J Sci Educ Technol (2009) 18:7–22
DOI 10.1007/s10956-008-9119-1

# Affordances and Limitations of Immersive Participatory Augmented Reality Simulations for Teaching and Learning

**Matt Dunleavy · Chris Dede · Rebecca Mitchell**

Published online: 3 September 2008


**Abstract** The purpose of this study was to document how teachers and students describe and comprehend the ways in which participating in an augmented reality (AR) simulation aids or hinders teaching and learning. Like the multi-user virtual environment (MUVE) interface that underlies Internet games, AR is a good medium for immersive collaborative simulation, but has different strengths and limitations than MUVEs. Within a design-based research project, the researchers conducted multiple qualitative case studies across two middle schools (6th and 7th grade) and one high school (10th grade) in the northeastern United States to document the affordances and limitations of AR simulations from the student and teacher perspective. The researchers collected data through formal and informal interviews, direct observations, web site posts, and site documents. Teachers and students reported that the technology-mediated narrative and the interactive, situated, collaborative problem solving affordances of the AR simulation were highly engaging, especially among students who had previously presented behavioral and academic challenges for the teachers. However, while the AR simulation provided potentially transformative added value, it simultaneously presented unique technological, managerial, and cognitive challenges to teaching and learning.

**Keywords** Augmented reality · Immersive participatory simulations · Classroom technology practices · Handheld devices · GPS devices

## Introduction

The last several years have seen an explosion in the amount of young people playing video games as well as the number of children and adolescents using mobile handheld technologies, such as portable music players, gaming platforms, and smart phones (Roberts et al. 2005; Squire 2006; Dieterle et al. 2007; Lenhart and Madden 2007). As school systems struggle with how best to deal with this cultural and technological shift, it is highly likely that the technology will continue to progress towards more powerful, GPS-enabled, location-aware, WIFI handheld computers that can deliver high quality, multimedia, computer processing power. Viewing this phenomenon as neither a panacea nor a plague, leading researchers in educational technology have stressed the need for more studies that explore if and how these technologies can be leveraged for enhanced learning (Heinecke et al. 2001; Means and Haertel 2004).

Three complementary technological interfaces are now shaping how people learn, with multiple implications for K-12 education (Dede 2002).

- The familiar *"world- to- the- desktop"* interface provides access to distributed knowledge and expertise across space and time through networked media. Sitting at their laptop or workstation, students can access distant experts and archives, communicate with peers, and participate in mentoring relationships and virtual communities of practice. This interface provides the

M. Dunleavy (✉)
Radford University, Radford, VA, USA
e-mail: mdunleavy@radford.edu

C. Dede · R. Mitchell
Harvard University, Cambridge, MA, USA

models for learning that now underlie most tools, applications, and media in K-12 education.

- Emerging *multi-user virtual environment (MUVE)* interfaces offer students an engaging "Alice in Wonderland" experience in which their digital emissaries in a graphical virtual context actively engage in experiences with the avatars of other participants and with computerized agents. MUVEs provide rich environments in which participants interact with digital objects and tools, such as historical photographs or virtual microscopes. Moreover, this interface facilitates novel forms of communication among avatars, using media such as text chat and virtual gestures. This type of "mediated immersion" (pervasive experiences within a digitally enhanced context), intermediate in complexity between the real world and paint-by-numbers exercises in K-12 classrooms, allows instructional designers to construct shared simulated experiences otherwise impossible in school settings. Researchers are exploring the affordances of such models for learning in K-12 education (Clarke et al. 2006; Barab et al. 2007; Neulight et al. 2007).
- *Augmented reality (AR)* interfaces enable "ubiquitous computing" models. Students carrying mobile wireless devices through real world contexts engage with virtual information superimposed on physical landscapes (such as a tree describing its botanical characteristics or a historic photograph offering a contrast with the present scene). This type of mediated immersion infuses digital resources throughout the real world, augmenting students' experiences and interactions. Researchers are starting to study how these models for learning aid students' engagement and understanding (Klopfer et al. 2004; Klopfer and Squire in press).

Immersion in virtual environments and augmented realities shapes participants' learning styles, strengths, and preferences in new ways beyond what using sophisticated computers and telecommunications has generated thus far, with multiple implications for K-12 education. Dede (2005) describes learning styles enhanced by mediated immersion in distributed-learning communities based on MUVE and AR interfaces as: (a) fluency in multiple media; (b) learning based on collectively seeking, sieving, and synthesizing experiences, rather than individually locating and absorbing information from some single best source; (c) active learning based on experience (real and simulated) that includes frequent opportunities for reflection; (d) expression through non-linear, associational webs of representations rather than linear "stories" (e.g., authoring a simulation and a webpage to express understanding, rather than a paper); and (e) co-design of learning experiences personalized to individual needs and preferences.

If we examine students' technology use outside of school, we see these shifts in learning styles happening in their informal, voluntary educational activities (Clarke et al. in press). For example, while the gaming model of one player sitting in front of a console is still prevalent, collaborative, mediated gameplay is rising. Massively multi-player online games (MMOG), such as the World of Warcraft (Blizzard Entertainment) and Everquest (Sony Online Entertainment), bring players together online where they can interact in a virtual, immersive, collaborative context. Emerging communities such as "modding," in which users create new content for games (often contributing to a shared database of models), and "machinima," in which users create new content via video capturing techniques, are further shaping how our nation's students now express themselves outside of school via collaborative digital experiences. Using their cell phones, portable gaming platforms, or personal digital assistants, kids also infuse virtual resources as they move around in the real world. For example, they use their cell phones to text their friends, to take and send pictures across distance, to access streaming audio and video files—even to make telephone calls! in their learning processes, many of these distributed communities among kids parallel the activities of twenty-first century professionals in knowledge-based workplaces.

In considering immersive participatory simulations for learning, the MUVE and AR interfaces pose an interesting contrast. In a MUVE, students are virtually embodied in a digital world. Everything they encounter is in virtual form, including fellow students with whom they are collaborating. Each one of their actions is captured and time-stamped by the interface: where they go, what they hear and say, what data they collect or access, etc. In contrast, in an AR students interact with a mixture of virtual and physical objects, people, and environments. They can communicate with teammates face-to-face, rather than the mediated interaction among avatars characteristic of MUVEs. Some of their actions are captured, so as where they walk and what data they collect; other behaviors, such as what they say to each other, are more difficult to collect. Unique affordances of MUVEs include the ability to do magic (for example, to teleport from place to place) and to capture every aspect of the learning experience for formative and summative assessment. Unique affordances of AR include the greater fidelity of real world environments, the ability of team members to talk face-to-face with its bandwidth on multiple dimensions, and the capacity to promote kinesthetic learning through physical movement through richly sensory spatial contexts.

However, despite the proliferation of sophisticated technology use outside of schools, typical classrooms seldom leverage the MUVE and AR interfaces described above for teaching and learning through immersive participatory simulation. This article describes early research into AR that attempts to assess its current strengths and limits for student engagement and learning in typical classroom settings. In particular, we research how participation in an augmented reality game, Alien Contact, supports teaching and learning at the same time illuminating the unique technological, managerial, and cognitive challenges.

