Environmental Detectives—The Development of an Augmented Reality Platform for Environmental Simulations

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DEVELOPMENT ARTICLE

Environmental Detectives—the development of an augmented reality platform for environmental simulations

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Abstract The form factors of handheld computers make them increasingly popular among K-12 educators. Although some compelling examples of educational software for handhelds exist, we believe that the potential of this platform are just being discovered. This paper reviews innovative applications for mobile computing for both education and entertainment purposes, and then proposes a framework for approaching handheld applications we call "augmented reality educational gaming." We then describe our development process in creating a development platform for augmented reality games that draws from rapid prototyping, learner-centered software, and contemporary game design methodologies. We provide a narrative case study of our development activities spread across five case studies with classrooms, and provide a design narrative explaining this development process and articulate an approach to designing educational software on emerging technology platforms. Pedagogical, design, and technical conclusions and implications are discussed.

Keywords Augmented reality · Handheld computing · Design research

Introduction: moving to handhelds

The mantra for bringing computers into schools has changed over the past 10 years going from "a computer on every desktop" to a "computer on every lap" and now to a "computer in every child's hand" (Soloway et al., 1999). While this recent push from desktop and laptop computers to handheld computers has advantages in terms of cost and maintenance, the educational potential of this new platform has been sparsely explored. The limitations of the handheld computer, including its display

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size, stylus-interface, storage capacity and processing power limit make simply porting desktop applications to the handheld less than desirable (Ledbetter, 2001). Most handheld applications to date have been created to replicate the functionality of desktop applications. These early projects show that handheld computers have potential for getting digital technologies into students' hands and transforming learning, but educators may have to rethink traditional genres of educational software to take advantage of the affordances (i.e. interaction between the attributes of an object and their potential uses by users) of handheld technologies for learning (Norman, 1986; Roschelle & Pea, 2002; Soloway et al., 2001).

Indeed handheld computers have several unique features associated with this form factor which suggest intriguing educational opportunities. Klopfer, Squire, and Jenkins (2002) describe five properties of handheld computers that produce unique educational affordances:

(a) *portability*—can take the computer to different sites and move around within a location
(b) *social interactivity*—can exchange data and collaborate with other people face to face
(c) *context sensitivity*—can gather data unique to the current location, environment, and time, including both real and simulated data
(d) *connectivity*—can connect handhelds to data collection devices, other handhelds, and to a common network that creates a true shared environment
(e) *individuality*—can provide unique scaffolding that is customized to the individual's path of investigation.

These affordances suggest an array of unique modes of interacting, such as distributed, collaborative investigations, peer-to-peer networking or coupling physical space with virtual space in instruction.

Educators have begun taking advantage of these affordances as handheld computer applications mature. Roschelle and Pea (2002) review seven design experiments in handheld computing to better understand the educational potential of handheld applications. Roschelle and Pea observe five characteristics of emerging handheld applications. Handheld applications: (a) augment physical space with the simulated data; (b) leverage topological (or physical) space; (c) aggregate individual's participation into group reflection opportunities; (d) situate the teacher as a conductor of activity; (e) use students' actions as artifacts for discussion. Roschelle and Pea conclude that these affordances, which tend to create learning environments where individuals are engaged in different activities distributed across space, may create new design tensions around system couplings (in this case the system of students and handhelds). Citing Morrison and Goldberg (1996), they argue that how information flows from device to device and how this information flow is controlled may become the critical issues in handheld computing applications. Roschelle and Pea (2002) write,

> Overly tight coupling, where every information exchange among personal devices is centrally controllable and tracked, may be too close to Orwellian scenarios. Overly loose coupling, where each Palm is an information island, will not lead to interesting shared knowledge spaces and activity artifacts (p. 163).

How to balance competing drives for individuality with distribution and decentralized information flows with guided educational activities may be tensions central to the platform. We believe that developing applications which explicitly explore these tensions is one way to advance our understandings of handheld computing.

This paper outlines a design research program (Barab & Squire, 2004; Brown, 1992) around handheld computers through a design narrative of the development of Environmental Detectives, a multi-player, handheld augmented reality simulation game designed to support learning in late high school and early college environmental science. We define 'augmented reality' broadly as a situation in which a real world context is dynamically overlaid with coherent location or context sensitive virtual information. Our goal is to understand the potential of augmented reality simulation games while also proposing the idea of a general software development platform—an underlying code base which can be used for developing multiple augmented reality simulation games. This platform includes not only an engine for core game functions, but also authoring tools for creating other handheld applications. Our approach focuses on providing a discussion of the science of design in the context of innovative technologies for gaming and simulations, and not empirical results. Consistent with Brown (1992), we provide a narrative case study account of the design over multiple iterations and multiple contexts, using short cycles of analysis, design, implement, and revise toward building both a working design and theoretical insights, which in this paper, are toward the design of emerging software platforms.

