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EcoXPT: Designing for Deeper Learning through Experimentation in an Immersive Virtual Ecosystem

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ABSTRACT

Young people now must compete in a global, knowledge-based, innovation-centered economy; they must acquire not just academic knowledge, but also character attributes such as intrinsic motivation, persistence, and flexibility. To accomplish these ambitious goals, the National Research Council (2012) of the United States recommends the use of "deeper learning" classroom strategies. These include case-based learning, multiple representations of knowledge, collaborative learning, apprenticeships, life-wide learning, learning for transfer, interdisciplinary studies, personalized learning, connected learning, and diagnostic assessments. Immersive media (virtual reality, multi-user virtual environments, mixed and augmented realities) have affordances that enhance this type of learning. EcoXPT is an inquiry-based middle school curriculum on ecosystem science that invites students into immersive experimentation with scaffolding tools that support deeper learning. This includes a *case-based approach* situated in an unfolding eutrophication scenario in which students learn new information from their observations over space and time, speaking with virtual characters in the world, and gathering information in the field guide and other sources. *Diagnostic assessments* of students' progress are based on multiple sources, including process data from various types of logfiles. *Multiple varied forms of representation* convey perceptual, graphical, and experimental data, enabling students to investigate relationships between variables. Students are *apprenticed* in the ways of knowing of ecosystems scientists, which involves *interdisciplinary knowledge*. Students *collaborate* in teams of two, subdividing the tasks of gathering evidence.

Keywords

Immersive learning, Virtual worlds, Deeper learning, Ecosystems science

Deeper learning to prepare young people for life and work in the 21st century

Young people now must compete in a global, knowledge-based, innovation-centered economy (Araya & Peters, 2010). In order to secure a reasonably comfortable lifestyle, they now must go beyond a high school diploma (Wagner, 2008), and they must acquire not just academic knowledge, but also character attributes such as intrinsic motivation, persistence, and flexibility (Dede, 2010; Levin, 2012; National Research Council, 2008). As described by the National Research Council (NRC) in its landmark report *Education for Life and Work in the 21st Century* (2012), cognitive, intrapersonal, and interpersonal dimensions of knowledge and skills are best developed in combination. Table 1 categorizes a broad range of knowledge and skills vital in the 21st century, according to these dimensions. Moreover, and in contrast to industrial-era schooling with its emphasis on multiple choice and short-answer testing, mastery now requires the ability to apply knowledge and skills in real-world contexts, demonstrating proficiency via effective, authentic performances (Dede, 2014).

Table 1. Dimensions of knowledge and skills for the 21st century drawn from 2012 NRC report

Cognitive outcomes	Intra-personal outcomes	Inter-personal outcomes
Cognitive processes and strategies	Intellectual openness	Teamwork
Knowledge	Work ethic and conscientiousness	Leadership
Creativity	Positive core self-evaluation	Communication
Critical thinking	Metacognition	Responsibility
Information literacy	Flexibility	Conflict resolution
Reasoning	Initiative	
Innovation	Appreciation of diversity	

For all students to reach such ambitious standards, not just an elite few, how must schools change? In order to make these types of learning outcomes possible, on a large scale, what kinds of instruction would have to become common practice?

To accomplish these ambitious goals, the 2012 NRC report recommends the use of "deeper learning" classroom strategies. The approaches promoted by advocates of deeper learning are not new, and historically these instructional strategies have been described under a variety of terms. Until now, however, they have been rarely practiced within the industrial era schools:

- *Case-based learning* helps students master abstract principles and skills through the analysis of real-world situations;
- *Multiple, varied representations* of concepts provide different ways of explaining complicated things, showing how those depictions are alternative forms of the same underlying ideas;
- *Collaborative learning* enables a team to combine its knowledge and skills in making sense of a complex phenomenon;
- *Apprenticeships* involve working with a mentor who has a specific real-world role and, over time, enables mastery of their knowledge and skills;
- *Self-directed, life-wide, open-ended learning* is based on students' passions and connected to students' identities in ways that foster academic engagement, self-efficacy, and tenacity;
- *Learning for transfer* emphasizes that the measure of mastery is application in life rather than simply in the classroom;
- *Interdisciplinary studies* help students see how differing fields can complement each other, offering a richer perspective on the world than any single discipline can provide;
- *Personalized learning* ensures that students receive instruction and supports that are tailored to their needs and responsive to their interests (U. S. Department of Education, 2010; Wolf, 2010);
- *Connected learning* encourages students to confront challenges and pursue opportunities that exist outside of their classrooms and campuses (Ito et al., 2013); and
- *Diagnostic assessments* are embedded into learning and are formative for further learning and instruction.

These types of learning entail very different teaching strategies than the familiar, lecture-based forms of instruction characteristic of conventional schooling, with its one-size-fits-all processing of students. Rather than requiring rote memorization and individual mastery of prescribed material, these approaches involve in-depth, differentiated content; authentic diagnostic assessment embedded in instruction; active forms of learning, often collaborative; and learning about academic subjects linked to personal passions and infused throughout life (Dede, 2014).