## Theoretical Foundations for Augmented Reality Use in Education

Research on how people learn suggests that learning and cognition are complex social phenomena distributed across mind, activity, space, and time (Chaiklin and Lave 1993; Hutchins 1995; Wenger 1998). A student's engagement and identity as a learner is shaped by his or her collaborative participation in communities and groups, as well as the practices and beliefs of these communities. Yet creating classroom activities that allow students to engage in authentic practices that involve communities of learning is challenging, especially when it comes to authentic practices of science (Chinn and Malhotra 2002). For example, several investigators (Griffin 1995; Hendricks 2001) developed curricular activities in an attempt to validate parts of situated learning theory, but were forced to modify their research designs due to the difficulty of implementing situated learning within the constraints of a K-12 classroom. As an alternative to practices located within a school, bringing students to a local hospital to work with epidemiologists and doctors to study an outbreak of whooping cough might provide an authentic, meaningful, and motivating context for students to master scientific content and inquiry skills (Clarke and Dede 2007). Yet, this is not feasible for a myriad of reasons including prohibitive cost and managerial challenges. Until recently, researchers have struggled to conduct research on natural and emergent learning situated in complex and authentic classroom practices in K-12 education.

Central to the situated learning theory perspective is belief that learning is embedded within, determined by, and inseparable from a particular physical and cultural setting (Brown et al. 1989; Chaiklin and Lave 1993). The unit of analysis is neither the individual nor the setting, but the relationship between the two, as indicated by the student's level of participation (Greeno 1998). From this perspective, learning and cognition are understood both as progress along trajectories of participation in communities of practice and as the ongoing transformation of identity (Wenger 1998). Through participation in schools, students develop patterns of participation that shape their identities as learners, including the ways in which they engage in learning and hold beliefs about their abilities to learn. As a trajectory, an identity is not an object that one owns once and for all; it is defined over time, evolves, and has a momentum of its own. Identity is what gives a flexible continuity to the various forms of participation in which one is engaged (Eckert and Wenger 1994, p. 17).

Furthermore, technology-mediated simulations and games afford opportunities to "recruit identities and encourage identity work and reflection… in clear and meaningful ways" (Gee 2003, p. 51). As defined by Gee (2003), video games have a unique capacity to activate, recruit, and cultivate a sense of projective identity that serves as a mediation between the students' real world identity and their virtual or game identity. Via gaming environments, students create and foster simulation or game identities whose goals and values intersect and interact with their real-world identities. If students buy-in and take ownership of these virtual identities, the virtual identities can then be leveraged to influence and shape the ongoing transformation of real-world identities (Gee 2003). The transformational potential of this *identity principle* is integral to the AR project described in this paper.

In the first of the two JSET issues on the special theme of games and immersive participatory simulations, Squire and Jan (2007) describe AR as:

> …games played in the real world with the support of digital devices (PDAs, cellphones) that create a fictional layer on top of the real world context… Place-based augmented reality games are played in specific real-world locations (historical, geographical sites) and use handheld computers with global positioning systems to augment users' experience of space with additional data (text, numerical data, audio, video). (p. 6)

Similarly, we used handheld computers coupled with Global Positioning System (GPS) devices to develop outdoor AR simulations. However, instead of a place-dependent approach, we developed a place-independent AR simulation, which can be superimposed onto any physical area. As conducting multiple field trips in school settings can be problematic, we wanted an AR curriculum that any teacher could implement immediately outside the school building in an area such as a school playground, sports field, or parking lot. Drawing upon a recurring popular theme in the video game and entertainment industry, e.g., Halo 3 (Microsoft), Alien vs. Predator, etc., our research team developed an AR simulation called *Alien Contact!*

## Alien Contact! Simulation Overview

With funding from the U.S. Department of Education and in collaboration with MIT and the University of Wisconsin at Madison, we designed *Alien Contact!* to teach math, language arts, and scientific literacy skills to middle and high school students. This narrative-driven, inquiry-based AR simulation is played on a Dell Axim X51 handheld computer and uses GPS technology to correlate the students' real world location to their virtual location in the simulation's digital world (Fig. 1).

As the students move around a physical location, such as their school playground or sports fields (Fig. 2), a map on their handheld displays digital objects and virtual people who exist in an AR world superimposed on real space (Fig. 3). When students come within approximately 30 feet

Fig. 1 Dell Axim & GPS receiver

Fig. 2 Students exploring school grounds


Fig. 3 Handheld display of digital objects on school grounds

of these digital artifacts, the AR and GPS software triggers video, audio, and text files, which provide narrative, navigation and collaboration cues as well as academic challenges.

In *Alien Contact!* the students are presented with the following scenario: Aliens have landed on Earth and seem to be preparing for a number of alternative actions, including peaceful contact, invasion, plundering, or simply returning to their home planet. Working in teams (four pupils per team), the students must explore the AR world, interviewing virtual characters, collecting digital items, and solving math, language arts, and scientific literacy puzzles to determine why the aliens have landed.

Each team has four roles: Chemist, Cryptologist, Computer Hacker, and FBI Agent. Depending upon his or her role, each student will see different and incomplete pieces of evidence. To successfully navigate the AR environment and solve various puzzles, the students must share information and collaborate with their teammates. For example, when presented with a digital piece of alien spacecraft debris, each team member receives a different dimension of the wreckage to measure or a unique clue as to how to measure it. If the students do not collaborate and jigsaw their individual pieces of information, they will not be able to solve the problem and advance to the next stage. As students explore the physical space and collect digital data, they will discover evidence supporting alternative possibilities for why the aliens may have landed. For the purposes of this study, the roles were randomly assigned to the students regardless of academic strengths and weaknesses. However, future implementations may purposefully use roles and the role-specific content to accommodate, leverage, remediate or reinforce various skills sets of individual students.

*Alien Contact!* is based on Massachusetts state standards and fosters multiple higher-order thinking skills. In designing this unit, the research team targeted concepts in math, language arts, and scientific literacy typically difficult for middle school students to master. Using the spring

2005 8th grade Massachusetts Comprehensive Assessment System (MCAS) test as a reference to determine high-need areas, the researchers focused primarily on aspects of ratio, proportion, and indirect measurement (Math Standard 6.M.3, 8.M.4, 8.N.3) in combination with how English vocabulary has been influenced by Latin and Greek languages (ELA Standard 4.18, 4.21, 4.24). However, other math and English language arts standards are embedded within the unit, such as reading graphs (Math 6.P.6, 8.D.2) as well as group discussions and presentations (ELA 2.4, 3.8, 3.9, 3.11, 3.13).

In addition, the simulation content and structure are designed to allow for multiple entry points on which teachers may build in future iterations. The design allows teachers the flexibility to emphasize: (1) different academic standards; (2) different content areas (math, English/language arts, science, social studies/history); and (3) different current events (energy crisis, oil shortage, global nuclear threat, cultural differences). In addition, *Alien Contact!* is designed with multiple potential layers of complexity. For example, during the game the students are asked to solve mathematical puzzles to get four-digit codes that unlock virtual buildings containing evidence. The sequence of the resulting codes represents a Fibonacci sequence, i.e., 1, 1, 2, 3, 5, 8, 13, 21, 34.