Augmented reality simulation games use the handheld computer to provide a layer of data that 'augments' users' experience of reality by connecting data on the handheld (e.g., multimedia), to physical space (e.g., a particular building or location). Building a general software platform allows (a) developers to create new augmented reality simulation games more rapidly and cost-effectively, (b) teachers and instructional designers to create games for specific geographic locations, taking advantage of local conditions, such as an historical or environmental site, (c) teachers to custom-tailor games to meet students needs and refine games to meet students' needs, and (d) students to become game designers, creating simulation games. In short, developing one or two particular games without the capacity to quickly generate more is unnecessarily expensive; developing such software in the absence of theory will not help future developers to learn from past efforts.

This design research study uses a design narrative (Hoadley, 2002) to trace the process of creating Environmental Detectives from initial conceptualization through four field trials and finally to initial attempts at building a set of game development tools for creating augmented reality games. Research on other new technologies such as the automobile suggests that case studies focusing on users' actions are a valid way of understanding an emerging technology (Kline & Pinch, 1996). As a software development process, this approach borrows from rapid prototyping methodologies where designers create multiple disposable programs to test the usability and pedagogical potential of specific functions and theories, rather than prescribing a list of functions and then building a robust platform from scratch. This process values assembling quick solutions to problems guided by theory and then adjusting design requirements and user specifications as prototypes are used and evaluated. This process may is particularly suited to educational software domains where developers are building genres of software. The paper concludes by reporting the findings of four case studies and articulating the functional specifications included in the current handheld gaming platform.

Software development on handheld computers

In recent years, an array of applications have emerged for handheld computers displaying their pedagogical potential. Applications in the entertainment sector, which incorporate multiplayer interactions and location awareness, suggest powerful new models for interacting with handheld computers which have implications for the educational sector. Media and technology theory suggest that users develop expectations about how educational software should behave as they use new applications (Kline & Pinch, 1996).

Applications on handhelds and mobiles

Emerging educational software programs on handheld computers showcase the potential for portable, socially interactive, context sensitive, connected and individual computing, as described in the examples below.

Probeware

Probeware applications capitalize on the portability, connectivity and individuality of computers. Using attached electronic metering equipment students collect data in real time using handheld computers covering everything from dissolved oxygen in a stream to the velocity of a person running (Bannasch & Tinker, 2002). Enactments of probeware curricula usually involve student splitting into groups, gathering data from different vantage points, and then aggregating and analyzing results, so that each student is a component of a knowledge building process.

Knowledge aggregation

Knowledge aggregation software, such as Picomap (Luchini, Quintana, & Soloway, 2003), use the connectivity and individuality of handheld computers to have students engage in research activities such as concept mapping, and then aggregate information into knowledge networks. Students might develop concept maps of how a toxin flows through a watershed, and then upload their concept maps to a central computer where they compare maps and develop a more unified map reflecting the experience of their peers, building on the social constructivist notion of knowledge-building communities (Scardamalia & Bereiter, 1994).

Classtalk

Classtalk (Dufresne, Gerace, Leonard, Mestre, & Wenk, 1996) is an application that networks individual machines to a central server. Students answer questions and see their responses, allowing for instantaneous feedback and adjustment of instruction. This format may allows creative teachers use Classtalk to propose challenging problems, elucidate misconceptions, or spur student discussion, using the individuality and connectivity of machines to create perturbations in both psychological and social systems so that students confront existing ideas and beliefs.

Participatory simulations

Participatory simulations leverage the individuality and connectivity of handheld computers (Soloway et al., 2001) or wearable computers (Colella, 2000; Klopfer & Woodruff, 2002), to immerse learners in simulated dynamic systems. Participants become everything from viruses to agents in economic simulations, trading and sharing data which is digitally processed and fed back into the system. Participatory simulations often rely on wearable computers to display information about the participant's role or state in the simulation as both a mode of communicating information as well as engaging learners as they scan other participants and attempt to understand their role within a broader simulated system (Klopfer & Woodruff, 2002).

Location aware field guides

Handheld computers allow students to take rich databases into the field—databases which if made location-aware can provide context-sensitive information, such as on-demand information about a local watershed, animal population, or historical site (Gay, Reiger, & Bennington, 2001). Cybertracker (Parr, Jones, & Songer, 2003), one of the most widely used software systems, uses global positioning satellite technology to allow students to record not just values for given measures, but exact positional or local information. Students might gather data from about local wildlife where it is fed back into a database for other people (often trained scientists) to examine. Location-aware field guides provide new opportunities for relationships with spatial data, relationships that are both connected to geographic location and can be spatially dispersed.

