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Immersive simulations for smart classrooms: exploring evolutionary concepts in secondary science

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This article presents the design of an immersive simulation and inquiry activity for technology-enhanced classrooms. Using a co-design method, researchers worked with a high school biology teacher to create a rainforest simulation, distributed across several large displays in the room to immerse students in the environment. The authors created and evaluated two iterations of a design where students gathered evidence of evolution using networked tablet computers that scaffolded their interactions with peers and with the room itself. Outcomes suggest that the immersive simulation engaged students, helped them to establish and build upon ideas about evolution and promoted learning of challenging biological concepts. Student explanations from the second implementation demonstrated increased variation in ideas about evolutionary topics compared to those in the first iteration. Relevant design features from the two iterations are discussed.

Keywords: collective inquiry; collaboration; embodiment; immersive environments; knowledge community; smart classrooms

Introduction

The advent of new technologies, in combination with our understanding of how people learn, offers new opportunities to engage students and teachers in transformative ways of learning. Students and our modern society will require an increasingly wide range of knowledge and skills from schools, particularly in STEM (Science, Technology, Engineering and Mathematics) disciplines, where knowledge and information is rapidly expanding, and students must understand complicated concepts while acquiring twenty-first-century knowledge skills such as critical thinking, collaboration and communication (NSF Task Force on Cyberlearning, 2008; Partnership for 21st Century Skills, 2009).

In order to respond to recent calls for the transformation of teaching and learning in schools (e.g. Collins & Halverson, 2009; Tapscott, 2008), we require basic research of new approaches that address these goals. 'The classroom of the future' can only be achieved gradually, evolving (as any institution), within an ecology of culture, practice and expectations. While it is impossible to simply design and implement a revolutionary new design for schools, it is possible to support the evolution of classrooms through basic research of new pedagogical models, and the clear specification of our learning designs (Slotta, 2010).

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This article presents our research of a new form of technology-enhanced learning that we call 'immersive simulations', that is integrated with a rich set of collaborative inquiry activities to constitute a 12-week high school biology curriculum. The design of our immersive environment is based on a pedagogical model known as Knowledge Community and Inquiry (KCI), where students work collectively to establish a knowledge base which then serves as a resource for subsequent inquiry activities (Slotta, 2007; Slotta & Najafi, 2012). To achieve a room-sized immersive simulation, we employ a 'smart classroom' where the physical space is transformed using several large projector displays. In such a space, students interact with peers as well as the environment itself. The amount of time that students spend within the simulation environment is not very large, in comparison to the overall curricular time. Hence, the experience that we design for them must be of a capstone nature, supporting their synthesis and reflection about the many ideas and resources that they have encountered in activities leading up to the immersive experience.

One of our first design decisions was the selection of an instructional topic that would be sufficiently challenging to students so as to allow a sophisticated treatment using KCI, and ensure that students' experience within the immersive environment would provide distinct opportunities for perception, reflection or integration of scientific understandings. We also required a topic that was broad enough in scope to engage students for several sessions, including introductory (i.e. non-immersive) activities, as well as follow-up activities where they applied their new understandings. We chose the topics of biodiversity and evolution, which have many characteristics that would support our development of robust, engaging materials and interactions. The present paper focuses on the activities pertaining to the topic of evolution within the curriculum.

Evolution is a central idea in biology instruction, accounting for fundamental issues about how organisms came to their present form, explaining relatedness among different species, as well as how certain traits are passed down and accumulated over many generations (Kampourakis & Zogza, 2008). However, biological evolution has been recognised by teachers and researchers alike as being extremely challenging to learn and to teach, perhaps as a result of its complex systemic nature (Chi, Krisensen, & Roscoe, 2012), and the incommensurability of the scientific conceptualisations with students' incoming ideas (Demastes, Good, & Peebles, 1995; Mayr, 2002). In general, prior research on the learning and instruction of evolutionary biology promotes a constructivist approach that takes into account students' epistemic positions (see for example, Alters & Nelson, 2002; Anderson, 2007; Sandoval, 2003).

Chinn and Buckland (2012) advocated a model-based inquiry approach, as well as a focus on macroevolution (i.e. evolution on a grand scale, as opposed to the smaller scale processes within microevolution, such as allele frequency changes). However, such evolutionary phenomena are not easily accessible to student manipulations within a classroom setting. The present study seeks to leverage technology-enhanced learning environments to help students deeply engage in scientific inquiry, providing them with opportunities to experience evolutionary phenomena that would be otherwise geographically or temporally inaccessible to them. This paper addresses the following research question: *How can immersive environments and embodied interactions support a co-located group of students to collaboratively develop their understanding of evolutionary concepts?*

In the next two sections below, we review our theoretical perspective as well as the technology-enhanced learning environments that informed this work. We then report on two iterations of our design-based research project, with findings from the first influencing the designs of the second. We report on students' inquiry experience, examine their learning artefacts, and discuss the success of our environment and interactions.

Collaborative inquiry and knowledge communities

The theoretical foundations of constructivism and social constructivism underlie the efficacy of collaborative inquiry (Bransford, Brown, & Cocking, 2000; Krajcik, Slotta, McNeil, & Reiser, 2008) and knowledge communities (Slotta & Najafi, 2010). Many researchers have developed interventions where students engage in design, experimentation or other forms of inquiry, resulting in opportunities for the construction of scientific understandings (Linn & Eylon, 2006). Our emphasis on developing a collective learning experience, where all students are engaged as a coherent social body, adds an additional layer of sociocultural interactions (Lave & Wenger, 1991).

The notion of 'learning in a community' has been introduced by scholars to emphasise shared interests and goals, where community members (e.g. students in a classroom) share the responsibility of generating and building on each other's ideas (Kling & Courtright, 2003; Scardamalia & Bereiter, 2003). This idea of a knowledge community for classroom learning is often espoused as a means of helping students to develop twenty-first-century skills (Bereiter & Scardamalia, 2003; Slotta & Najafi, 2010). By engaging as a knowledge community, students can investigate a phenomenon and draw conclusions about it as a class, rather than as individuals working in a class. This learning approach includes an emphasis on traditional inquiry skills such as posing questions, gathering and analysing data, and constructing evidence-based arguments, but adds a strong focus on collaborative or collective processes (e.g. negotiating problems, or working towards a common goal) and seeks to establish a culture of inquiry (Lui, Tissenbaum, & Slotta, 2011).