This design rationale is three-fold: (1) build in multiple entry points for teachers; (2) build in mathematical and linguistic patterns that, when recognized, reveal the ubiquity and mystery of mathematics and language; and (3) build in multiple layers of complexity that will engage and challenge students regardless of ability and will provide teachers opportunities for differentiation. As the researchers are trying to engage students in math, language arts, and science, they are attempting to capitalize on some of the inherent properties in these fields that are fascinating (e.g., Fibonacci sequence, golden ratio, ancient languages and cultures) beyond the particular academic standards targeted. Additionally, we draw on principles of good pedagogy, such as the modified jigsaw method discussed above. The jigsaw method is an integral component of *Alien Contact!* and seems perfectly suited for the affordances of AR, which has the capacity to present each student with distinct and incomplete pieces of data or the game space. This method overlaps significantly with the areas of reciprocal teaching, distributed knowledge, and other socio-cultural approaches to learning (Gee 2003; Palincsar 1998).

Beyond good pedagogy and building connections to academic concepts, the units were designed to leverage principles of high-quality game design. AR and *Alien Contact!* in particular incorporate several elements from popular video games to increase learning and engagement: (1) narrative and setting; (2) differentiated role-playing; (3) master goal divided into subtasks; (4) interactivity; (5) choice; and (6) collaboration (Gee 2003). In *Alien Contact!* the narrative and setting is the unfolding saga of the aliens' interactions with Earth.

The master goal of the curriculum unit is to discover why the aliens have landed. However, in order to collect sufficient evidence to form a hypothesis, the students must successfully complete multiple subtasks requiring math, language arts, and scientific literacy skills. Throughout the scenario, the students have rich interactions with virtual characters, digital items, and each other to navigate the game space. Choice and collaboration are embedded within the entire unit. Finally, the entire scenario is open-ended, with multiple possible explanations for why the aliens have landed.

## Methods

### Methodology

The purpose of this study was to understand how middle and high school teachers and students describe teaching and learning within a participatory AR simulation; hence, a design based approach with an emphasis on multiple case study design was employed (Stake 1995; Miles and Huberman 1994; Yin 2003). The research aimed at understanding how teachers and students made sense of and used AR while participating in *Alien Contact!* Three case study sites were chosen for in-depth examination of this phenomenon. Across the three case study sites, the researchers sampled a total of six teachers from the core subject areas of math, science, and English in order to understand generally the phenomenon of AR simulations within varied school contexts and content areas.

As the research progressed, the design was formalized so that attention was focused on contextual variables derived from the conceptual framework (see Appendix A) that influenced the desirability, practicality, and effectiveness of the AR simulation design (Dede 2005; Stake 1995). The researchers triangulated the data through the use of multiple types of data (observations, interviews, documents), multiple sources (teachers, students), and multiple researchers. The two primary research questions are:

1. How do students describe and comprehend the ways in which playing AR simulations aids or hinders their

understanding of math and their development of literacy skills?
2. How do teachers describe and understand their experience using AR curricula in their classrooms?

## Sites and Participants

The participants in this study were students and teachers in two middle schools (6th and 7th grade) and one high school (10th grade) in the northeastern United States. Researchers identified these schools primarily through convenience sampling (willingness to participate). Over the course of the year, the research team collected data from the six teachers and approximately 80 middle and high school students. Table 1 presents demographic information on the population from which the sample analyzed for this paper were drawn.

## Data Collection

A team of seven researchers spent approximately 100 hours over the course of a the 2006–2007 academic year on site at the three schools collecting data (see Table 2 for a summary of the data collection procedures). As can be inferred from the ratio of researchers to teachers, providing adequate support to the teachers during the implementation was critical. The research team had on average of three people in the class/field to support the teacher and collect data. This was sufficient to do both well. These high teacher support numbers directly impact the feasibility of scalability, which will be detailed in the *Implications and Conclusions* section. The data sources are formal and informal interviews, direct observations, site documents, and web site postings. The researchers conducted observations with a modified version of the Reformed Teaching Observation Protocol (RTOP), which was designed to document teaching practices in practices in science and mathematics classrooms. One of the rationales for using the RTOP was the presence of strong training materials as well as online video resources to increase the inter-rater reliability among multiple observers (Sawada et al. (2002). The entire research team conducted the online training to increase inter-rater reliability. Interviews were conducted with: (1) all six participating teachers; and (2) a sample of students from each site. The interviews and focus groups were structured around a set of questions derived from the conceptual framework and research questions. All interviews were videotaped while the researchers took notes on responses. The researchers systematically observed each teacher an average of approximately 9 h. The teachers volunteered to participate in the AR study and were aware that they would be observed throughout the implementations. Observations were conducted using an observation protocol congruent with the conceptual framework and research questions. Observation notes, field notes, and video data were compiled for within-case analysis and cross-case analysis.

**Table 2** Data collection procedures

| Procedure | Number | Total time (h) |
|---|---|---|
| Observations | 61 | 87 |
| Formal interviews | 9 | 9 |
| Informal interviews | 20+ | 4 |
| Website postings | 50 | – |
| Total | 140+ | 100 |

## Data Analysis

### *Within-Site Data Analysis*

Using *Atlas*, a qualitative analysis program, the researchers analyzed the observation field notes and interview transcripts using a structured coding scheme based on the conceptual framework of the study and an initial round of open coding (Strauss and Corbin 1998). The first round of open coding resulted in 30 descriptive codes. These descriptive codes were used in an iterative process of within-site pattern-matching analysis, which was progressively more inferential and explanatory with each round of coding (Miles and Huberman 1994). Using the data gleaned with this first level coding process, the researchers analyzed the code reports for the possible linkages between the effective learning environments theoretical framework and AR affordances.

**Table 1** Demographic Information for School Sites

| School name | Level | Grades served | Enrollment | District type | Percentage poverty[a] | Percentage minority[b] |
|---|---|---|---|---|---|---|
| Jefferson high school | High | 9–12 | 424 | Urban | 72.5 | 95 |
| Wesley middle school | Middle | 6–8 | 551 | Urban | 29.7 | 17 |
| Einstein middle school | Middle | 6–8 | 972 | Urban | 81.8 | 87 |

[a] Free and reduced lunch percentage

[b] African American, Hispanic, Asian, Pacific Islander, American Indian, Filipino

*Cross-Site Data Analysis*

The individual case studies were used for the cross-case analysis. The focus of the cross-site analysis was on various factors identified from the conceptual framework; hence emphasis was placed on the similarities across the cases with regards to the phenomenon and factors of interest (Stake 1995). Variations in the phenomenon of use and causal explanations of those variations were not the focus of this study. Returning to the theoretical and organizational conceptual framework, the authors created a case ordered cross-site data matrix categorizing the data accordingly. Pattern-matching analysis, in which each case served as a comparative context for the other, was used to determine if there were significant patterns of use that capitalized on the unique affordances of AR across sites as well as significant patterns of limitations across sites. Tactics used for the pattern matching were making comparisons and contrasts among cases, as well as counting the frequency of a use or challenge across cases.

Across case studies, the authors documented high student engagement, which the teachers and students attributed to the unique affordances of the AR simulation. However, the authors also documented significant teaching and learning challenges within the AR environment, which at this point in the research and development cycle makes large-scale AR implementations prohibitively difficult.