Entertainment applications

Probeware, knowledge aggregation, participatory simulations, classtalk, and location-aware field guides are five families (or genres) of emerging educational handheld computing software packages. Other ideas of how to use educational technologies have been arising within the humanities, games, and research spheres, which provide intriguing new opportunities for rethinking interactions with handheld computers (Holland, Jenkins, & Squire, 2003). Several handheld games use emerging platforms in creative ways that have been, in our opinion, been underutilized in educational applications.

Pirates

Players use location-based information on their cell phones to navigate a multiplayer virtual world of pirates (Falk, Ljungstrand, Bjork, & Hannsonn, 2001). Players' physical location triggers events where they might gather clues and battle other pirates. Importantly, the game board corresponds to the real world, as islands, reefs, and other barriers are placed in the real-world and corresponding objects are placed in the game world, suggesting educational opportunities by connecting digital simulations to real world structures.

MAD Countdown

Steffen Walz and colleagues developed *MAD Countdown*, a game where players work in teams using location-aware PDAs to diffuse a bomb that is hidden somewhere in the building (http://www.madcountdown.de/). *MAD Countdown* suggests opportunities for collaborative problem solving role playing games.

It's Alive

It's Alive® has produced several proof of concept pervasive games on cell phones. *BotFighter®* is a virtual paintball game and *SupaFly®* is a virtual soap opera in which characters that you create interact with nearby characters and places. Both games take place in real place and in real time using positioning technologies and suggest intriguing opportunities for games that span "real" and "virtual" lives.

Majestic®

The most well-known example of pervasive gaming may be Electronic Arts' *Majestic*, which shipped in summer 2001. Majestic was a multi-channel conspiracy game played over instant messenger, FAX, cell phones, and the web. Players investigated an arson attack on a games company working on a government conspiracy game, quizzing virtual characters, gathering data across multiple media channels, and exchanging information with other players. Majestic suggests how with significant resources, a ubiquitous game could require substantial problem solving to complete.

The Beast® and Cloudmakers®

The Beast was released in the summer of 2001 as advanced promotion for Steven Spielberg's *A.I. The Beast*, a game released in secret and played over the Internet, featured thousands of players collaborating across the globe completing puzzles ranging from distributed data-gathering and problem-solving tasks where players needed to be in several locations at once to code-breaking tasks that demand knowledge of foreign languages. What sets *The Beast* apart from other similar games was its *distributed nature which requires collaboration*; no one person could possibly solve *The Beast* which gave rise to several organizations of game players, most notably *Cloudmakers* (http://cloudmakers.org) who are still together and pursuing the goal of making and solving large-scale collaborative games. While *The Beast* was not a game specifically made for handheld computers, its distributed nature and mix of online and offline game play make it an interesting model for handheld gaming.

Our discussion of these games from the entertainment sector suggests the idea of *augmented reality*—how handheld computers can supplement real world interactions, relying on context sensitivity and social interaction to create compelling new media. With most desktop educational software, student–computer interactions are the focus activity, whereas in these applications social connections and connections with physical space are the basis of experience. This hybrid virtual/actual world that is created allows the small, unobtrusive interface of a PDA to become an asset for applications instead of a liability.

Purpose: exploring educational, augmented reality gaming on the handheld

The purpose of this study is twofold: (1) to explore and understand the educational potential of augmented reality games, (2) to investigate a sustainable, platform-based software development process for creating augmented reality games. This study describes and examines a process of beginning with brainstorming new uses of emerging technologies, conducting trials with user groups, and describing the software development platform prototype. We propose this as one process for innovation with emerging technologies. Other development paths are more appropriate in more established design areas. Specific learning outcomes are discussed in greater depth elsewhere (Klopfer & Squire, 2004).

Design-based research methodology

Creating software for new hardware platforms is paradoxical. Designers want to rethink fundamental assumptions and learning experiences but cannot ignore successful principles of design from similar areas. We argue for a rapid prototyping process whereby many different possible solutions are proposed and developed, using each instantiation with multiple user groups to learn about the design space. Using case study and discourse analysis techniques to understand users' experiences, we generate a list of functional specifications which can guide the development of a more generalized software platform (Gee, 1999; Stake, 1995). There are two primary reasons for this approach: (1) Creating software design platforms instead of single software instantiations may allow developers to optimize development paths and create reusable digital content (a growing need in educational technology being addressed by standards movements such as SCORM); (2) This approach allows the platform to be responsive to participants' needs.