Designing immersive authentic simulations to promote deeper learning

As can be seen from the list above, deeper learning experiences designed to teach complex knowledge and sophisticated skills are often based on "guided social constructivist" theories of learning. In this approach, learning involves mastering authentic tasks in personally relevant, realistic situations. Meaning is imposed by the individual rather than existing in the world independently, so people construct new knowledge and understandings based on what they already know and believe, which is shaped by their developmental level, their prior experiences, and their sociocultural background and context (Palincsar, 1998). Instruction can foster learning by providing rich, loosely structured experiences and guidance (such as apprenticeships, coaching, and mentoring) that encourage meaning-making without imposing a fixed set of knowledge and skills. This type of learning is usually social; students build personal interpretations of reality based on experiences and interactions with others.

Immersive media have affordances that enhance this type of learning. Psychological immersion is the mental state of being completely absorbed or engaged with something. For example, a well-designed game in a multi-user virtual environment (MUVE) draws viewers into the world portrayed on the screen, and they feel caught up in that digital context. The use of narrative and symbolism creates credible, engaging situations (Dawley & Dede, 2013); each participant can influence what happens through their actions and can interact with others. Via richer stimuli, head-mounted or room-sized displays can create sensory immersion to deepen the effect of psychological immersion, as well as induce virtual presence (place illusion), the feeling that you are at a location in the virtual world rather than the place where your physical body is (Slater, 2009).

EcoMUVE as an immersive authentic simulation

Immersive virtual learning environments can enhance learning of science concepts by situating students' investigations in realistic, yet scaffolded contexts (Colella, 2000; Dawley & Dede, 2013; Ketelhut et al., 2010). Situated experimental tools let students interpret results contextually and integrate their findings with other sources of evidence--including observations and data collected in the virtual world--to build and test hypotheses.

EcoXPT is based on a prior immersive authentic simulation project, EcoMUVE. The EcoMUVE middle grades curriculum focuses on the potential of immersive authentic simulations for teaching ecosystems science concepts, scientific inquiry (collaborative and individual), and complex causality (see http://ecomuve.gse.harvard.edu). The curriculum has two MUVE-based modules, which center on pond and forest virtual ecosystems. Each module consists of ten 45-minute lessons and represents an ecological scenario involving complex causality. The curriculum is inquiry-based; students investigate research questions by exploring the virtual ecosystem and collecting data from a variety of sources over time, assuming roles as ecosystems scientists. Overall, EcoMUVE enables internship-like experiences in immersive simulated ecosystems that support authentic scientific practices, including collaborative inquiry.

EcoMUVE is an ill-structured problem space in which students collaborate to construct meaning about scientific phenomena embedded in the immersive pond or forest environment (Kamarainen, Metcalf, Grotzer, & Dede, 2015). Within the immersive virtual environments, students have multiple ways of accessing information about the relationships among components of the system, students find opportunities to collect multiple forms of evidence, and the rich relationships among sources of evidence render these open to various interpretations. Thus, the complexity of the immersive world provides a context in which students must justify their interpretation of the relationships as they build and revise a conceptual model of these relationships during an ongoing concept mapping activity. Using immersion to position students within an ill-structured problem space helps them engage in collaborative sense making that encouraged use of evidence in support of claims. The behaviors of students included collecting data, distinguishing between problem-relevant and problem-irrelevant information, and collaboratively reasoning about the claims represented in their concept maps by combining prior knowledge and repeated visits to the virtual environment to revise their understanding. Thus, immersion in the virtual world, supporting design and curricular features, and the concept mapping task elicited behaviors that are closely aligned with the epistemic work of experts in the field of ecosystem science.

Prior research with EcoMUVE demonstrated significant student gains in ecosystem science knowledge (Kamarainen et al., 2012; Metcalf et al., 2011) and in causal understanding (Grotzer et al., 2013). A study on teacher perceptions of EcoMUVE in the classroom surveyed 16 teachers who had used the curriculum with their students, about the value, effectiveness, and feasibility of EcoMUVE based on their experiences; some teachers additionally participated in a comparison study of EcoMUVE with a non-MUVE curriculum (Kamarainen et al., 2012). Teachers felt EcoMUVE was effective, aligned well with standards, and compared favorably with a non-MUVE alternative. Particular technological and curriculum features that were identified by teachers as valuable included both technological aspects, such as immersion in the virtual environment and easy-to-use data collection and analysis tools, and also pedagogical features, particularly the opportunity for self-directed learning by students and the inquiry, role-based pedagogy (Metcalf et al., 2013).