While any specific knowledge community approach would have its own distinctive features, common elements include: a shared knowledge base, a focus on collaboration and discourse, building on the other's ideas, and a sense of collective epistemology (Bielazcyc & Collins, 2006; Slotta & Najafi, 2010). Having access to a collective knowledge base not only allows for ideas to be jointly developed, but it provides a shared artefact that can be discussed, explored and applied as a resource in inquiry activities, which serves to enhance a sense of product and purpose for the community.

Knowledge community approaches also share many implementation challenges. There is a challenge of meeting curriculum expectations – particularly for secondary science, where teachers are accountable to a heavy load of content expectations. Knowledge community approaches tend to emphasise depth of understanding over breadth of coverage. As Kling and Courtright (2003) observed, 'developing a group into a community is a major accomplishment that requires special processes and practices, and the experience is often both frustrating and satisfying for many of the participants' (p. 221). A potential explanation for the limited uptake with the research community is the high demand of time and human resources that is required for the design, implementation and evaluation of any knowledge community approach. The few published studies of a knowledge community approach report major challenges regarding instructional design and implementation (Sherin, Mendez, & Louis, 2004). Thus, while the knowledge community research tradition has earned great respect among scholars, it has not enjoyed great popularity or success within K–12 classrooms.

For teachers, there is a mismatch between the open-ended nature of a knowledge community approach and the requirements placed on them for content coverage – particularly in secondary science. Most teachers find it challenging to adopt a knowledge community approach, requiring substantial professional development and years of trial and refinement (Mintrop, 2004; Rico & Shulman, 2004; Sherin et al., 2004). In order for science classrooms to become twenty-first-century knowledge communities as envisioned by educational leaders and researchers (e.g. Collins & Halverson, 2009), we require research into new pedagogical models that include the effective elements of inquiry and knowledge communities, but are not as challenging for instructors (Slotta, 2010).

Knowledge community and inquiry

In an effort to make the knowledge community approach more accessible to K–12 science, Slotta and his colleagues (e.g. Slotta & Najafi, 2012; Slotta & Peters, 2008) have developed the Knowledge Community and Inquiry (KCI) model, which integrates scripted inquiry activities into a knowledge community to facilitate a culture of collective inquiry while still targeting specific curriculum objectives. Central to the KCI model are collaborative knowledge construction activities where students explore and investigate their own ideas as a community of learners and create knowledge artefacts that are aggregated into a knowledge base. The community knowledge base then serves as a resource for subsequent inquiry activities, where students are engaged in collaboration and reflection. A final requirement at the outset of any KCI design is that the inquiry activities must produce assessable learning outcomes that are aligned directly to the learning goals. At the end of the KCI unit, teachers must be in possession of student-generated artefacts that can be assessed to determine their learning of the science content and process goals that underlie the unit.

In order to assure a sense of 'real community', KCI further requires that common themes, ideas or interests that emerge during inquiry must also be incorporated into the design of the inquiry activities. This presents a difficult challenge for curriculum designers because the inquiry activities cannot be fully specified, since the community themes and interests will not emerge until during the curriculum enactment (Peters & Slotta, 2010). Technology can play an essential role in aggregating information within the knowledge base, in visualising the collective knowledge, in promoting and supporting student contribution and in connecting the knowledge base to the inquiry activities as an essential resource (Najafi & Slotta, 2010). KCI requires a co-design process (Penuel, Roschelle, & Shechtman, 2007), where the classroom teacher (or teachers) works closely with researchers to develop a multi-week (often semester-long) curriculum that adheres to the KCI model while also meeting curriculum expectations.

In the first implementation of KCI, 104 grade ten biology students from four class sections worked as a community, creating and then collaboratively editing wiki pages that described human diseases from one of three different body systems:

respiratory, digestive or circulatory. Over the two-week physiology unit, students became experts in one of the systems, then worked in groups to create 'challenge cases' (involving fictitious characters exhibiting physical symptoms that required diagnosis) from their system that peers from the other systems were required to solve. Students worked across the four class sections to create a comprehensive and creative wiki (the knowledge base) and then engaged enthusiastically in the inquiry activities: creating challenge cases within their disease system (e.g. respiratory) and solving cases from the other two systems (e.g. circulatory and digestive). The knowledge base served as an important resource in the inquiry activities, and the challenge case provided assessable evidence of students' domain learning. In one learning outcome measure, the scores for the physiology section of the exam were found to be significantly higher than scores from the same teachers' students on that section of the exam from the previous two years (Peters & Slotta, 2010).

A more recent KCI curriculum on climate change followed 109 grade ten students from five sections of a high school biology course as they created a more complex knowledge base in a technology environment based on the Drupal content management system (Najafi, Zhao, & Slotta, 2011; Slotta & Najafi, 2012). Here, KCI was implemented in a much more substantive, 14-week curriculum unit that targeted specific science content goals. Students created a knowledge base that was defined according to important cross-cutting climate change issues. Each issue included specific sections for the various scientific areas (e.g. carbon sinks and sources, energy circulation in oceans and atmosphere etc.). Students worked in small groups across the course sections, and then engaged in focused inquiry tasks where they created, modelled and evaluated other groups' environment remediation proposals. Analysis of this study focused on the extent to which KCI was implemented in the design, the fidelity of enactment (i.e. did teachers and students perform what was designed) and level of student achievement on various inquiry and summative assessments (Slotta & Najafi, 2012).

These research efforts, and current work in progress, have suggested that the KCI model in its general form (i.e. from the basic principles outlined above) can be used to guide the design of an effective inquiry experience where the students in a classroom (or across several classrooms) work together to explore important issues and develop deep understandings of relevant science content. Ideally, KCI would benefit from interactions that encourage a richer, more social learning experience, where students are truly working or experiencing phenomena together in a community (i.e. as compared with the relative isolation of each student working on his or her own laptop). New forms of technology-mediated interaction can be supported through the use of large displays, small computers such as smart phones or tablets, location or identity tracking devices (e.g. RFID) and a variety of sophisticated techniques for the coordination of students, groups, activities and materials (Slotta, 2010).