This paper reports multiple methods as a part of a larger design-based research project as suggested by Collins (1992) and Laurel (2004). We divide our design work into six phases: brainstorming, design, development, field trials, classroom implementations, and platform design, each of which employs different methods from different disciplines. First, we borrow methods from the humanities, using genre analysis of detective stories to uncover how dilemma-driven stories engage readers. Next, we use qualitative research techniques—observations and unstructured interviews—to understand the disciplinary practices of environmental scientists (Silverman, 2004). Specifically, the environmental scientists we consulted described past research methodologies, did "think aloud" descriptions while looking at past studies, and answered queries about environmental science investigations. The results from these studies, were used internally and are not reported here. Last, we create a series of case studies (Stake, 1995) to understand how these technologies are taken up in use. These case studies use participant observations, unstructured interviews, focus groups, and discourse analysis to understand the emergent unfolding activity. Underlying these diverse research techniques is a commitment to *responsive* techniques that capture both intended and unintended consequences of emerging activity (Stake, 1995).

Creating a coherent logic of inquiry from techniques originating in disparate fields is a challenge common to design-based researchers (Kelly, 2003). We have tried to create methodology that coheres around a *pragmatic* logic of inquiry, whereby design theory is developed through recursive cycles of action, analysis, and reflection toward making unknown situations more knowable (Barab & Squire, 2004; Cobb, Stephan, McClain, & Gravemeijer, 2001). This methodology is empirical in that it is driven by data and observations. It may not yield generalizable truth in the classic sense, but is often useful in practice-oriented fields such as education interested in answering questions of "what works" (Reigeluth & Frick, 1999). Generalizability comes through multiple studies that confirm or reject a deeper theoretical framework.

How to capture and communicate such knowledge is challenging, but a number of instructional technologists have turned to design narratives as method for studying and reporting the design process (Barab & Squire, 2004; Hoadley, 2002). Design narratives, accounts of how software develops over time, are hypothesized to be more relevant to software design than experimental studies in that they take into account complex interacting variables and are more usable to designers because they capture knowledge in the form of stories, the lessons from which designers can apply to their own contexts. These generalizations are not unlike Stake's (1995) petite generalizations, generalizations that are contextually-defined and rely on the reader to apply toward new situations.

In each case, a minimum of two trained researchers followed each group, observing interactions, recording field notes, and video taping interactions. Researchers were instructed to minimize interfere with the group's progress, only asking them to explain actions that were not clearly articulated and providing technical guidance only when specifically asked. The video tapes that resulted from these observations were analyzed for broad themes, as well as specific moment to moment interactions. Over the course of these cases, we examined 12 groups and conducted interviews with 25 participants. At the time of this writing, approximately 200 students have used the software. In previous work, we used discourse analysis techniques to examine how the activity was constructed and unfolded (Klopfer & Squire, 2004). The goal of this study is to draw upon these earlier studies in order to trace the design and development of Environmental Detectives across several iterations, using narrative techniques to explain the changes in the platform and in our conceptual thinking.

The core focus—simulating an environmental investigation of a toxic spill—remains the same. The core learning goals also remained the same while different teachers took up the game in different ways. Specifically, they were *to learn the importance of balancing desktop research and fieldwork*, *understand that investigations are a social enterprise, constrained by time and budgets* (rather than "purely" scientific enterprise), and that *alternative acceptable solutions to environmental* *problems and disasters typically can be found.* The core features of both the simulation and the educational goals of the experience shift across contexts, as our understanding of the design problem shifted and the demands of a particular situation change. By reporting the results of several studies in the form of a design narrative, we hope to walk the reader through our design process, hopefully explicating the educational potential (and challenges) of augmented reality simulation game design on handheld computers and posing a rapid prototyping design approach for the design of software platforms. This approach may be particular useful for educators seeking to design new *suites* of applications with similar functionalities in hitherto unexplored areas.

Design narrative

Phase one: brainstorming new genres of educational software

The goal of the first development phase was to generate new educational software genres that leverage the proposed affordances of the handheld computer. After examining existing applications for engaging learners in authentic, inquiry-based science practices, such as probeware (Tinker & Krajcik, 2001), we looked for ways to extend the authentic inquiry of probeware to investigate hypothetical phenomena such as toxin spills in a watershed. Investigating a toxin spill which is engaging and potentially scientifically interesting would allow us to investigate users' experiences with a simulation distributed across real and virtual contexts. We hoped to add narrative elements to create a more compelling context for investigation, drawing heavily from the detective work in *Erin Brokovich* or *A Civil Action*, stories which effectively marry the dramatic potential of human heath problems and basic environmental science. Such a game would allow learners to learn investigative skills (i.e. data collection, analysis, reporting), as well as think with chemistry and biology concepts core to most environmental science (i.e. introductory chemistry). Elements of the game that we considered are listed in Table 1. Building on these established genres, we imagined how these functionalities might be combined in a game where players see a rash of health problems, do desktop research, and then gather data to ascertain their potential causes—relating back to the core practices described to us by environmental engineers.