## Results

### High Student Engagement

The research team documented high student engagement across the three sites over the course of the year. While high motivation and engagement seems logical and almost a given during an activity that has students go outside with handheld computers and search for clues about aliens, it was nonetheless a critical threshold that needed to be reached during this first year of the AR design development. Furthermore, in light of the nascent status of AR research and the use of the design-based research approach, identifying the specific elements that students and teachers found most motivating is critical for developing progressively more effective AR curricula.

Students and teachers reported the most motivating and/or engaging factors of *Alien Contact!* were:

*Using the Handhelds and GPS to Learn*

The students most frequently reported that using the handheld computers and the GPS to navigate and collect data were highly motivating. The following student interview and chat room responses are representative of this finding:

> The handheld was cool. We got to learn math and English not in the classroom but outside with the handhelds…it made it more fun than just in the classroom writing on the board (Student Interview 11/22/06).
> Using the handhelds was pretty fun. It was new… nothing (like) we really do in school…exciting (Student Interview 11/22/06).
> It gave us a chance to go out of school to learn math and English. Plus you learn teamwork and you get to learn how to use those cool handhelds (Student Chat Room Posting 11/19/06).

In addition, observation data revealed students exchanging handhelds to communicate information and to solve problems collaboratively. The students would often exchange machines to look at each other's problems or simply show their screens to the team members rather than telling them what information they had (see Figs. 4, 5). This behavior is indicative of a high level of observable comfort with new or unfamiliar technology.

Finally, the research team documented two additional handheld-related behaviors, which while seeming to indicate a high level of engagement with the handheld may also present teaching and learning challenges unique to AR. As students navigated through the game space, they were frequently observed ignoring the physical space around them to focus exclusively on the data being presented via the handheld. The research team recorded multiple examples of students being so engaged in the game environment that they lost track of their real environment. Beyond the obvious safety concerns related to students ignoring their environment while walking in an urban setting, this engrossment could actually be counterproductive if the AR simulation is designed to incorporate

**Fig. 4** Students showing each other information on a handheld

**Fig. 5** Students exchanging/sharing handhelds to solve problems

the physical space into the learning experience. Furthermore, students often become so engrossed in beaming information to each other via the infrared function that they ran out of time to complete the more important activities, such as finding and analyzing data or sharing and discussing the data with their teammates.

### *Collecting Data Outside*

Students and teachers also reported that the physical exploration of the school grounds (i.e., playground, sports field, neighborhood) was highly motivating.

The following student interview and chat room responses are representative of this finding:

> This project also gave a chance for us to go out of the school and learn more stuff (Student Chat Room Posting 11/19/06).
> …the fact that we got to go outside more than one day at a time…it was different and fun, mostly in school we just sit here and do nothing basically (Student Interview 11/22/06).

In response to the question of what they liked about the implementations, students often mentioned going outside:

> …usually we don't go outside and interact like how we did (Student interview, 11/22/06).
> When we go outside, we use our handhelds to try and interact with our environment (Student interview, 11/22/06).

When probed about why being outside was beneficial, most students talked about the novelty of being outside and doing mathematics in a non-typical manner. To students and teachers both, engaging in mathematical tasks on evidence found in the field, whether digital or physical, also felt more authentic, more like the way a real scientist might use mathematics as a tool to solve a problem. Since students were engaged in academic subjects outside of the classroom, it seemed more like real work. Some students became so immersed in the context of the alien crash, that they would ask researchers if "aliens really crashed" at their school or if the researchers were" really FBI agents".

At the same time, there are some issues that AR developers might keep in mind regarding gameplay outside. The first is that when the weather was too warm or cold, student engagement dropped significantly, and rain (although wrapping the machines in sandwich bags worked well for light rain) often meant staying indoors, hindering student ability to fully engage with the AR. The second is that many students have a difficult time orienting themselves in the real world based on where they appear on the handheld. The research team often observed students looking for characters in the opposite direction from where they should have been, walking toward the baseball diamond when the character was located further away from the diamond. Gaining orienteering strategies might be an unexpected learning outcome from student use of AR curricula.

The inherent physical component of AR is not only motivating but also provides unique opportunities to create authentic and novel learning environments, which utilize both real and digital items within an outdoor physical space. In *Alien Contact!* students encounter both digital items via their handhelds and physical artifacts via the environment that, when combined, require them to solve mathematics, literacy, and science challenges. As reported by students and teachers, this experientially immersive affordance of AR allows students to develop a strong sense of engagement with the narrative and the physical space.

### *Distributed Knowledge, Positive Interdependence and Roles*

During the AR simulations, each student would receive distinct and incomplete pieces of data that required him or her to collaborate with team members to successfully navigate the area and solve the problems. For example, when students encounter a physical artifact representing an alien wing, the team members each received a different piece of digital data via the handhelds that helped them measure the wing and determine its significance (Figs. 6–9).

The fourth member of the team, Computer Hacker, also receives information and prompting questions that helps the team organize their data and discuss their strategy.

As this example shows, the research team created team-based problem solving challenges in which each student provided a unique, necessary, and complementary area of

A piece of alien wing debris was found at this exact spot on the crash site. The FBI took the wig but left a scale model for you to look at. Locate the purple triangle on the ground.

This is the scale model, which your team will now need to measure using an object of your choice. Unfortunately, you do not have any rulers with you and you will have to improvise. Each of you has a different clue to figure out how best to measure and analyze the wing dimensions. Good luck!

**Fig. 6** Chemist wing information

You have had practice measuring the length of a footprint with a pencil. Help your teammates find a way to measure the lengths of the sides of this triangle using any of the objects you have with you (we suggest something smaller than a pencil).
When you are done, go see what else can be found at the crash site.

**Fig. 7** Cryptologist wing information

Data on Military Spacecraft
**Top Secret**
According to CIA data, in a **military spacecraft** the ratio of the longest side to the shortest side makes a fractions that reduces to 5/3

In other words, if this debris is from a military alien wing, it will have a proportion of:

$$\frac{\text{Longest side } =5}{\text{Shortest side } =3}$$

**Fig. 8** FBI agent wing information

knowledge. This jigsaw pedagogy capitalized on the affordance of handheld AR to provide differentiated information to each student. The vast majority of students reported that this interdependent nature of their teams as one of the most engaging and interesting features of AR:

> This project gave us a chance to communicate with our teammates to solve questions, to work together (to) solve problems. As long as we work together, we would get what we expect to get which is a good thing (Student Chat Room Posting 11/19/06).
> The part that I like is that we all had different things (pieces of information) (Student Interview 11/22/06).
> You needed everyone's help to figure out the code (Student Interview 4/9/07).

**Fig. 9** Team measuring "Alien Wing"

In addition to positive interdependence, students also reported that the related issue of roles was motivating:

> I like the fact that we were all in the same group but we weren't the exact same person… we each had separate roles so we were all one team but we also had our solo stuff, but we still needed everyone else in order to have a full picture or idea of what was going on. It gave you a sense of independence but it also gave you the (idea) that you have to ask for help when you need it (Student Interview 11/22/06).
> I enjoyed the group activities and the thought of having to be somebody you're not like an FBI Agent, a chemist, a linguist. I enjoyed it a lot (Student Interview 11/22/06).
> I like this project because…in normal projects we don't have special roles and now we have roles and we need each other and that makes us know each other more and (have) better teamwork (Student Interview 6/8/07).