Smart classrooms for knowledge communities

New interactive technologies (e.g. Smart boards, Nintendo Wii, Microsoft Kinect) and real-time computational platforms (e.g. context-aware applications or real-time messaging) have made it possible to develop applications that allow for more seamless collaboration, supporting new forms of collaborative inquiry in classrooms. With the parallel emergence of mobile and ubiquitous technologies, more complex and participatory forms of scientific inquiry may be envisioned. We have begun to re-focus our understanding of KCI, with renewed emphasis on the learning environment, including the physical space, as well as distributed forms of learning (i.e. where students might contribute their own observations or found content from their mobile phones, collected in various contexts).

To support such activities, we have advanced the concept of a 'smart classroom', where the physical environment (e.g. walls, furniture etc.) is infused with carefully designed digital tools and materials to support student interactions across multiple social planes, scaffolding seamless and dynamic collaboration, enhancing real-time face-to-face interactions and capturing the collective wisdom of the entire class (Slotta, 2010). Inspired by the research tradition in immersive virtual worlds, such as River City (Dede, 2009), we are investigating a possible new educative role for immersive simulations, where the room itself is converted into a rich simulation, and conceptual content is embedded within ubiquitous technology to support students in their inquiry activities. In the next section, we describe some of the relevant research that has informed our own efforts.

Technologies for collective inquiry

With the emergence of mobile and ubiquitous technologies, as well as Web 2.0 notions of social networking and semantic aggregation, more complex and participatory forms of collective inquiry may be realised, where students are engaged in scientific inquiry as a whole class, jointly negotiating problems and working towards a common goal (Lui et al., 2011). We apply the notion of collective inquiry to address student learning within a mixed-reality environment that augments face-to-face interactions with pertinent 'awareness' that is context-sensitive. Ideally, our smart classroom environment itself (i.e. the walls and furniture) could help orchestrate complex inquiry designs, capture student contributions and present aggregate visualisations, and respond to student interactions in real time.

Other scholars have recognised the potential for engaging students as a whole class within their physical environment. In Embedded Phenomenon, for example, a persistent scientific simulation is embedded within the walls or floor of the classroom (Moher, 2008). Students are tasked with monitoring and manipulating the state of the simulation, and gathering evidence to solve a problem or answer a question. In an Embedded Phenomenon known as WallCology, computer monitors placed on various walls of the room act as viewports to an imaginary space inside the walls filled with the virtual flora (e.g. mould and scum) and fauna (e.g. various insects). Elementary school students identify and classify species, observe their habitat selection, perform population estimation, create food webs, evaluate predator–prey relationships and predict response to environmental change. Another interesting example is provided by the 'Mr. Vetro' Collective Simulation, where different organ systems are simulated on wirelessly connected computers in the classroom (Ioannidou et al., 2010). A central computer manages Mr. Vetro's vital signs based on the aggregated information from the distributed client machines. High school students work in groups to vary parameters based on specific goals (e.g. students in the lung group realise that they need to provide more oxygen when Mr. Vetro engages in intense exercise), resulting in a summative representation of Mr. Vetro's health, which is projected on the front wall of the classroom.

The examples above illustrate the potential for scaffolding rich, collaborative learning activities in technology-enhanced classrooms – particularly if they are integrated with interactive or immersive media. However, there remains a need to understand how mixed-reality learning environments can contribute to classroom learning. How can we leverage computer-mediated communications to capture emergent knowledge, reflecting the 'wisdom of the crowd' while carefully balancing more active and engaging face-to-face interactions? In this paper, we explore how immersive environments may be used to augment face-to-face interactions and investigate their potential for social forms of learning.

Embodiment and immersive environments

Research from the Learning Sciences and Human–Computer Interaction reveal an increasing focus on theories of embodiment in learning (Price, Roussos, Falcao, & Sheridan, 2009). According to Varela, Thompson, and Rosch (1991), cognition 'depends upon the kinds of experience that comes from having a body with various sensorimotor capacities, and … these individual sensorimotor capacities are themselves embedded in a more encompassing biological, psychological, and cultural context' (p. 173). Multiuser online immersive virtual worlds aim for a sense of embodiment by representing the movement of 'avatars' that have location within a space, clear roles and a variety of possible interactions within that space (Birchfield et al., 2008). In the River City environment, for example, students are immersed in a nineteenth-century city, where they collaborate in teams of three or four to discover why people are getting sick and how they can resolve disease transmission issues (Dede, 2009). Using River City, students show improved learning of science concepts and scientific inquiry skills compared to those taught with conventional instruction or with a board game (Ketelhut, 2006; Nelson, 2007).

Unlike the avatars in online immersive environments, participatory simulations allow students to be *actually* embodied in particular roles – perhaps as a discrete element within a complex system – so that the properties or behaviour of the system are directly effected by their motions within the room or interactions with peers, objects or digital elements (Wilensky & Stroup, 1999). Such participatory role-playing can be augmented with networked technologies, such as wearable computers (e.g. 'Thinking Tags') to help collect information for the participant during the simulation (Resnick & Wilensky, 1998). Colella (2000) provided students with 'Thinking Tags' that transformed them into potential virus carriers; their mission was to greet as many people as they could without getting 'sick' and in so doing, to come to better understand the concepts underlying disease progression.

Other examples that incorporate immersion and embodiment include the Cave Automated Visualization Environment (CAVE; Cruz-Neira, Sandin, & DeFanti, 1993). The CAVE is a small surround-screen projection space in which audio and visual media are projected in order to present users with a walk-in feeling, as if they are in a certain geographical or historical space (Cruz-Neira et al., 1993). Such immersive environments have been developed for purposes of professional training in a number of disciplines, such as submarine operation (Hill, Gratch, & Johnson, 2001), medical preparedness (von Lubitz et al., 2001), rehabilitation (Tarr & Warren, 2002), mining (Kenyon & Afenya, 1995) and flight simulation (Simpson et al., 2004). SMALLab (Birchfield et al., 2008) is an example of a recent mixed-reality learning environment that allows students to interact through full-body 3D movements and gestures within a collaborative, digitally mediated space (Birchfield & Megowan-Romanowicz, 2009). It has been used with high school students studying geologic evolution by collaboratively constructing and then monitoring the earth's crust, identifying uplift and erosion over time (Birchfield & Megowan-Romanowicz, 2009).