Because location-based games are inherently tied to geographical conditions which may afford different kinds of investigations, games need to be customized to local contexts in order to accurately depict local watersheds, airflows and conditions. Particular chemicals, such as Tri-Chloro-Ethelene (TCE), may be commonly found across the country, but most teachers may want to customize games to capitalize on local features, such as waste treatment facilities, industrial plants, or power stations. In the long term, an augmented reality game toolkit would allow teachers and students to build custom scenarios.

We first set out to test the core features of the user experience in a stripped down game which could be run locally. Then, after building two or three instantiations of the game, we could create a standard format for building and deploying games. Last, we would create a toolset for building and deploying augmented reality games.

Table 1 Features, functions, and pedagogical purposes behind the augmented gaming platform

Feature	Function	Pedagogical value
Simulated tools	Recreate tools similar to those used in probeware environmental sampling, but with capabilities beyond the scale of what actual probeware is capable.	Allow players to encounter pedagogically valuable but practically unfeasible hypothetical situations.
Location awareness	Move about in a real space and while provided with location specific information.	Encourage mapping of simulation to the environment; encourage interaction with physical space.
Non-player characters	Receive information by "interviewing" non-player characters distributed throughout the game in the form of text, graphics, and video.	Contextualize story through characters to appeal to broad audiences, encourage engagement, and facilitate meaningful learning (e.g., Cordova & Lepper, 1996).
Spatial data collection	Collect and analyze data that is inherently spatial.	Leverage affordances of the environment for learning and situate simulated activities in the real world.
Library access	Provide background information on the problem at hand that is accessible to all.	Allow students to access just-in-time resources to better support learning.
Collaborative tools	Allow players to share data through infrared beaming.	Support collaboration and knowledge building.
Covert interactions	Enable events to happen to a player without their knowledge, triggered through timed events, location information or player interaction.	Increase engagement through surprise and create meaningful learning moments by triggering teachable moments.

Phase two: designing the first instantiation

Envisioning scenarios

Similar to rapid prototyping methodologies, a number of software engineers advocate writing user scenarios as a first step in software design (Microsoft Framework, 2001). User scenarios help the developer "get inside the head of the user" thinking of functions and needs that the user might want rather than software specifications the developer might want to provide. User scenarios can also help the developer imagine new interaction possibilities and uncover holes in the overall design process or design concept before coding begins. We believe that scenarios, which can include screen mock-ups and paper-based interfaces, are especially important in helping concretize the abstract, helping different parties imagine new kinds of interactions.

Our first goal in designing a particular scenario was to specify the core dilemmas in the investigation, the problems that would drive students' inquiry and suggest the kinds of learning outcomes we might expect. We determined that the toxin should be a *ground-water contaminant*, have *moderate long-term health effects*, and be *common*, but not something that was common knowledge to local inhabitants. *Ground water contaminants* were chosen because airborne contaminants would spread too rapidly for the time-scale of this game and soil-borne contaminants move more slowly and have more dispersed effects. *Moderate long-term health effects* were ideal symptoms because stronger correlations between a toxin and health effects would make the responsible agent too easy to identify and demand less rigorous investigations. Last, we decided that the toxin should be *common but not common knowledge*. Common toxins allow for multiple possible origins (as opposed to say, a leak from a nuclear reactor), but common knowledge toxins, such as PCBs (Poly-Chlorinated Biphenyls) in some areas would drive players too quickly toward a correct solution, forgoing any data collection, analysis, and argumentation.

Consulting disciplinary experts

Once we deduced that such a game was feasible, we contacted disciplinary experts to determine the ideal toxin, and to establish disciplinary practices that we could capture in the game. Environmental engineering faculty persuaded us TCE was an ideal toxin for the game. One of the engineers had already designed a similar board game and found that TCE fulfilled relevant criteria; there were many case studies of TCE contaminations; and, this engineer offered to share information about TCE, its cleanup, and local geology.

Most importantly, the environmental engineers introduced us to the practice of environmental engineering investigations. We learned that investigations are run under tight time and money constraints with no anticipation of finding perfect answers. A core component of this investigation is understanding the interaction of primary (raw data collected by the researcher) and secondary (summative and background information from texts) data. Good researchers understand how to do deskwork on the nature of the chemical, its health effects, toxic levels, legal limits, similar cases, historical records and local geology, *while simultaneously* integrating fieldwork, in which they collect data on local concentrations. Often the cause of a contamination can be found by visiting a library or talking to a worker in a local factory or machine shop, which can save the investigator months of work and thousands of dollars. Most students, however, want to sample for toxins and treat the entire enterprise as one of sampling until they find the correct answer. This tension between deskwork and primary data collection and the tendency for students to blindly collect data became a core feature of our game design.