When asked about how she thought the roles worked with the students, a participating teacher responded:

> They all took on an identity. They all felt strong ownership that they were an expert at this…and if they didn't have roles they may not have been as eager to work together because they really did need each person (Teacher Interview 6/8/07).

Both the students' and teacher's quotations capture the essence of *projective identity* that can be leveraged within AR simulations to motivate students and enhance instruction in a novel and potentially transformative way (Gee 2003).

## Logistical Limitations

In addition to the high engagement associated with the affordances of the AR simulation detailed above, significant challenges unique to AR environments were documented as well. The challenges fall generally into three categories listed in order of significance: (1) hardware and software issues; (2) logistical support and lesson management; and (3) student cognitive overload.

### *Hardware and Software Issues*

The most significant limitation of the AR simulation reported by both students and teachers was GPS-error. It is a safe prediction that much of the error documented in this study will most likely be eliminated as the technology evolves. However, currently the GPS error is prohibitively high for large-scale implementations. GPS failure rates of 15–30% were observed during the study, presenting significant challenges. The authors documented two major sources of the error: (1) software instability; and (2) the research team incorrectly setting up the handheld configurations. Both sources affect scalability and will be discussed further later. When students were asked what they did not like about learning using AR, GPS error was the most frequent response:

> The computer problems were really annoying (Student Interview 4/9/07).
> People were left behind when the computer froze (Student Interview 4/9/07).
> My GPS didn't work for like 10 minutes and I had to keep my team back (Student Interview 6/8/07).

Exacerbating the problem is the interdependent team-based approach, which is facilitated with the AR affordances and integral to *Alien Contact!* As reflected in the last two quotations, if one member out of a four-student team does not trigger a character/item while they are standing in the same location, problems cascade on multiple levels: management, engagement, learning, team cohesiveness, and jigsaw collaboration.

Participating teachers also identified the GPS error issue as highly problematic. When asked to identify the most critical component of the program, a participating teacher responded:

> Having the GPS work…For me that was the most frustrating in the whole project when we actually got out there the most exciting times…to have handfuls of kids that were just helpless and they couldn't do anything and that is such a buzz kill for them that everyone else is running around and so excited and they are just sitting there… You need to get that figured out…if this is a handheld and GPS-driven project (Teacher Interview 6/8/07).

This pointed statement by the teacher highlights the greatest challenge for AR developers and researchers. As a result of the high GPS-error, the research team needed to provide a significant amount of support and materials management.

### *Logistical Support and Management*

One of the themes emerging from the data is the high management overhead that accompanies an AR simulation implementation. The observation and interview data clearly reflect the reality that one or two teachers could not implement this AR unit as it is currently designed. In addition to maintaining the GPS signal during implementations, the support team also: (1) distributed and collected all hardware; (2) tried to keep groups together; (3) answered content and handheld interface questions (4) provided alternative handhelds to students whose machines had crashed (average 2 out of 15 per class); and (5) corralled the students out of the street. While some of these issues cannot be completely eliminated (1, 5), some will decrease in severity with improved design (3) and more sophisticated hardware and software (4). When asked how well they could implement an AR unit on their own, the teachers stressed the need for additional support:

> …From the teacher perspective, I think it was very overwhelming for me (Teacher Interview 11/22/06).
> Getting the kids out there, handing out the handhelds, getting all the glitches figured out, doing the activity, recollecting the handhelds, and getting them back into the building absolutely limits what you can do (Teacher Interview 6/8/07).
> If you guys (researchers) weren't jumping in and assisting…this would have flopped. There were too many glitches still that if… it was sink or swim for us, we would have sunk (Teacher Interview 6/8/07).

As a result of the high management requirements, providing adequate support to the teachers during the implementation was crucial. On average, three support personnel were present in every class or field implementation to support. The researchers documented that a minimum of two and an optimal number of three people on site were necessary to support the implementation and collect data. If research tasks such as data collection were removed, approximately two people in addition to the classroom teacher would be sufficient to manage the hardware and maintain the GPS signal through the implementation. This is a prohibitively high level of logistical support for scalable use.

*Student Cognitive Overload*

Students reported feeling frequently overwhelmed and confused with the amount of material and complexity of tasks they were asked to process during the simulation. When asked about this phenomenon, students and teachers highlighted some of the major problem areas:

> …some of the codes were confusing…so we just like gave up (Student Interview 11/14/06).
> A few of them said that they were clueless the entire time. It was too tough to try to learn the technology while also solving problems at the same time (Teacher Interview 4/13/07).
> …synthesizing is a difficult skill for 6th graders and this program requires a significant amount of consensus and synthesis (Teacher Interview 6/8/07).

As mentioned in the quotations above, students were exposed to and required to quickly apply multiple complex skills: geo-spatial navigation, collaborative problem solving, handheld manipulation, as well as the mathematics and literacy problems presented within the narrative. While it could be asserted that in isolation any of these skills would be easily accomplished, the synthesis of all these skills was problematic.

Unanticipated Emerging Themes

*Competition*

The researchers documented strong group identity and competition developing around most, but not all of the teams. Video data documented students whispering among their teammates when students from other teams approached, to avoid sharing information. A strong example of this was documented when the case study group was measuring the alien wing model (see Fig. 9 earlier). Other students accused the team of 'hogging' the wing, and the team accused another student of cheating as he tried to learn the information the team had uncovered as a result of measuring the wing (see Fig. 10). When another student from a different site was asked about helping other teams, he responded: "We are not helping anybody, we want to win" *(Observation Field Note 4/9/07).*

Directly related to competition, students were also observed racing through the simulation in an attempt to 'beat' the other teams (Fig. 11). According to students and teachers, this rushing/racing phenomenon seems to be a result of three factors: (1) unforeseen competitive nature developing between teams (as discussed above), which led to a "race through it" mentality; (2) too many characters and items on each day, which forced the students to rush through in order to complete that days' activities; and (3) the proximity of the teams and small simulation space led students to try to get answers from other teams by over hearing or looking over shoulders. Having two teams walking side-by-side and encountering the same data seems to naturally lead them to feel like it is a race to see who can solve the problems first.

**Fig. 10** Competition between teams: the female student with the clipboard is blocking another team's member who was trying to see their answers

**Fig. 11** Rushing/racing: the students are rushing to catch up with other teams who were further ahead in the scenario. This behavior led to skipping important text-based information

*Challenges of Working in a Hybrid Learning Environment*

The researchers encountered several challenges unique to this particular area of research, which involves using both digital and real artifacts to create a learning environment. The most obvious challenges resulted from using hardware that was not designed for outdoor use. For examples, while the handheld screen resolution, clarity, and contrast are excellent indoors, the information on the screen was often difficult to read on bright, sunny days due to the glare. A related challenge is the difficulty students encountered trying to listen to critical information while outside in a relatively noisy environment. The handheld speakers are adequate for indoor listening, but the audio tends to wash out and become difficult to hear in large open areas with ambient street and pedestrian noise. As a result, students were observed holding the handheld to their ear even when presented with video in order to hear the information. Obviously this defeats the purpose of presenting visual information, as the students cannot see the screen while holding the speaker to their ears. An inexpensive and effective solution for the audio is the use of headphones and antiglare screens work with varying degrees of success.