Below, we introduce our own design of an immersive simulation that builds upon these ideas from the research literature, incorporating aspects of participatory simulations and full-body immersion to deeply engage students in conducting embodied scientific inquiry about their immediate surroundings. We then present our curriculum designs, and review two iterations of a design-based research project, with findings from the first incorporated into our designs of the second. We report on students' inquiry experience and examine the content of their learning artefacts. We close with a discussion of the features of our environment and interactions that made it successful.

EvoRoom

EvoRoom is a simulation of the rainforest ecosystem of Borneo and Sumatra, designed as an integrated element within a Grade 11 biology curriculum unit. Implemented within a 'smart classroom' research environment (Slotta, 2010), the room is equipped with computers, servers, projection displays and customised software to coordinate the flow of participants and content materials, as well as collect data during the activity. The smart classroom technology includes a user portal, allowing students to register and log into the room, an intelligent agent framework, allowing custom software 'agents' to track real-time interactions between students, peers and materials, and a central database for curriculum materials and the products of student interactions. In order to support a common, shared experience for students, the room is set up with two sets of large projected displays (typically six metres wide, achieved by 'stitching' together three projector displays) on opposite sides of the room that students examine together (Figures 1 and 2). Two interactive whiteboards are located at the front of the room. The simulation files are networked and controlled with a custom tablet application that allowed the teacher to manage the time spent in each portion of the activity, controlling the pedagogical flow within the room.

During the immersive simulation activities, students take on the role of 'field researchers' and work in various group configurations to complete tasks delivered to them on their personal tablet computers. The tablets provide scaffolds, place them in small groups and give real-time updates and resources. Student contributions (e.g. written reflections) are aggregated and displayed on the interactive whiteboards in real time and stored within a collective knowledge base.

Methods

Our study followed a design-based research method (Brown, 1992; Collins, Joseph, & Bielaczyc, 2004), where the central aim is to advance knowledge on implementing viable and effective educational innovations (Bereiter, 2002; Design-Based Research Collective, 2003). In design-based research, the innovation itself becomes an important outcome of the research, providing theoretical insight to inform improvements of the design. We also include an emphasis on co-design, where our curriculum was designed in close collaboration with the teacher who would be

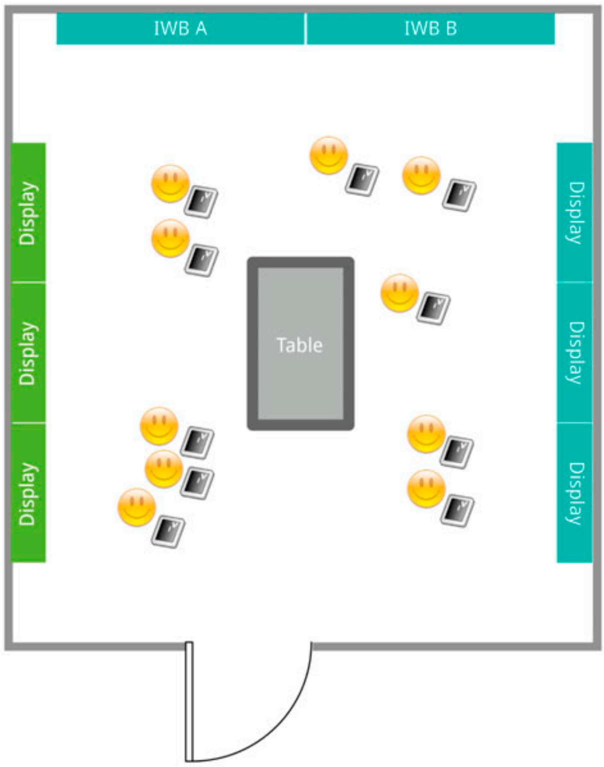

Figure 1. Smart classroom setup for EvoRoom.

Figure 2. Three projectors make up a sidewall of EvoRoom.

enacting it in her classroom. Co-design has been advanced (e.g. Penuel et al., 2007) as a means of ensuring that the classroom teacher is a true research partner, providing important pedagogical input and developing a deep appreciation of the end product. Co-design ensures that, at the endpoint of the design process, the teacher will feel a sense of ownership and command over the (potentially quite complex) instructional design.

Our team of researchers, designers, technology developers and a high school teacher met regularly to develop curriculum activities and the immersive simulation itself. The first iteration was evaluated after six months of design work as a pilot study, with the second iteration implemented in the following school semester (after another six months of re-design) as part of the biology course.

Participants

The first iteration was conducted with eight high school student volunteers who had completed Grade 11 biology. The second iteration was an evaluative study, including 45 students from two class sections of Grade 11 biology (taught by our co-design teacher).

Procedure

Iteration 1 was conducted in a single two-hour session, which took part in the smart classroom one week after the end of the academic school year, and provided important insight into formative aspects of the design, including the collaborative activities, media elements and interactions. Iteration 2 was embedded within a broader 12-week curriculum design, but included approximately the same amount of contact with EvoRoom – approximately two hours. Iteration 2 included three 45-minute visits to EvoRoom, carefully designed to leverage a set of in-class and homework activities (Table 1). We examine the impact of EvoRoom on student ideas about evolutionary concepts across the two iterations.

Assessments and measures

For each design iteration, students completed pre-/post-activity questionnaires. During the activity, video recordings captured student interactions, while knowledge artefacts created by students (e.g. notes) were collected as measures of the quality of student ideas. In the second iteration, a pre-/post-test was also administered to determine students' understanding of evolution concepts. The Concept Inventory of Natural Selection (CINS; Anderson, Fischer, & Norman, 2002) was used as a source of the conceptual elements on the pre-/post-assessments.

Activity design

Iteration 1

The first iteration of EvoRoom was quite basic, with students entering the room to find large projected animations of the rainforest ecosystem on the left- and right-hand walls, with the rainforest scenery, plants and animals rendered as computer animations. Using the smart classroom's integrated audio system, we played

Table 1. Summary of the activity sequence for Iteration 2: in-class (I), homework (H), and smart classroom (S).