Phase three: developing a first generation prototype

Building a rapid prototype

Consistent with rapid prototyping methodologies (Maher & Ingram, 1989; Whitten, Bentley, & Barlow, 1989; Wilson, Jonassen, & Cole, 1993), our goal was to build a working, small-scale prototype early in development in order to test key system features. In particular, we needed to develop a method for providing *context-sensitive information*. Subsequent to background research and field-testing, we chose Global Positioning System (GPS) technologies as the best technology for serving data to users based on their location, although this technology also prevented us from taking the game indoors.

The goals of the first prototype were to: (1) establish proper protocols for interfacing between the Pocket PC and the GPS modules, and (2) create a working scaleable architecture for the suite of tools that was emerging for the Pocket PC platform (an initial release of C# in the .NET Compact Framework). Reinforcing the

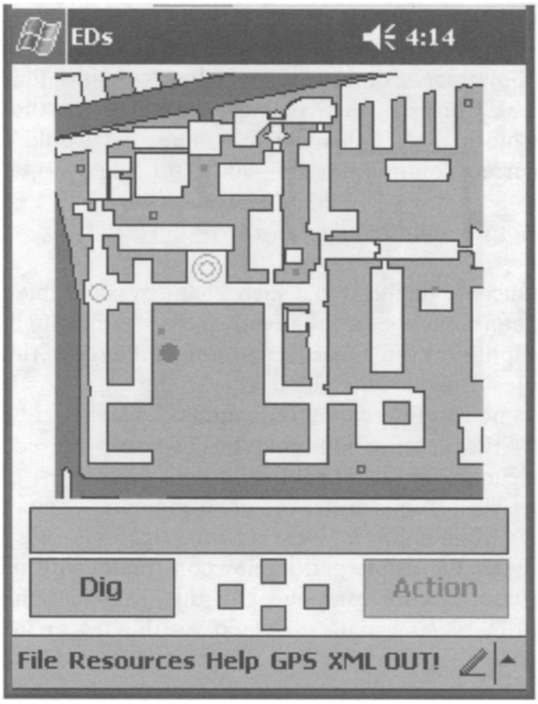

Fig. 1 Map-based interface to Environmental Detectives

pedagogical goals of the unit, buttons for the two primary actions—digging sampling wells and interviewing contacts were on the screen at all times. Since the game was also built on a spatial metaphor, we used a map as the focus of the interface. This would allow users to see locations where they had drilled for samples and where there were contacts available for interviewing at all times (see Fig. 1). The map depicts the college campus where this version of the game was played. Players' location is represented by the large red dot on screen. The smaller red squares are interviews; the blue dots are locations where players placed drills to sample the groundwater quality. Players can dig wells at any point by depressing the Dig button. By design this interface was done quick and dirty, intended to allowing us to better understand system requirements and how well the concept is meeting design goals before specifying the functions of the end platform. Despite many unanticipated issues with GPS devices within eight weeks we had a map-based interface prototype that displayed data based triggered by players' physical location, allowed players to sample a very simple underlying simulation, and used images and text to create a cover story.

The game positions players as environmental scientists responding to a call from their University president, who just learned that a toxin has been found in the campus groundwater during routine testing at a construction site. The player must report back to the President in 90 minutes with a description of the problem, a list of possible causes and culprits, and recommendations for addressing the problem. The causes of the problem are somewhat determined, but the solutions are open-ended; there are multiple viable solutions for addressing the problem. Players then move about the campus gathering readings with the handheld computer from different locations of their choosing. Players also can interview experts receiving interviews and documents to learn more about how quickly the toxin spreads, what its causes are, and what its health affects are. Game play involves making choices between what information to obtain within the limited time.

A primary goal of this phase was to see how users responded to the new delivery system of augmented reality, where there are several unknowns, including how players make sense of augmented reality, how participants responded to the technology, and the viability of using different methods for determining location within instructional settings. In particular, we were concerned with examining how porting design elements and technologies developed in gaming contexts (competition, collaboration, new styles of play, and unstable technologies) into classrooms affects learning.

Location and audience

The initial target audience and location were chosen on the basis of convenience; a local university was starting an environmental sciences program for freshmen and needed a kick-off event orienting students to environmental science. We focused the game around a scenario involving a large, highly publicized construction project under way on campus. We hoped that choosing a freshmen cohort would allow the game to be adaptable to college and high school audiences.