In a study looking at changes in student motivation as a result of using EcoMUVE (Chen, Metcalf, & Tutwiler, 2014), quantitative data indicated that students' interest in *science* did not change from pre-intervention to post-intervention. However, a closer analysis revealed that students who identified more strongly with science did become more interested in science, whereas those who did not identify with science evinced no change in interest for science. A companion study (Metcalf et al., 2014) showed that, over the two-week EcoMUVE curriculum experience, student interest in EcoMUVE decreased somewhat but remained high; students' beliefs about EcoMUVE's utility increased; and students saw EcoMUVE as less of a "waste of time." Student responses to questions of what they liked about EcoMUVE changed from being primarily about the opportunity to interact in a virtual computer environment to an increasing appreciation of the pedagogical aspects of the self-directed, collaborative, inquiry-based activities. These findings demonstrate that, although there is a novelty effect for EcoMUVE, engagement didn't ultimately depend on novelty. This is an important contribution to the teaching and learning of science because it demonstrates and reinforces the importance of sound pedagogical methods. As technology becomes more prevalent in science classrooms, this study serves as a reminder that, regardless of the medium, it is fundamental to design the technology to allow for active, collaborative student involvement in inquiring about scientific phenomena.

EcoMUVE is a first-generation ecosystems science curriculum that focuses on the observational methods of ecosystems science. We designed and developed EcoXPT (described below) as a second-generation, more complex curriculum that builds on EcoMUVE, but adds new components to the digital ecosystem and includes six types of experimental tools authentic to ecosystems science. The initial pilot of EcoXPT in a few classrooms has just been completed, and data has not yet been analyzed; large-scale trials of EcoXPT will take place in the 2017-18 school year. For this special issue focusing on design, the emphasis is on showing how EcoMUVE and EcoXPT incorporate design for deeper learning, rather than on efficacy studies of the extent to which this design succeeds.

EcoXPT extends EcoMUVE with authentic experimentation in ecosystems science

As a follow-on to EcoMUVE, EcoXPT is an inquiry-based middle school curriculum (see http://ecolearn.gse.harvard.edu/ecoXPT/overview.php) that extends the EcoMUVE Pond curriculum by adding experimental methods authentic to ecosystem science to complement observation and correlation, enabling students to reason about causes. Students investigate why all of the large fish in a virtual pond have died (Figure 1). In addition to the environmental features in EcoMUVE Pond, a farm, a second pond, a second housing development, and a drainage ditch have been added. While immersed in the virtual world, students can assess the slope of the land, thereby gaining a tacit understanding of landscape topography and the boundaries between watersheds. They can further explore the influence of slope on the transport of materials through the ecosystem by using a “tracer tool” to track where water, and the fertilizer it carries, flows on a rainy day. Water flows in a variety of directions, and determining this becomes important in understanding the causes of the fishkill. Students collect environmental and population data over time, and conduct a variety of experiments in the virtual ecosystem. Teams of students construct hypotheses, supporting their arguments with data and experimental results.

Figure 1. EcoXPT virtual pond

Reasoning in purely observational environments, like EcoMUVE Pond, tends to be inferential, based on visual information, measurements and correlations observed over time. In EcoXPT, we are studying whether the ability to conduct experiments in order to test various causal hypotheses about variables and relationships will support students in deeper, evidence-based reasoning. Further, by situating the simulated experimental tools within the context of the virtual ecosystem, we are studying whether students can adopt more sophisticated approaches to investigation that mirror the thinking moves that ecosystem scientists use when investigating environmental problems. We hypothesize that EcoXPT will give students opportunities to extend their observational learning by applying their experimental findings to building hypotheses about the ecosystem scenario.

EcoXPT invites students into immersive experimentation with multi-dimensional experiences that support deeper learning. Consistent with the instructional strategies of deeper learning, this includes a *case-based approach* situated in an unfolding eutrophication scenario in which students learn new information through their observations over space and time, from virtual characters in the world, and from gathering information in the field guide and other sources. *Multiple varied forms of representation* convey perceptual (Figure 2), graphical (Figure 3), and experimental data (Figure 4) to the students, enabling them to investigate relationships between variables. The use and interpretation of varied forms of representation is further supported by the EcoXPT notebook and concept mapping tools, which help students integrate various forms of evidence into their scientific arguments.

Figure 2. The Submarine tool can be used to observe and measure populations of microscopic organisms