Week	Description	Curricular goals
1	• Introduction (I) • Assign groups and specialty categories (i.e. plants & insects, birds, primates, and other mammals; I) • Review field guide (H) • Zoo field trip group assignment (I)	• Become familiar with assigned organisms • Understand scientific connections (e.g. taxonomy and phylogeny) between related species
2	• Collaborative food web activity (I) • Assign environmental impact variable (I) • Prediction analysis group assignment (H)	• Understand relationships among a set of species (e.g. in the Borneo rainforest) • Understand how environmental factors (e.g. high/low rainfall, tsunami, earthquake) affect ecosystems
3	• EvoRoom: Biodiversity activity (S) • EvoRoom debrief discussion (I) • Personal reflection (H)	• Improve understanding of complex interrelationships within an ecosystem and implications of environmental factors on biodiversity
4	• Traditional teaching on the origin of life, contributions to the theory of evolution	
5	• Traditional teaching on molecular evidence of evolution and micro-evolution	
6	• Traditional teaching on variation, selective advantage, natural selection	
7	• Traditional teaching on mechanisms of evolution, including sexual selection, gene flow, genetic drift	
8	• Understanding of evolution survey (H)	• Reflect on personal understanding of evolution
9	• Relatedness of species in Borneo and Sumatra assignment (H)	• Understand concept of 'relatedness' and how assigned species are related to each other
10	• EvoRoom: Evolution processes day 1 (S)	• Make connections between evolutionary mechanisms (learned in class) to the organisms in a specific ecosystem

(*Continued*)

Table 1. (*Continued*).

Week	Description	Curricular goals
	• Evolutionary mechanisms tagging (H)	• Improve understanding of different organisms' lineages with respect to evolutionary forces over millions of years
11	• EvoRoom: Evolution processes day 2 (S)	
12	• Personal reflection (H)	

ambient background recordings of rainforest insects, hung mosquito nets from the ceiling and included large potted palm plants in the corners of the room. The result was an immersive experience of *Sundaland*, a region in Southeast Asia predating Borneo and Sumatra, about two million years ago. After the premise of the activity was introduced, and the historical context of the rainforest environment explained, students were scaffolded by their tablets to record field observations about various species within the EvoRoom. This employed a custom software application that was integrated within the broader smart classroom infrastructure. An interactive whiteboard was designed to represent the emerging aggregation of student observations, updated in real time as students entered them from their tablet computers.

The teacher also had a tablet computer, providing controls to the various elements of the room. For example, using a tablet screen controller, she could advance the room through time, revealing a sequence of geologic events that affected the Sundaland landscape over the span of two million years. On the interactive whiteboards at the front of the room, students observed changes in sea level that broke Sundaland's central landmass into a peninsula and several islands, including Borneo and Sumatra. When the teacher then set the room's timeline to 'present day', one side of the room showed Borneo's ecosystem, while the other side showed Sumatra's. Observable differences between the two sides of the room reflected evolutionary separation that resulted when they became separated by ocean. Students spent 15 minutes making observations of the two sides of the room in this context. Next, they were divided into two field researcher teams: Borneo and Sumatra. Each group answered a set of questions designed to have students review and compared notes about their individual observations (e.g. in the Borneo group, students were asked *What common species were found in both Sundaland and Borneo?*). These observations were displayed on the summary board at the front of the room.

In the final step, the two teams came together to gather their collective observations about the process of evolution over this two-million year span (as captured by the emerging differences between the two sides of the room). Students were encouraged to discuss their ideas with others and to post ideas about evolution concepts. The posts were aggregated to the interactive whiteboard, visibly representing the collective knowledge base of the students at the end of the activity. The teacher was able to use the content of this display to lead a synthesis discussion to close the activity.

Iteration 2

The second iteration of the curriculum was informed by our analysis of student interactions within the first. We integrated the EvoRoom activities more deeply within the broader curriculum (see Table 1). All designs were guided by the goal of improving student learning about topics of evolution and biodiversity. Using a combination of in-class activities, a field trip to the zoo and homework activities, students engaged with several modes of instructional media, including paper and pencil for zoo worksheets, tablets computers, interactive whiteboards and large displays, and a class website (to support group work, reflections and homework).

Each class was divided into two cohorts, with one cohort at a time (approximately 12 students) engaging with EvoRoom. Students in each cohort were divided into four specialist categories: plants & insects, birds, primates, and other mammals. They held these specialisation topics for the duration of the curriculum, receiving specialised (i.e. differentiated) information about species via their class website (during non-immersive activities) and tablet computer (during EvoRoom activities).

Two EvoRoom sessions were developed (designated as 'day 1' and 'day 2'). For the first session, we greatly extended the timeline, such that students examined the Borneo rainforest as it may have appeared at nine different time periods: 200, 150, 100, 50, 25, 10, 5, 2 million years ago and present day (i.e. expanding on the 2 million year span that was depicted in Iteration 1). Students were assigned to teams, based on a strategy of maximising specialisations in each team (e.g. ideally, a group would include one student from each of the four specialisations).

On day 1, students used tablets to collectively construct a cladogram (a diagram showing descendancy relations amongst species over time) of their species, following five main steps. *Step 1: Orientation* – The teacher introduced the time periods (i.e. 200, 150, 100, 50, 25, 10, 5, 2 million years ago) that students were to examine. Using a custom-designed 'control tablet', the teacher stepped through each time period in sequence, giving an overview of important historical geological events through time. *Step 2: Rotation 1* – The teacher used the control tablet to start rotation 1, resulting in four projection stations showing the Borneo rainforest as it may have appeared at 200, 150, 100 and 50 million years ago. Students were asked to go to each station and look for their assigned specialty species. If the species were not present, they were asked to identify their predecessors from a short list that popped up. Their answers were recorded, resulting in the emergence of an aggregated, interactive cladogram on the interactive whiteboards at the front of the room. *Step 3: Meetup 1* – Students were instructed to get together with their team members at a location assigned by the software agents to review their work thus far. Each student was asked to discuss a specific question with his or her team and record the answer on the tablet. The students' answers were shown at the front interactive whiteboards. *Steps 4 and 5* (*Rotation 2* and *Meetup 2* respectively) were identical to steps 2 and 3, except students examined the remaining time periods (i.e. 25, 10, 5 and 2 million years ago). The result of this activity was an elaborate cladogram that expressed the historical emergence of the various species of interest across a 200 million year window (Figure 3).