Finally, as discussed previously, the research team recorded multiple examples of students being so engaged in the handheld game environment that they lost track of their real environment. While this seems to be a positive indicator of high students engagement, students ignoring the physical space around them to focus exclusively on the handheld while walking in any environment represents a real threat to physical safety. During implementations in urban environments, researchers had to repeatedly remind students to get out of the street and move to the sidewalk. Furthermore, while this engrossment seems to be indicative of high engagement it is counterproductive to initially developing a strong sense of engagement with the physical space and then subsequently leveraging the space as part of the learning context.

*Previously Disengaged Students*

One of the more intriguing findings from this study is the documented engagement and motivation of students who had previously been disengaged and disinterested in school. Across sites, teachers reported a significant difference in the behavior and engagement of students during the AR implementation as compared to their normal classroom behavior:

> I saw a lot of the kids…the lower end ones who are sort of turned off of class at this point in the year…those kids were some of the most engaged (Teacher Interview 6/8/07).
>
> Most of the time in my classes, they can do the work, but they tend to get off track so easily. They love to chit chat and talk, but throughout this entire week and a half, they were focused, they were really engaged, they really wanted to figure out what the problem was…I think that group stands out to me as one of the strongest changes from how they used to work together before (Teacher Interview 11/20/06).
>
> Some of the kids who are on IEPs…I did notice the kids with ADD, there are a couple kids that will not sit in class at all and they were 100% engaged (Teacher Interview 6/8/07).

One of the greatest challenges for classroom teachers is trying to engage students who are unmotivated in conventional classrooms. The finding that these students are highly engaged during an AR unit is significant and encouraging.

## Discussion

As mentioned in the introduction, the students we work with are already using their cell phones seamlessly to communicate and share information with their peers throughout the day. The findings from this study emphasize how engaged students become simply by using similar tools to learn. While this use will continue to be a motivating factor regardless of content due to the inherent novelty effect, we can safely predict that this novelty engagement will fade as the students become accustomed to this method of learning. Therefore, identifying curricular-specific and technology-specific characteristics that the students found engaging or disengaging is critical for future development of AR curricula. It is reasonable to assert that the high level of engagement documented in this study can be maintained if the tools are coupled with sound pedagogy to teach meaningful skills.

The use of positive interdependent AR provides unique socio-cultural opportunities and challenges. One of the most obvious themes emerging from the findings is how dependent this iteration of AR is on student collaboration. As detailed above, the use of roles and the positive interdependence are integral components of *Alien Contact!* and are well suited for the affordances of AR, which has the capacity to present each student with distinct and incomplete pieces of data (Klopfer and Squire in press). Furthermore, the students reported that roles and the interdependent nature of their teams were engaging and interesting features. However, challenges derive from the fact that, if the students are not accustomed to this type of learning, it is difficult to successfully implement an interdependent AR unit without significant modeling, facilitating, and scaffolding of this skill. Working in groups is a skill set that must be fostered for it to effectively translate into desired behaviors such as reciprocal teaching, collaborative problem solving, or other social constructivist-based behaviors (Palincsar 1998).

Researchers also need to explore if designing an interdependent AR game that is not completely dependent upon each team member being present is a possibility. As is, if one of the roles is absent, it severely restricts if not disables the game. As a result of inevitable absences and scheduling conflicts, we created a couple of larger student groups, which in turn created redundant roles, (e.g., two chemists in the same team). We documented less collaborative activity in the larger groups, as some students simply relied on one or two of the seven members to do the majority of the work. Sometimes redundant roles worked together, but more often than not, the redundant roles resulted in one of the students being ignored since his or her information was not unique and, therefore, unnecessary. As a result, the student who was most successful in solving the problem was able to actively participate, while the less successful student was ignored. The use of roles and positive interdependence intersect significantly with the areas of reciprocal teaching, distributed knowledge, and other socio-cultural approaches to learning, but future AR implementations will have to determine how best to leverage these affordances.

In addition, the student competitiveness documented in this study may be a positive indication of engagement, but it also results in students rushing and skipping over critical text-based information. Future AR implementers can address this rushing tendency in several ways: (i) decrease the number of activities the students accomplish in one period; (ii) build in more opportunities for deep discussion and collaboration, which would slow the students down in their quest; (iii) create a less linear path so the students do not follow the same path as their classmates; and (iv) if space allows, expand the game space so that more physical space was possible between each team.

While the associated challenges detailed above need to be addressed in future AR implementations, the opportunity to leverage AR affordances to create rich collaborative inquiry via technology-mediated narrative holds great potential. For example, while the physical space and resulting physicality present unique challenges, they also provide unique opportunities. One of the more interesting areas for future research is to determine how best to leverage the hybrid environment of real and digital artifacts. As seen in this study, the use of a simple prop such as a model 'wing' (Figs. 4, 7), allowed for multiple teaching and learning opportunities that would otherwise be impossible. In addition, the use of the physical environment, even in a place-independent model, needs to be further explored. The use of generic physical items that can be found on any school playground, i.e., trees, fire hydrants, trash cans, etc., opens up multiple opportunities to enrich the narrative and subsequently the problems solving tasks required of the students.

Further, the physical activity inherent within AR implementations affords the students physiological exercise embedded within cognitive tasks such as problem solving. The relatively recent development of 'exergaming' or 'exertainment' products such as Dance Dance Revolution (Konami) signal a growing interest in combining children's interest in gaming with physical activity. In part, this interest is in response to an ever-increasing obesity problem among youth, both in America and abroad. As evidenced by a research report from the FutureLab in the United Kingdom, the obesity crisis and how education might address it is not an American phenomenon: "Given recent debates on children's obesity levels, there is also an increasingly urgent need to understand how we can combine physical activity as part of the learning process" (Facer 2004, p. 42). As the students reported in this research project, the physical exploration of the school grounds, i.e., playground, sports field, neighborhood, was highly motivating and it is reasonable to assume that AR and other mobile learning technologies could be leveraged to address this growing health crisis.

Finally, AR as an interactive medium enables a pedagogy in which knowledge is grounded in a setting and distributed across a community, rather than isolated within individuals. Contrary to conventional K-12 instruction, where knowledge is decontextualized and explicit, in AR the learning is situated and tacit. This parallels the nature of twenty-first century work, in which *problem finding* (the front-end of the inquiry process: making observations and inferences, developing hypotheses, and conducting experiments to test alternative interpretations of the situation) is crucial to reaching a point where the work team can do *problem solving*. Workers' individual and collective metacognitive strategies for making meaning out of complexity (such as making judgments about the value of alternative problem formulations) are vital.

## Implications and Conclusion

The importance of the research detailed in this paper is not the technology itself, but rather what added value the technology brings to the learning environment. AR holds great promise for enhancing student learning, but we are only beginning to understand effective instructional designs for this emerging technology. At this early stage of AR research, its most significant affordance is the unique ability to create immersive hybrid learning environments that combine digital and physical objects, thereby facilitating the development of process skills such as critical thinking, problem solving, and communicating utilized through interdependent collaborative exercises. As detailed above, the preliminary findings from the resulting digital/physical hybrid environment is promising and we need to further explore how best to leverage this affordance.

A related affordance unique to AR is the ability to blend a fictional narrative such as the arrival of aliens with the real and familiar physical environment such as a school playground. The ability to superimpose digital characters onto any physical space allows educators to continually repurpose their school grounds with multiple immersive narratives to meet various teaching objectives across the curriculum. Via immersive AR, the once familiar playground can become an alien landing pad, a whale stranding site, a chemical spill disaster area, the solar system, or any other narrative that provides the desired context to reach the instructional goals.