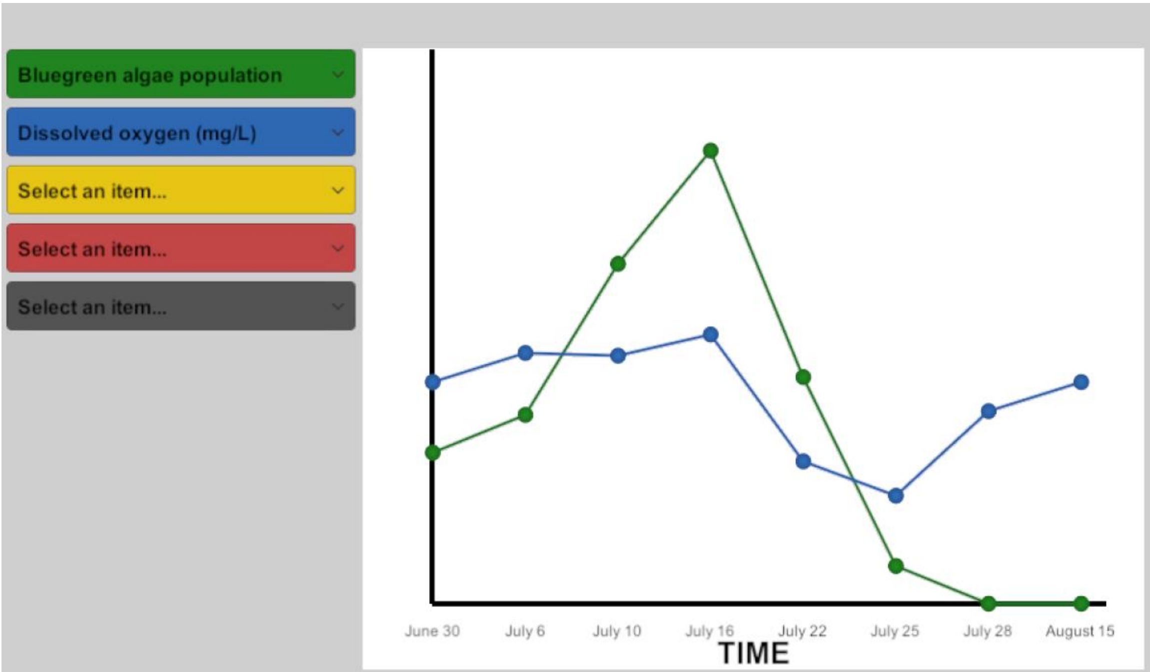

Figure 3. The Data Visualization tool supports viewing tables and graphs of up to five variables

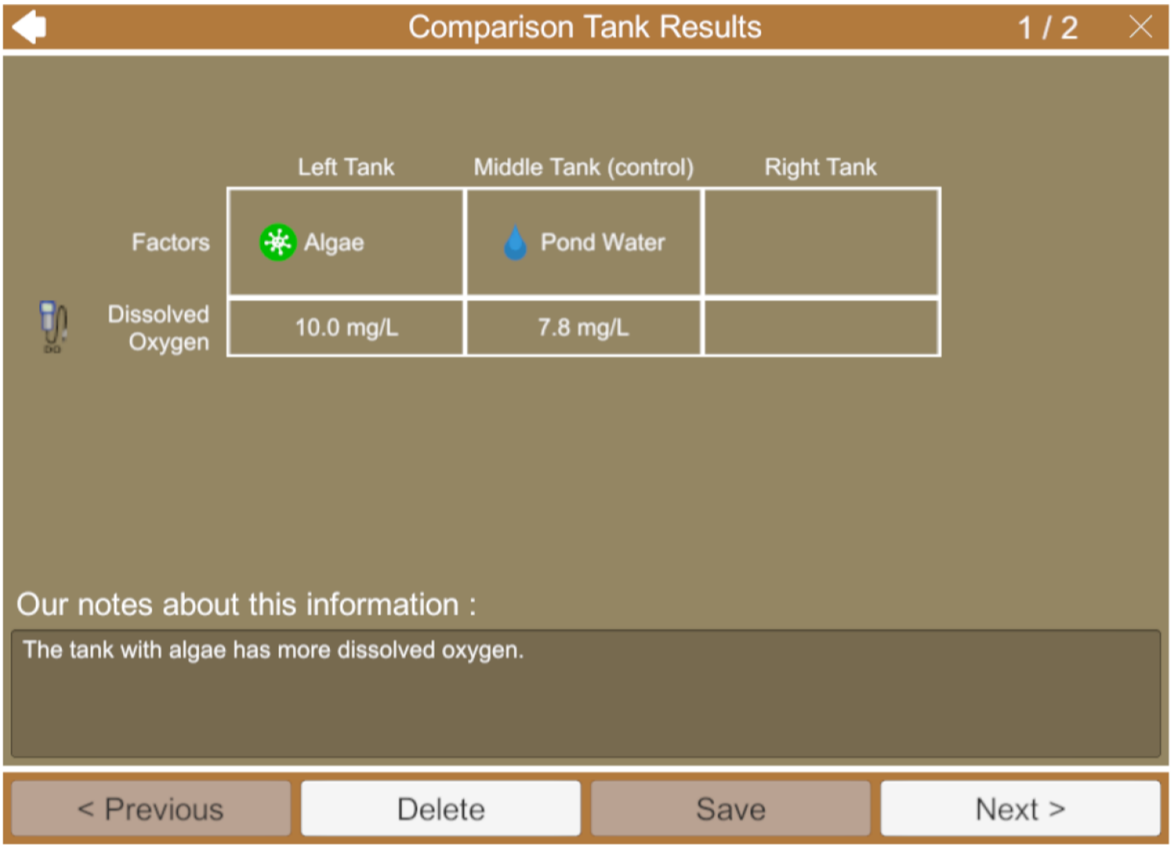

Figure 4. The Notebook tool stores observations, graphs, testimony, and experimental data, with student annotations

EcoXPT illustrates the capacity of immersive simulations to support a wide range of instructional strategies for deeper learning, through design that enables extended, multi-dimensional, authentic experiences.