As homework, students were assigned three organisms during day 1 of the activity. For each organism, they identified the main evolutionary mechanisms that were at work between 200 and 2 million years ago. All homework activities were implemented in the class website (which was a Drupal content management

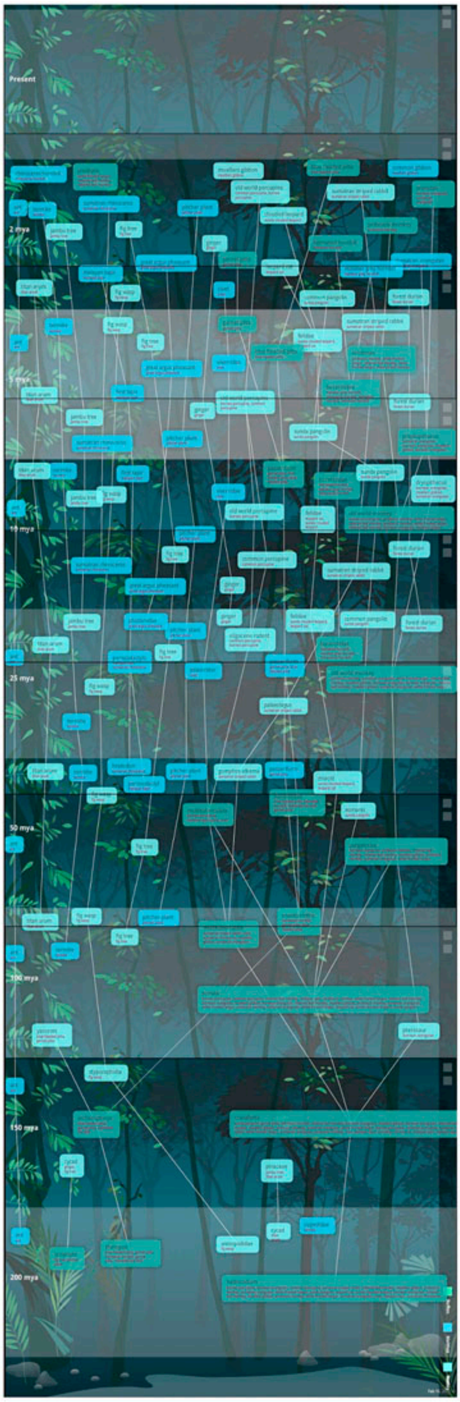

Figure 3. Cladogram that one cohort of students created during day 1 of the EvoRoom evolution processes activity.

system), created to support the student community for this course. Day 2 of the activities was similar in nature and goals to the activities of Iteration 1, but with more structured and scaffolded tasks (Figure 4).

Day 2 consisted of five main steps. *Step 1: 2 million years ago* – The room was 'set' at 2 million years ago, with the same rainforest version occupying both large screens on opposite walls of the room. Students were prompted by their tablet computers to write a brief note describing a specific feature (e.g. long limbs) for each of their assigned organisms, and to reflect on what evolutionary mechanisms might be responsible for that feature. This step was designed to integrate the information from day 1 of the activity and their homework. *Step 2: Transition* – Using the control tablet, the teacher transitioned the room from 2 million years ago to present day, by launching an animation sequence. During the animation, the teacher described how climate changes had caused water levels to rise and fall, and noted that the Sumatran mainland eventually became a peninsula and several islands, which included Borneo and Sumatra. Animals on the two islands had evolved along separate trajectories, particularly once the connecting land bridge had disappeared for the last time. *Step 3: Present day* – Students were presented with the Borneo rainforest on one side of the room and the Sumatran rainforest on the other side. The students' task was to take notes about their assigned organisms on both sides. *Step 4: Brainstorm* – Using the aggregated information from the previous step (presented on the interactive whiteboards) as well as the cladogram they had created on day 1, students worked with their team members to articulate the evolutionary mechanisms, contributing notes about the mechanism and the species involved. Each student was responsible for making notes about his or her assigned organisms. *Step 5: Class discussion* – The notes from step 4 were sent to the interactive whiteboards, which the teacher used to facilitate a class discussion about evolution. As homework after the evolution activity, students were asked to write a reflection of their experience in EvoRoom.

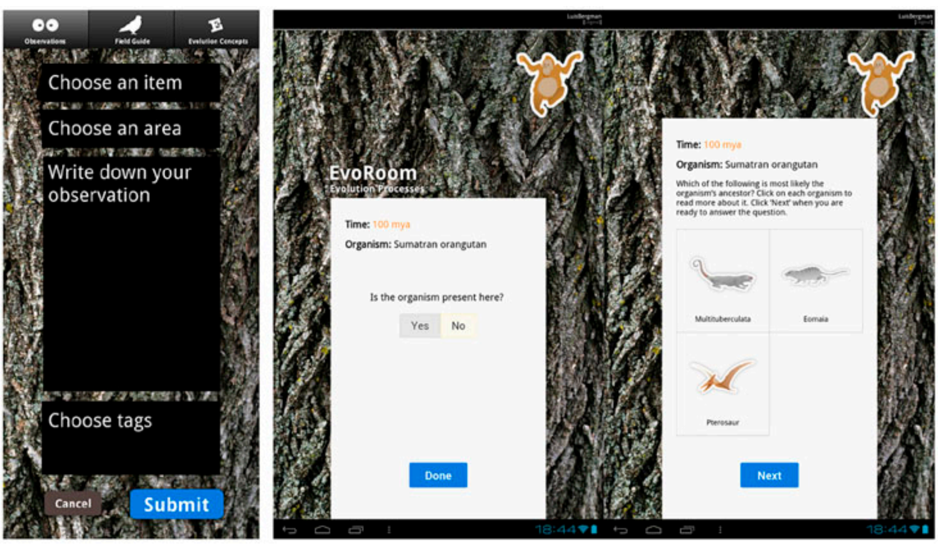

Figure 4. Tablet computer screens for Iteration 1 (left) and Iteration 2 (right). Note the open-ended nature of tasks given in the first iteration versus more structured format in the second.

Findings

Pre-/post-activity questionnaire

On a scale of 1 to 10 (with 1 being *unsuccessful* and 10 being *very successful*), students in Iteration 1 rated the use of tablets for accessing information with an average of 9 (*SD* = 0.58), while the use of tablets for adding observations was scored an average of 8 (*SD* = 1.35). Students from Iteration 2 rated the use of personal tablets in the smart classroom with an average of 7 (*SD* = 2.76). The immersivity of EvoRoom was rated highly, at an average of 9 out of 10 in both iterations (*SD* = 0.95 in Iteration 1, *SD* = 1.48 in Iteration 2).

