pursuing explanations about why the fish are dying seem necessary to the observation of complex relationships, and to finding connections between the macro and micro levels of complex systems. Third, the content in the hypermedia tool focused on what students needed to know and its design enabled students to locate information just as it was needed.

We were surprised, however, that students generated so few questions when they created models of an aquarium system. More typically, generating models presents opportunities for learners to articulate and revise their observations and explanations as a means of supporting conceptual change (e.g., Lehrer & Schauble, 2004; Schwarz et al, 2009; White, 1993). However, except for clarifying how ammonia is transformed during the nitrification process, students used the modeling tool as an activity for demonstrating knowledge rather than as a tool for learning. Whether this is a function of the design of the ACT tool or a function of instructional design is unclear and should be further explored.

Design should facilitate learning in complex inquiry learning environments in ways that enable learners to observe the effects of their actions and to observe multiple dimensions of complex systems. Intentionally designing learning environments so that scaffolding is distributed across multiple sources is one strategy for doing so. In this study, the computer environment set the stage for inquiry by providing critical sources of domain content, tools for selectively manipulating and repeatedly observing parts of an aquatic system, and tools for students to record and organize information. Even so, the teacher played an equally critical role in mediating student understanding of the seen and unseen parts of a complex system and mediating student participation in scientific practice. The teacher's questions not only facilitated purposeful exploration of the simulations and hypermedia and cued students about what is important to observe, but also modeled how to make connections between domain knowledge and domain practices.

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