EcoXPT enables students to use the tools and the inquiry practices of ecosystem scientists

Part of deeper learning is helping students to understand that science is not just a body of facts to be memorized, but also a set of practices used collaboratively to expand on what is known about the natural world. EcoXPT supports this integration of knowledge and practice by promoting engagement in use of scientific tools, while aiding reflection on the value of using those tools in conjunction with larger investigative strategies in order to develop and support an evidence-based argument.

EcoXPT tools that illustrate situated experimentation include:

- *Tolerance Tanks* – Students adjust the levels of an environmental factor, such as fertilizer, in three tanks containing different species of fish (e.g., minnow, bluegill), to determine the level (if any) at which each type of fish is affected by that factor (Figure 5).
- *Tracers* – Chemical markers show the movement of matter in the environment. Adding tracers to bags of fertilizer lets students test how the spatial layout and topography affect fertilizer runoff when it rains (Figure 6).
- *Comparison Tanks* - Students configure one to three tanks with experimental factors, and collect measurements – e.g., discovering that a tank with algae has a higher dissolved oxygen than one without algae (Figure 7).
- The *Weather Simulator* enables students to model the effect of various environmental factors (e.g., wind, temperature) on the level of dissolved oxygen in water (Figure 8).
- *Mesocosms* are containers in an outside location that provide a similar, but smaller, environment to the pond (Figure 9). This enables the investigator to assess the impact of variables of interest (e.g., addition of fertilizer) in addition to environmental factors (e.g., sunlight, weather) in ways that more closely mirror the pond than small, indoor tolerance and comparison tanks can.
- The *Sensor Buoy* immersed in the pond provides a steady stream of data about its dynamics over time. (Figure 10).