Evolution content knowledge: the Concept Inventory of Natural Selection

In evaluating the overall curriculum, we wanted to know if it helped students to understand the challenging scientific concepts that characterise the topic of biological evolution. An independent-samples *t* test was conducted on the pre- and post-CINS questions to evaluate whether the curriculum supported students in understanding evolution concepts. The mean post-test score (*M* = 78.75, *SD* = 16.16) was significantly greater than the mean pre-test score, for CINS items (*M* = 59.40, *SD* = 19.00), $t(75) = 4.68$, $p < 0.001$. Because these items have been developed and validated by assessment researchers as a measure of the evolutionary processes concerned with natural selection, we are satisfied that this overall curriculum engaged students and helped them to learn within this notoriously challenging domain.

Student observations

In Iteration 1, students were asked to make free-form observations about any organism shown in the simulation. A total of 157 observations were made, with 49% about the species at 2 million years ago, 27% about those in the present-day Borneo environment and 24% about the species in Sumatra. Students wrote an average of 13 words per observation (e.g. ranging from 1 to 277 words). These notes were analysed following Chi's (1997) method for content analysis. Using an 'observation posting' as a unit of analysis, we coded for nature of the content: presence, physical characteristics, behaviour and evolution (see Figure 5). An inter-rater reliability analysis using the Kappa statistic was found to be 0.80 ($p < 0.001$), indicating substantial agreement. The notes tended to be about physical characteristics of certain organisms (41%) or about the animal's behaviour (57%).

In Iteration 2, students made structured observations about whether their assigned organisms were present at different time points, and if not, which ancient organism was most likely its predecessor. These observations were scored for accuracy: with a total of 1047 entries, 81% (*SD* = 10.33) were correct.

Students' conceptual learning: explanations of evolution

At the end of both iterations, students reflected on the following question: *What evolutionary forces do you think were at play in this environment?* They were asked to choose an evolution concept from a predefined list (e.g. adaptation, natural selection, sexual selection etc.) and explain their answers with sufficient evidence.

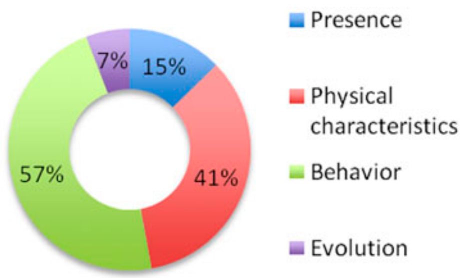

Figure 5. Content distribution of observations from Iteration 1 may be categorised as Presence (e.g. about the presence of species in a specific location), Physical characteristics, Behaviour or Evolution.

Fourteen explanations were collected in Iteration 1, while 43 were collected in Iteration 2 (Table 2). Figure 6 shows the distribution of evolutionary concepts that the explanations attempted to address. Explanations from the first iteration were predominately about adaptation (36%), with topics from the 'Other' category comprising of: co-evolution (21%), sexual selection (21%) and reproductive isolation (14%). In contrast, explanations from Iteration 2 covered a wider range of evolutionary concepts, with the highest levels of explanations focused on natural selection (33%) and adaptation (26%). Topics from the 'Other' category included: sexual selection (12%), co-evolution (7%), reproductive isolation (7%), gene flow (5%) and miscellaneous topics (12%).

The explanations were scored using a Knowledge Integration (KI) scale, that rewards valid scientific connections between concepts, scored on a 0 to 5 scale (Table 3; Linn & Elyon, 2011). While the explanations from Iteration 2 were scored higher, on average (M = 2.72, SD = 1.05) than those from Iteration 1 (M = 2.36,

Table 2. Descriptive summary of student explanations to the question, *what evolutionary forces do you think were at play in this environment?*

	Iteration 1 (n = 8)	Iteration 2 (n = 45)
Number of explanations	14	43
Average word count	24 (SD = 14.58)	33.28 (SD = 29.51)
Average KI score	2.36 (SD = 0.75)	2.72 (SD = 1.05)

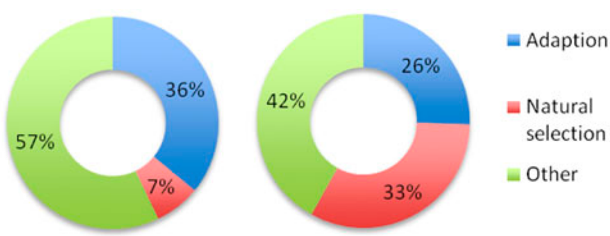

Figure 6. Distribution of evolutionary concepts that the explanations from the first (left) and second (right) iterations attempted to address.

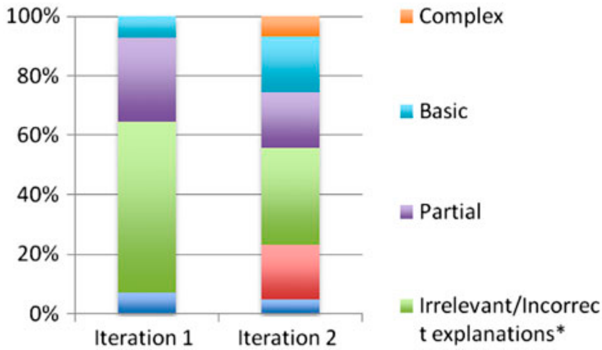

Figure 7. Distribution of KI scores for student explanations.

Table 3. KI rubric used to score student explanations. From Linn and Elyon (2011).

Score	KI level	Description
0	No answer	
1	Off-task	• Response is irrelevant or 'I don't know' • Student writes some text, but it does not answer the question being asked
2	Irrelevant/ Incorrect	• Have relevant ideas but fail to recognise links between them • Make links between relevant and irrelevant ideas • Have incorrect/irrelevant ideas
3	Partial	• Have relevant ideas but do not fully elaborate links between them in a given context
4	Basic	• Elaborate a scientifically valid link between two ideas relevant to a given context
5	Complex	• Elaborate two or more scientifically valid links among ideas relevant to a given context

SD = 0.75), this difference was not significant. In general, there was an increase in the complexity and sophistication of explanations from Iteration 1 (34%) to Iteration 2 (43%). Figure 7 displays the distribution of explanations based on their KI scores.