Phase four: classroom field trials

The goal of this phase was to pilot a functional set of hardware and software with a group of non-designers in a traditional educational setting. The goals of this trial were to (1) try the GPS navigation software with a set of users other than ourselves, as we feared that we might have become overly familiar with the idiosyncrasies of our software; (2) test out the concept of augmented realities to gauge students' reactions (i.e., Was it confusing? Engaging?); (3) play-test the basic game functions for good balancing; and, (4) examine how students interacted with the machines to brainstorm new modes of game dynamics. This version included a new GPS calibration mechanism to enhance the accuracy of GPS, a basic map with GPS navigation, the ability to drill sampling wells, text interviews with background information, and a cover story that provided a context for the investigation. Two hardware changes also occurred at this point which are instructive of the challenges with working on emerging platforms: (1) The Pocket PC processors changed, which meant recompiling code and making other software adjustments. (2) We switched to a different brand of GPS module, achieving a small gain GPS reliability.

For the first field trial, 12 university environmental engineering students (five groups of two to three) played the game in a Saturday afternoon session on a day with marginal weather conditions. The GPS only worked reliably for two groups; the other groups had intermittent signals that they supplemented by manual navigation that we had added to the interface for this event. There were minor critiques about information design and layout, and a few students thought that much of the game was about finding the right information rather than solving the environmental problem.

Observations and student feedback showed that students enjoyed the combination of real and virtual worlds as well as the interplay between primary and secondary information. Students were intrigued by the virtual characters and excited to see game play linked to character interactions (e.g., virtual races to locate information, interrogations, or virtual stalking). There was consistent approval of the format and concept, and all of the students requested to play the game again after the bugs were worked out. We were encouraged that students valued the game's premise and modes of interaction and that the game elicited the kinds of interactions (discussions over whether to drill for samples or interview more people) that we had hoped to see (c.f. Klopfer & Squire, 2004). Still, no one was able to satisfactorily diagnose the cause of the toxin and there was little evidence in post-test evaluations to suggest that students were deeply engaging with the scientific content.

Phase five: classroom implementations

The goal of the next phase was to stabilize the software platform and begin examining what teachers and students did with the software in authentic classrooms settings. In response to usability designs, we rethought the organization of interviews. An important ongoing design concern surrounded managing the level of complexity for players. On the one hand, we did not just want to hand them an EPA manual and say "go do an investigation." On the other hand, we did not want the activity to become a scavenger hunt where they went from interview to interview to collect data and then synthesize a response at the end. Consistent with the pedagogical goals of environmental engineering courses, we wanted to create an experience where players had to think about the nature of the problem, design data collection strategies, reflect on their data collection in progress, analyze and interpret data, and then revise hypotheses, data collection strategies, and emerging theories of the problem.

We made four design changes as a result of findings from user implementations:

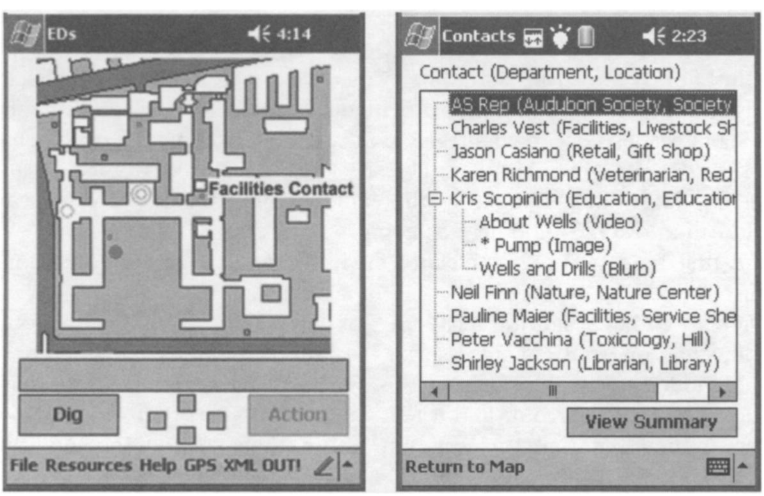

Fig. 2 Remade map-based interface and reorganized contacts list based on user feedback indicating an inability to understand