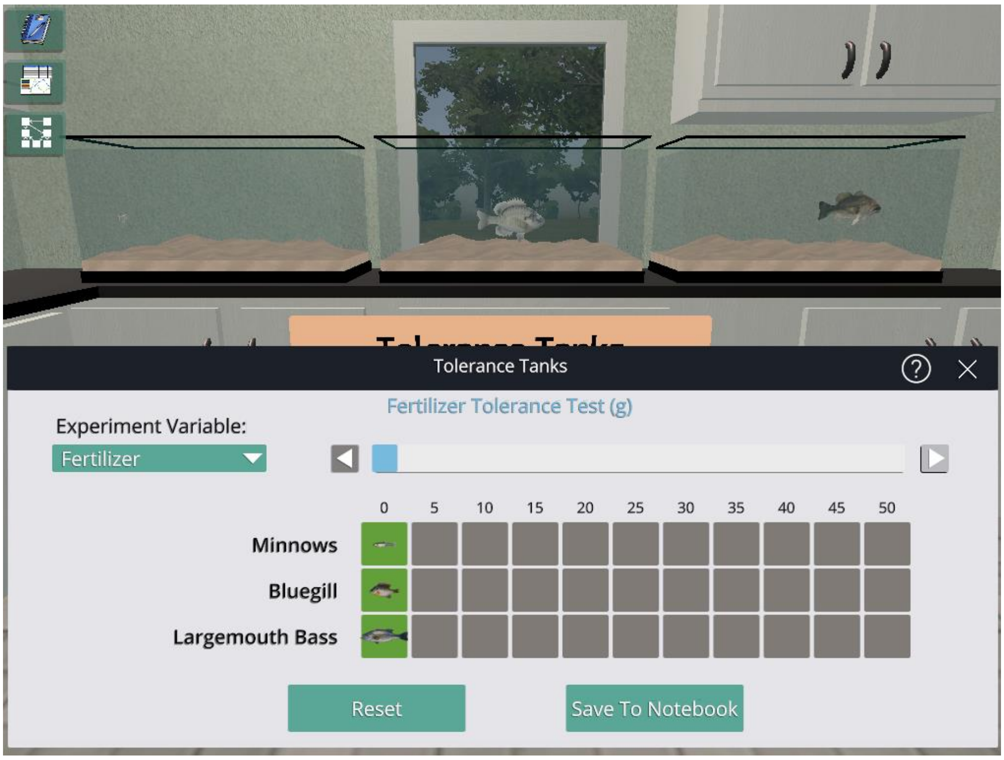

Figure 5. Tolerance Tank tool

Figure 6. Tracer tool

Figure 7. Comparison tank tool

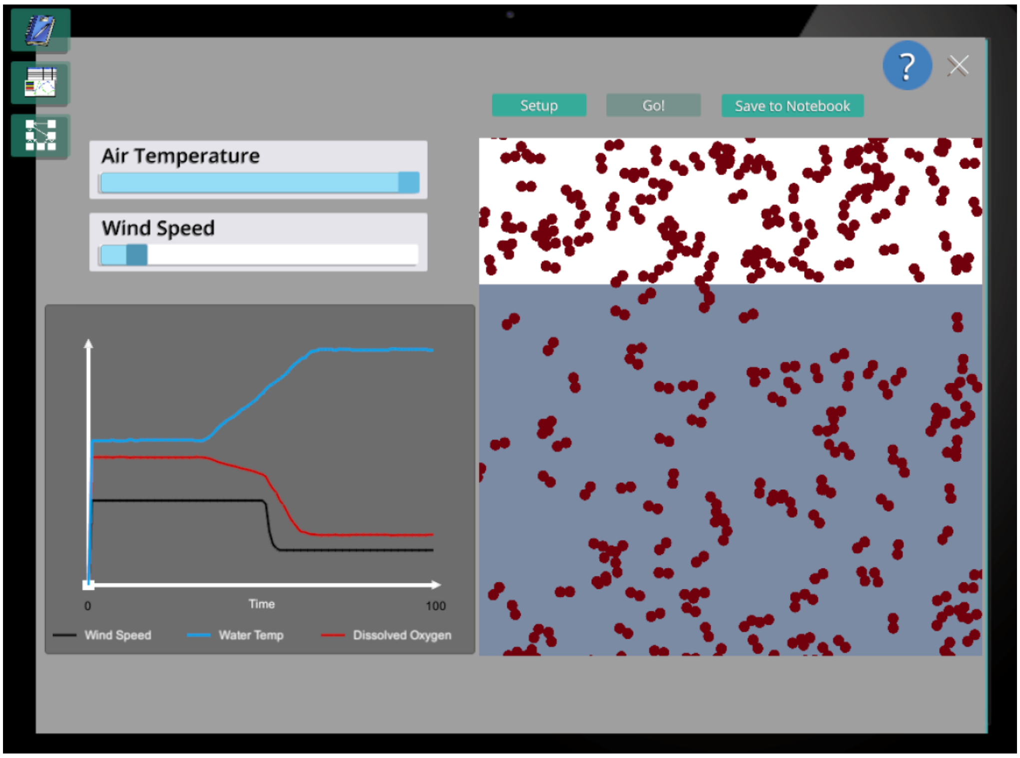

Figure 8. Weather simulator

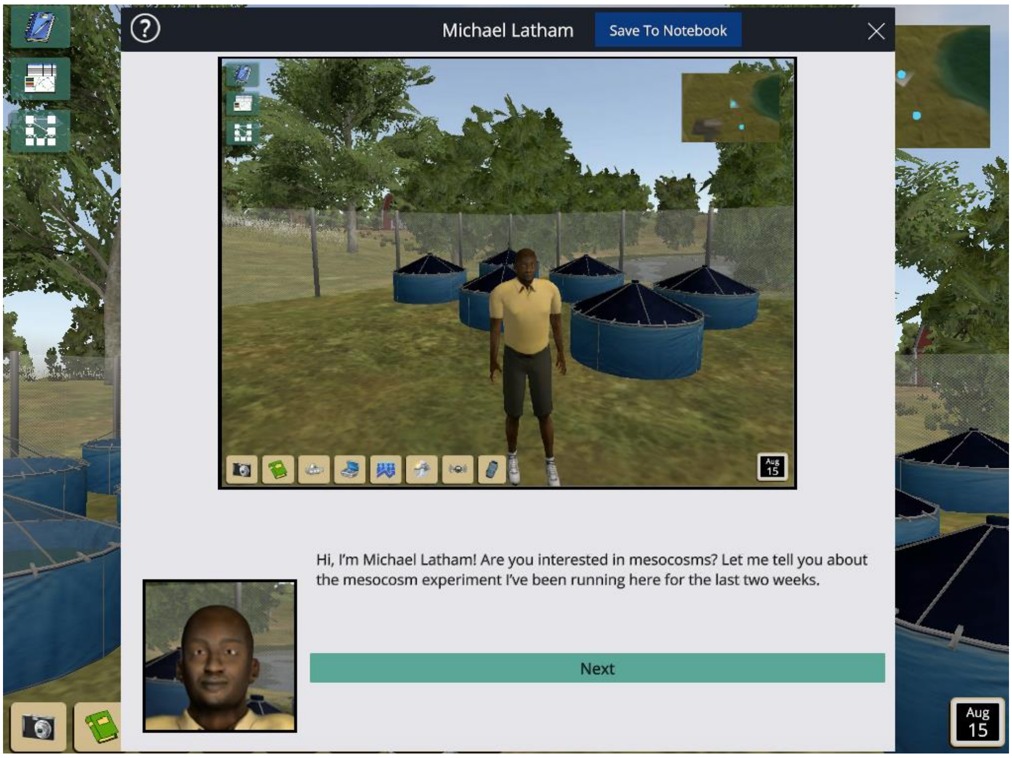

Figure 9. Mesocosms

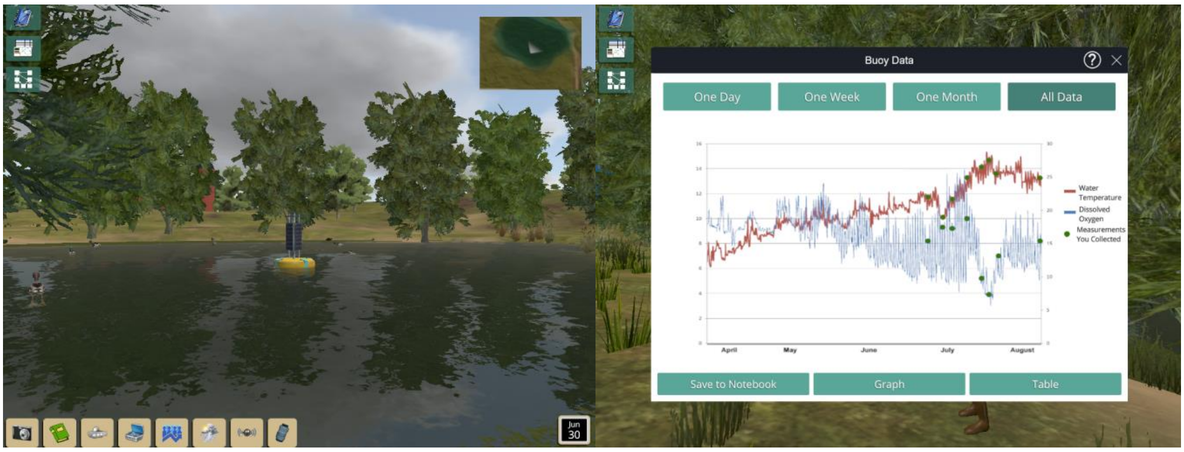

Figure 10. The sensor buoy and its datastream

These six tools provide a progression that initially enables students to test their hypotheses about simple relationships, then gradually introduces more sophisticated, multidimensional measurements that reveal the complex causality in the pond's dynamics over time.

In order to learn the thinking inherent in moving from seeking patterns to analysing causality, Thinking Moves accompany these experimental tools in order to help students understand the kinds of questions that ecosystems scientists might ask as they explore the potential causal dynamics of an ecosystem (Grotzer, Kamarainen, Metcalf, Tutwiler, & Dede, 2017):

- *Deep Seeing* encourages students to consider the natural history of the ecosystem and to engage in careful observation of what is there. It asks them to look while being careful to set their assumptions aside.
- *Evidence Seeking* encourages students to collect evidence from multiple sources, to seek corroborating evidence, and to evaluate the sources of their evidence.
- *Pattern Seeking* encourages students to notice patterns in the on-going processes and steady states of the system and to notice how certain variables change together or not.
- *Analyzing Causality* asks students to use experimental evidence and intervention to try to impact change in the patterns in an effort to discern the underlying mechanisms at work.

- *Constructing Explanations* encourages students to develop the best "story" or explanation that they can from the available evidence. It asks students to look for gaps in their explanation and to assess their explanations against rival explanations.

Studies on the effectiveness of these supports are now being conducted.

How the design of EcoXPT fosters deeper learning

Consistent with instructional strategies of deeper learning, EcoXPT presents an unfolding eutrophication scenario in which students learn new information from their observations over space and time, speaking with virtual characters in the world, and gathering information in the field guide and other sources. The complexity of the situation grows over time and is shaped by the decisions students make about what data to collect and what experiments to do. This pedagogical method is consistent with case-based teaching and problem-based learning, which extensive research has shown leads to outcomes characteristic of deeper learning (Lu, Bridges, & Hmelo-Silver, 2015).