Discussion

Design improvements between iterations

By informing our designs of Iteration 2 materials and activities according to observations of Iteration 1, we found improvement in how students explored evolutionary concepts. We were in new territory, as (to our knowledge) few if any such environments had ever been created, particularly those designed to emphasise group-level curricular interactions. Iteration 1 provided our first glimpse into a working immersive simulation, giving us experience in seeing the room in action. This was vital to our design of effective applications within a high school biology curriculum.

Students and the teacher were excited and engaged by this experience, as were the researchers, for whom this was a 'first' in terms of their design of large format displays and immersive simulations. Iteration 1 provided a wealth of experience and insight in all aspects of the research, from the technology implementation, to the development of visualisations, tablet-based collaborative software and representations of community knowledge (on interactive whiteboards). The first iteration also reinforced many positive aspects of our designs, and provided a near-constant source of reference in our subsequent curriculum development efforts.

In Iteration 1, students showed considerable focus in their interactions with the materials, but their exchanges with peers were fairly regimented, and students were only able to make superficial evolutionary connections. The teacher remarked that more context was needed, and that student understanding and engagement would benefit from being integrated with a companion biodiversity module. We thus created the EvoRoom biodiversity module, which used the same simulations (i.e. of the Borneo rainforest), but with a restricted focus on the distribution of species and their dependency on environmental variables (Lui & Slotta, 2012).

Improvements in pre-/post-test scores demonstrated that students in Iteration 2, with its expanded connections to the curriculum and added biodiversity module, were successful in improving their understanding of evolutionary concepts. Moreover, increased depth and variation of evolutionary explanations written during the Iteration 2 activities (compared to those in Iteration 1) suggest that the design improvements succeeded in engaging students, helping them to establish ideas upon which they could build and make connections between classroom and smart classroom activities.

From 'free-form' to structured observations

The observations from the first iteration were rather basic. For example, an observation that focused on behaviour was, 'There are two tapirs, one walking really slowly and one drinking from a shallow pool.' An observation that focused on physical characteristics was, 'The fig wasp has purple wings, long antenna, and a striped body.' To help promote deeper explanations, we designed scaffolding for Iteration 2 that resulted in more structured observations. For instance, students were asked simple yes or no answers to the question, 'Is the organism present here?' Students were also asked to reflect more deeply on the larger patterns (e.g. in Meetup steps). Since they only observed their own assigned species, students relied on the work of their peers to understand the complete picture of how all the organisms evolved over time. Their answers were aggregated in real time (i.e. as each new reply was added) into an interactive whiteboard display at the front of the room (Figure 6) where they could be reviewed by teams of students. With students providing structured observations, we were also able to assess more easily whether they were paying attention to the correct elements of the visualisations.

Increased variation of evolutionary topics

The comparable KI scores of explanations between Iterations 1 and 2 seem to indicate that there was little improvement from one iteration to the next. However, when reviewing the content of the explanations, we found increased variation in the types of evolutionary concepts that students addressed. The nature of the explanations in Iteration 1 tended to be about surface features of the species observed, while the explanations in Iteration 2 focused more so on the processes of evolution, which was encouraging to see.

Student perceptions of EvoRoom

Our analysis of student perceptions in EvoRoom uncovered several findings about student learning in immersive environments. Students were supported by the tablet computers, with all tablet user interfaces designed to support student interactions with the materials, including the rainforest animations and the aggregated front displays. One student (from Iteration 1) mentioned that the tablet was ‘Really useful, especially when researching biological relationships between animals.’ Tablets also allowed students to move around whilst remaining connected with peers and supported by clear instructions and observation scaffolds.

The underlying technology framework (i.e. the smart classroom) supported a variety of representations of materials, coordinated student inquiry on an individual and small group level (i.e. guiding their activities, presenting the tasks and collecting all data). The use of the smart classroom (e.g. large screen projectors, immersive environment etc.) was also rated highly, eliciting comments such as ‘The use of [the smart classroom] offered an immersive virtual environment that made the activity much more engaging and entertaining. The fact that the animals were moving really added to the realism of the activity and how I responded to it’ – from Iteration 2. On the whole, we found that students were excited about the immersivity of EvoRoom and the use of tablet computers for supporting their learning.

Implementing the KCI model

Throughout our curriculum design, we referred to the principles of the KCI model as a theoretical reference. The goal of our research was much greater than simply to develop an immersive rainforest environment. We wanted to investigate how a group of students could interact productively within such an environment, and what forms of activity and materials would foster such interactions. We also sought to explore the role of such learning experiences within a broader theoretical perspective about learning and instruction. These goals shaped our designs of student observations and their aggregated display (i.e. for further discussion and progress). While strict adherence to KCI was not the explicit goal of this research, the model served as a theoretical foundation for our collective inquiry design. Hence, we prioritised the basic elements of the model: a community knowledge base that was indexed to the domain content (in this case, the various species and their relationships, represented as food webs and cladograms); and collaborative inquiry activities where students made use of the knowledge base as a resource.

Conclusion

Our analysis of student outcomes in two enactments of EvoRoom revealed important early-stage findings concerned with the design of immersive environments for collective or collaborative group-level inquiry, and how best to design effective learning activities for such environments (including their integration within a broader classroom curriculum). In the initial designs, we had made explicit efforts not to overly 'script' our collaborative activities, so as to encourage organic rather than forced discussions. However, the Iteration 1 trials suggested that collaborative activities may benefit from scaffolding, as well as added curricular context, including time for productive face-to-face interactions amongst students. Design principles for augmenting face-to-face interactions and knowledge co-construction will be essential to the development of mixed-reality environments, which will require a continuing research programme. On the whole, we found that students were excited about their collective, immersive experience of EvoRoom, and their use of tablet computers and large projected displays for supporting their learning.

Notes on contributors

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Dr Jim Slotta is an Associate Professor with the Department for Curriculum, Teaching, and Learning and the Centre for Science, Mathematics, and Technology Education at the Ontario Institute of Studies in Education. His research employs technology-enhanced learning environments to investigate cognitive models of learning and instruction. He is developing a pedagogical model called 'Knowledge Community and Inquiry', where students in a classroom work together to create a persistent knowledge resource, which then serves as a source of materials and inspiration to subsequent inquiry projects. He leads the development of an open source technology framework for smart classrooms called the Scalable Architecture for Interactive Learning.

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