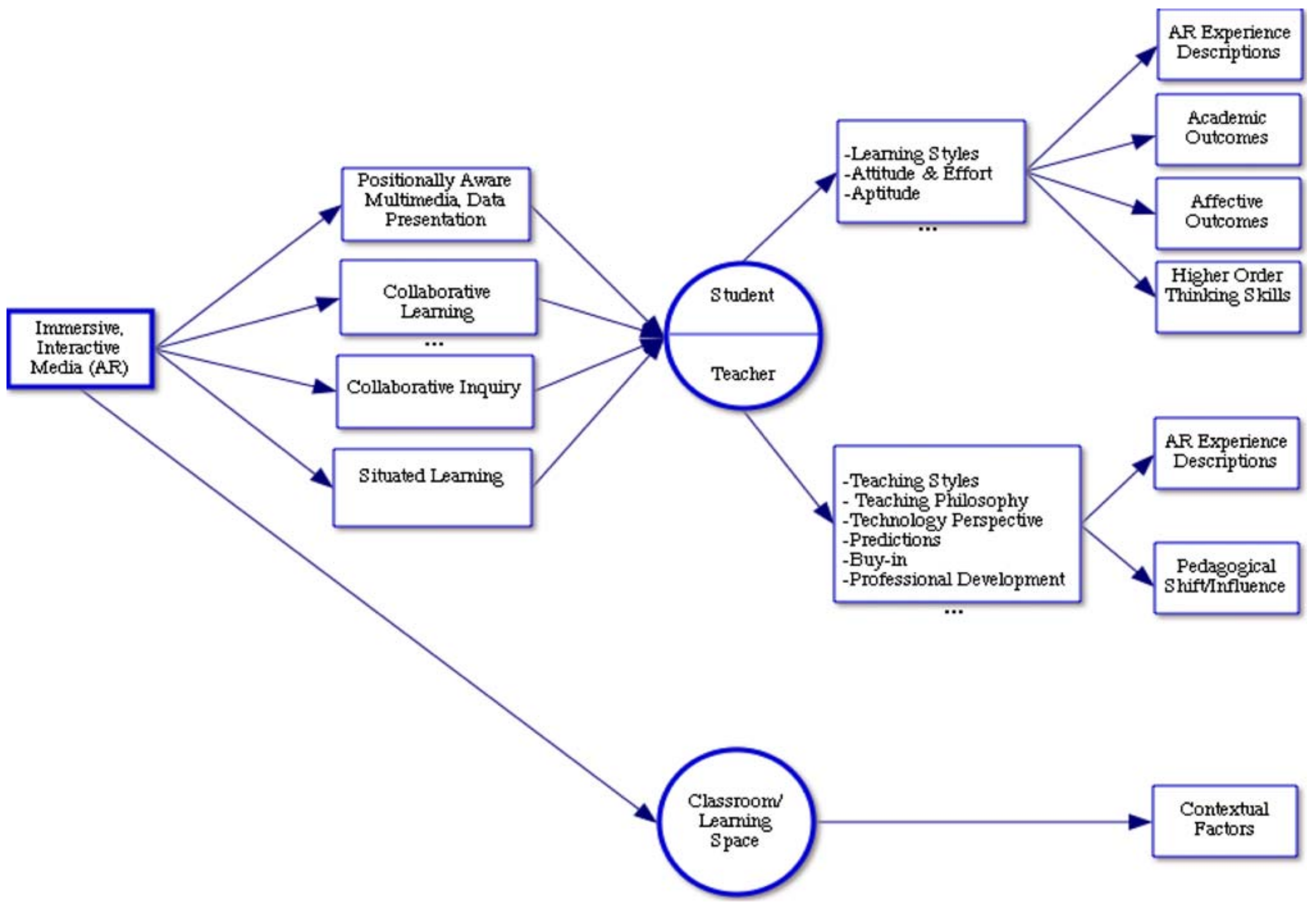
The most significant limitations result from the nascent stage of the software development and the inherent pedagogical and managerial complexity of an AR implementation. As we look toward scalability of AR curricula, the challenges of managing and debugging the technology equipment are significant. The equipment is also cost prohibitive for many schools. However, the wireless computers which we use for *Alien Contact!* allow for a wide range of learning activities, including the use of multimedia, data gathering/analysis, and connectivity with other users (Dieterle and Dede 2006; Gado et al. 2006; Swan et al. 2005), so schools could easily justify purchasing a class set for a variety of uses.

In the near future, the most likely platform for this instructional model will shift to GPS-enabled cell phones. While student cell phone use is currently discouraged in schools, it is highly likely that soon students will be encouraged to bring cell phones to school, enabling these powerful tools to be leveraged to deliver instruction using AR. One can easily imagine a teacher asking her students to take out their GPS-enabled, iPhone-like device as a shared technological infrastructure for engaging and effective learning. Incorporating an instructional model that leverages devices students already own and use for extra-curricular activities not only reduces the amount of hardware and networking investment required from perpetually under-funded education budgets, but also flattens the learning curve necessary for students to develop fluency with this educational tool.

Another issue regarding scalability is preparing teachers to utilize augmented reality and the different pedagogical strategies it requires (Van t Hooft et al. 2007). For example, after introducing handheld devices to teachers in graduate level courses, Dieterle and Dede (2006) describe a teacher who expressed fears about not being able to see what the students were up to on their handhelds, assuming they would be off-task. Our pilot data supports these findings in that teachers who rely on a lecture-practice style of instruction are uncomfortable relinquishing control of the learning to their students. Some of these teachers led their students step-by-step through tasks in a way that diminished their cognitive value. In fact, it is widely recognized in mathematics education research that not only do teachers adapt curricular materials, but they often do so in a way that converts high-level, open-ended problems into more traditional, simple, procedural exercises (Albert Shanker Institute 2005; Ball and Cohen 1996; Cohen 2001; Stein et al. 2007), despite the intentions of the curriculum developers. Many factors related to both the teacher and curriculum are thought to affect the ways in which teachers interpret and implement curricula (Remillard 2005)—such as teacher knowledge and beliefs about mathematics, teaching, and students and the ways in which the curriculum represents concepts and tasks (Brown 2002)—and these issues of interpretation and implementation are certainly not limited to mathematics education. AR designers must take these issues into account in developing instructional materials based on this technology.

In this article, we have begun to address some of the issues of augmented reality curricula facing teachers, something that is not usually addressed in the literature. This is surprising given Clark's (1983) assertion that it is the *teaching* that explains most of the difference in student learning gains on studies that compare technology-based versus control curriculum, rather than the *media* by which instruction is delivered. In the coming year, we will be looking closely at teachers' implementation of *Alien Contact!* namely how teachers adapt the curriculum and what factors affect the kinds of adaptations that are made. We hope to learn more about the pedagogical demands this augmented reality curriculum places upon teachers, so as to develop effective materials and professional development to expand students' learning via this promising instructional medium.