The experimental tools in EcoXPT provide a progression authentic to ecosystems science that aids the students in understanding the unfolding and increasing complexity of the eutrophication process. Initially, the tolerance tanks and the tracers provide evidence about the role of individual variables and environmental dynamics. Then the comparison tanks and the weather simulator show the interactions among variables. The mesocosms indicate the interactions between suites of variables and environmental dynamics. Finally, the buoy provides a detailed stream of longitudinal diurnal data. This suite of tools can be leveraged by students throughout their investigation to support their understanding of ecosystem science epistemology and experimental processes, as well as building their inquiry skills and their knowledge of eutrophication.

In terms of design for deeper learning, students *collaborate* in teams of two in a simulated setting designed for *transfer* of knowledge and skills to real world activities. Intra-team and whole class *collaboration* aids in both learning and engagement, as students socially construct knowledge and often provide complementary contributions in comprehending various types of representations. Scientists and a teenage virtual guide in the immersive world *apprentice* students in the ways of knowing of ecosystems scientists, which involves *interdisciplinary knowledge*. Overall, this is like an internship experience in ecosystems science, focusing on authentic epistemological methods that go beyond simply controlling all but one variable in a situation. To aid students in understanding the complex causality involved, *diagnostic assessments* of students' progress are based teachers' observations of students' activities and discussions, in-world and in-classroom, as well as the notebooks and concept maps as ways of making the progression of students' thinking visible.

Early research results on effectiveness

A full version of EcoXPT has just been completed, and studies of its usability and effectiveness in classroom settings are now being conducted. Below are summarized findings related to deeper learning from pilot studies on earlier, partial versions of the curriculum.