## Appendix A: Conceptual Framework




## References

Albert Shanker Institute (2005) From best research to what works: improving the teaching and learning of mathematics: a Forum. Albert Shanker Institute, Washington, D. C (May 5, 2005)

Ball DL, Cohen DK (1996) Reform by the book: what is-or might be-the role of curriculum materials in teacher learning and instructional reform? Educ Res 25(9):6–8, 14

Barab SA, Sadler TD, Heiselt C, Hickey D, Zuiker S (2007) Relating narrative, inquiry, and inscriptions: supporting consequential play. J Sci Educ Technol 16(1):59–82. doi:10.1007/s10956-006-9033-3

Brown M (2002) Teaching by design: understanding the intersection between teacher practice and the design of curricular innovations. Unpublished Ph.D. Dissertation, Northwestern University

Brown JS, Collins A, Duguid S (1989) Situated cognition and the culture of learning. Educ Res 18(1):32–42

Chaiklin S, Lave J (1993) Understanding practice: perspectives on activity and context. Cambridge University Press, New York

Chinn C, Malhotra B (2002) Epistemologically authentic inquiry in schools: a theoretical framework for evaluating inquiry tasks. Sci Educ 82(2):175–218

Clark RE (1983) Reconsidering research on learning from media. Rev Educ Res 53:445–459

Clarke J, Dede C (2007) MUVEs as a powerful means to study situated learning. In: Chinn CA, Erkens G, Putambekar S (eds) The 2007 computer-supported collaborative learning (CSCL) conference 2007. International Society for the Learning Sciences, New Brunswick, NJ, pp 141–144

Clarke J, Dede C, Ketelhut D, Nelson B, Bowman C (2006) A design-based research strategy to promote scalability for educational innovations. Educ Technol 46(3):27–36

Clarke J, Dede C, Dieterle E Emerging technologies for collaborative, mediated, immersive learning. In: Voogt J, Knezek G (eds) The international handbook of technology in primary and secondary education. Springer, New York (in press)

Cohen D (2001) A revolution in one classroom: the case of Mrs. Oublier. In: The Jossey-Bass reader on school reform. Jossey-Bass, San Francisco, pp 440–469

Dede C (2002) Vignettes about the future of learning technologies. In: 2020 visions: transforming education and training through advanced technologies. U.S. Department of Commerce, Washington, DC, pp 18–25

Dede C (2005) Planning for neomillennial learning styles. EDUCAUSE Quarterly 28(1):7–12

Dieterle E, Dede C (2006) Building university faculty and student capacity to use wireless handheld devices for learning. In: van 't Hooft M (ed) Ubiquitous computing: invisible technology, visible impact. Erlbaum, Mahweh, NJ, pp 303–328

Dieterle E, Dede C, Schrier KL (2007) "Neomillennial" learning styles propagated by wireless handheld devices. In: Lytras M, Naeve A (eds) Ubiquitous and pervasive knowledge and learning management: semantics, social networking and new media to their full potential. Idea Group, Inc, Hershey, PA, pp 35–66

Eckert P, Wenger E (1994) From school to work: an apprenticeship in institutional identity. Working papers on learning and identity, 1. Institute for Research on Learning, Palo Alto

Facer K (2004) Savannah: a futurelab prototype research report. Retrieved from the FutureLab website: http://www.futurelab.org.uk/projects/savannah

Gado I, Ferguson R, Van't Hooft M (2006) Using handheld-computers and probeware in a science methods course: preservice teachers' attitudes and self-efficacy. J Technol Teach Educ 14(3):501–529

Gee JP (2003) What video games have to teach us about learning and literacy. Palgrave Macmillan, New York

Greeno J (1998) The situativity of knowing, learning, and research. Am Psychol 53:5–26. doi:10.1037/0003-066X.53.1.5

Griffin MM (1995) You can't get there from here: situated learning, transfer, and map skills. Contemp Educ Psychol 20:65–87. doi:10.1006/ceps.1995.1004

Heinecke WF, Milman NB, Washington LA, Blasi L (2001) New directions in the evaluation of the effectiveness of educational technology. Comput Schools 18(2/3):97–110

Hendricks CC (2001) Teaching causal reasoning through cognitive apprenticeship: what are results from situated learning? J Educ Res 94(5):302–311

Hutchins E (1995) Cognition in the wild. MIT Press, Cambridge, Mass

Klopfer E, Yoon S, Rivas L (2004) Comparative analysis of palm and wearable computers for participatory simulations. J Comput Assist Learn 20:347–359. doi:10.1111/j.1365-2729.2004.00094.x

Klopfer E, Squire K Environmental detectives: the development of an augmented reality platform for environmental simulations. Educ Technol Res Dev (in press)

Lenhart A, Madden M (2007) Social networking websites and teens: an overview. Pew Internet & American Life Project, Washington, DC

Means B, Haertel GD (2004) Using technology evaluation to enhance student learning. Teachers College Press, New York

Miles MB, Huberman MA (1994) Qualitative data analysis: an expanded sourcebook, 2nd edn. SAGE Publications, Inc., Thousand Oaks, CA

Neulight N, Kafai YB, Kao L, Foley B, Galas C (2007) Children's participation in a virtual epidemic in the science classroom: making connections to natural infectious diseases. J Sci Educ Technol 16(1):47–58. doi:10.1007/s10956-006-9029-z

Palincsar AS (1998) Social constructivist perspectives on teaching and learning. Annu Rev Psychol 49:345–375. doi:10.1146/annurev.psych.49.1.345

Remillard J (2005) Examining key concepts in research on teachers' use of mathematics curricula. Rev Educ Res 75(2):211–246. doi:10.3102/00346543075002211

Roberts DF, Foehr UG, Rideout V (2005) Generation M: media in the lives of 8–18 year-olds. Henry J. Kaiser Family Foundation, Washington, DC

Sawada D, Piburn M, Judson E, Turley J, Falconer K, Benford R et al (2002) Measuring reform practices in science and mathematics classrooms: the reformed teaching observation protocol (RTOP). Sch Sci Math 102(6):245–253

Squire KD (2006) From content to context: videogames as designed experience. Educ Res 35(8):19–29. doi:10.3102/0013189X035008019

Squire KD, Jan M (2007) Mad city mystery: developing scientific argumentation skills with a place-based augmented reality game on handheld computers. J Sci Educ Technol 16(1):5–29. doi:10.1007/s10956-006-9037-z

Stake R (1995) The art of case study research. Sage Publications, Inc, Thousand Oaks

Stein MK, Remillard J, Smith MS (2007) How curriculum influences student learning. In: Lester Jr FK (ed) Second handbook of research on mathematics teaching and learning, vol 1. Information Age Publishing, Charlotte, NC, pp 319–369

Strauss A, Corbin J (1998) Basics of qualitative research. Sage Publications, Thousands Oaks, CA

Swan K, van 't Hooft M, Kratcoski A, Unger D (2005) Uses and effects of mobile computing devices in K-8 classrooms. J Res Technol Educ 38(1):99–112

Van't Hooft M, Swan K, Cook D, Lin Y (2007) What is ubiquitous computing? In: van t Hooft M, Swan K (eds) Ubiquitous computing in education. Lawrence Erlbaum Associates, Mahwah, NJ, pp 3–17

Wenger E (1998) Communities of practice: learning, meaning, and identity. Cambridge University U. Press, New York

Yin RK (2003) Case study research: design and methods, 3rd edn. Sage Publications, Inc., Thousand Oaks, CA