In 2016, a pilot study of EcoXPT was conducted with four teachers who taught a total of 14 classes of 7th grade students (N = 280) using an early version of the 2.5 week curriculum (Metcalf et al., 2016; Metcalf et al., 2017; Thompson et al., 2016a). Data collected included a pre-post content survey measuring content knowledge in ecosystems science, consistent with the US Next Generation Science Standards for this grade level, as well as the students' final presentations, which included concept maps hypothesizing causal relationships. This pre-post content survey (Thompson et al., 2016a) found statistically significant gains (t_{188} = 9.5045, p < .001) in ecosystem science content knowledge. This provides evidence that the deeper learning processes used (described in the section above) were successful in enhancing students' knowledge of ecosystems science concepts, as well as their understanding of complex causality.

Quotes from student presentations demonstrate ways in which students drew conclusions from their experiments.

- "An experiment we did in the mesocosms showed that the bacteria ate the dead matter which is the dead plants. Bacteria is able to do respiration so the bacteria uses the dissolved oxygen. So the bacteria use all of the limited dissolved oxygen, so both the bacteria and the fish die."
- "We used tracers to trace the fertilizer, the fertilizer ran off of the ground and into the pond. When the fertilizer got to the pond it caused the algae to grow, because the algae are plants."

Concept maps representing teams' hypotheses illustrate sophisticated learning about the ecosystem relationships (Figure 11). Further, student presentation slides show both situated learning and integrated reasoning with data. This type of evidence-based reasoning indicates the success of our deeper learning processes in achieving strong student outcomes.

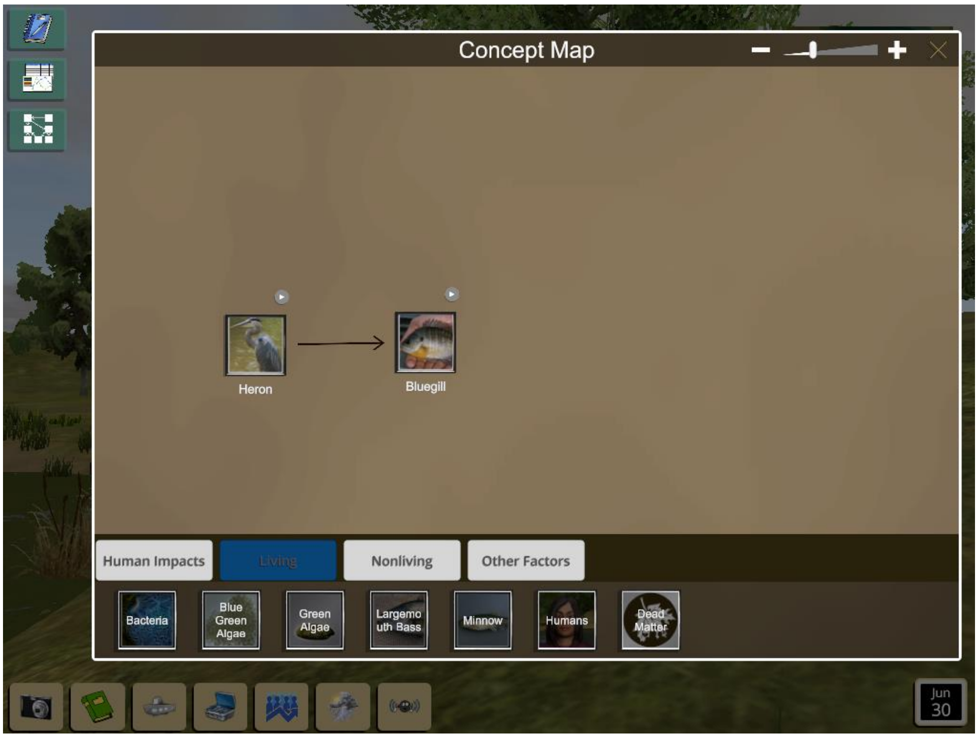

Figure 11. The digital tool for building concept maps

Two studies using mixed-methods analyses (including log file data, video, and think-aloud interviews) about students' use of and strategies toward experimentation using a set of virtual experimental fish tanks revealed diverse strategies for experimentation (Thompson et al., 2016b) and found that students used more expert strategies for experimentation over time (Metcalf et al., 2016). These cases provided a rich basis for developing supports for effective design of virtual experiments that support development of both conceptual knowledge related to important ecosystem relationships, as well as support for more effective and appropriate strategies for experimentation. Again, this is indicative of the success of our deeper learning processes designed into EcoXPT.

Conclusions

Overall, our research suggests that immersive experimentation with scaffolding tools integrated with multiple evidence sources can foster deeper learning about ecosystems. This may be because immersive authentic simulations like EcoXPT offer powerful support for six classroom practices known to lead to deeper learning outcomes: case-based instruction, the use of multiple representations, collaborative learning, apprenticeship-based learning, learning for transfer, and the use of diagnostic assessments.

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