(1) We strengthened the faculty/department metaphor by revealing the department that each contact is associated with in a viewable list (Fig. 2). We hoped to provide information cluing students in on what to information might be gleaned from each interview, a strategy designed to reinforce meaningful decision making which is at the heart of meaningful game play (c.f. Salen & Zimmerman, 2003). This information might serve as a scaffold to help students predict what data would result from interviews. This information might also suggest a secondary learning opportunity: introducing students to the different disciplines on campus (e.g. oceanic engineering, toxicology).
(2) We implemented *timed events*, events that are triggered based on players' actions and choices, such as a computer-controlled character telling the player to meet another game character in another location within a particular time window (e.g., 30 minutes). This element of game play provided a sense of urgency and forced students to revise their plans in situ based on their evaluation of the potential value of information. It was also intended to make the game feel more organic—there were other people in the game who had schedules and priorities with which they needed to contend. This feature was intended to counter students' inclination to turn the activity into a scavenger hunt rather than a problem-solving activity.
(3) We limited the number of simultaneous wells that could be dug. In the first generation students could sample wherever they wanted whenever they wanted instantaneously. Students tended to dig wells quickly and without much thinking, as well digging was not a limited resource as it would be in the real world. We limited students to three wells at a time, so they needed to retrieve the sample from a well before they could reuse that rig. We also required students to wait for one minute in order to process data from each well.
(4) In order to encourage students to analyze their primary data more effectively, we implemented sampling protocols that forced the students to make tradeoffs between processing time and accuracy of their samples. This tradeoff was intended to encourage more thorough consideration of sampling and did produce more critical discussions around what kinds of data were needed to address the core problem (Klopfer & Squire, 2004).
(5) This version also included additional pictures and video and interviews rewritten in response to students' requests for more human elements. We hoped that this feature would also improve the game's appeal for women.

In the spring, we tested this version of the game with three classes—two scientific writing classes that used this simulated research experience as a basis for writing a scientific report and a teacher education class that used the game to explore new technologies for teaching. Most of the students in these classes were able to complete or nearly complete their investigation in the course of a two-hour class, making this our first real playable implementation of the game. Students found the story compelling and enjoyed augmented reality modes of interaction (Klopfer & Squire, 2004). These students focused on primary data collection through drilling wells and were able to pinpoint the location of the contamination, but most were not good at conducting the desktop research and failed to present tenable action plans.

Several other factors emerged during this series of iterations. Within these limited samples, we found that female dominated groups tended to seek interview sources rather than drill for samples, whereas male groups tended to drill for samples.

Groups with students who favored interviewing and with other students who favored sampling were the most productive. They engaged in iterative discussion where they defined and redefined the problem, weighing the importance of interview data vs. environmental readings and arguing over the best plan of action. These results suggest that identifying different modes of game play and pitting different types of problem solvers against one another in different groups may be a productive way of fostering scientific argumentation within game play.

In an unanticipated event, one group stopped in the middle of the game and used Google® to search for information on the toxins, rate of flow, and so on, finding a good deal of information quickly—including much of the information that we took from the Environmental Protection Agency Website. This strategy of accessing other outside resources was not only acceptable within our rules but pretty smart, given the time constraints and use of authentic chemicals and historical data.

The fact that students could locate information quickly and easily on Google, suggests the role that a tool such as Google can play in transforming an educational experience; when nearly any information publicly available can be accessed within a matter of seconds, game dynamics that rely on simple factual hunting or trivia-type problems that require no processing or retention become irrelevant. Although the presence of Google did not seriously disrupt this group, it did cause us to pause and rethink future developments of our game, particularly in how we bridge fantasy and reality which we believe is critical for all educational technology designers. As game designers, we cannot assume that students would not find out about an historical case or the specific properties of a chemical; when the entire world is the gameboard and students have cell phones, PDAs and other devices, we must assume that if there is relevant information available on the Internet, that students might find it.

Phase six: expanding into new contexts

By the end of our third spring trial, we felt that we had sufficiently defined the technological components to start designing our toolkit for designing scenarios (easily importing maps, calibrating GPS, placing interviews, embedding media, defining the source of the contamination, and defining the rates at which the contaminant spreads in the environment). The toolkit operates through a click and drag interface as shown in Fig. 3. The libraries are all stored as a part of an XML database so that a customizable scenario can be created without any programming skills. All that is required to use the toolkit is to have the required media, interviews, media, and text, an appropriately scaled map, and GPS coordinates of two points on the map. The toolkit outputs a file that can be copied to the Pocket PC for playing, allowing an instructional designer to focus on game content rather than technological issues. We expect that even students will be able to build their own games in the near future.

To test the flexibility of the new toolkit, we created a game for an entirely new locale. A suburban nature center volunteered to host the game and match us with a local high school environmental science class. The site had ample open space with a clear view of the sky to support the GPS use. Additionally the site was a working farm, but formerly a missile base, which provided a rich history and context for the game, and new opportunities for combining different toxins and contaminants, in particular, new opportunities for creating "red herrings" around toxins that may have been left-over from the farm's days as a missile base.

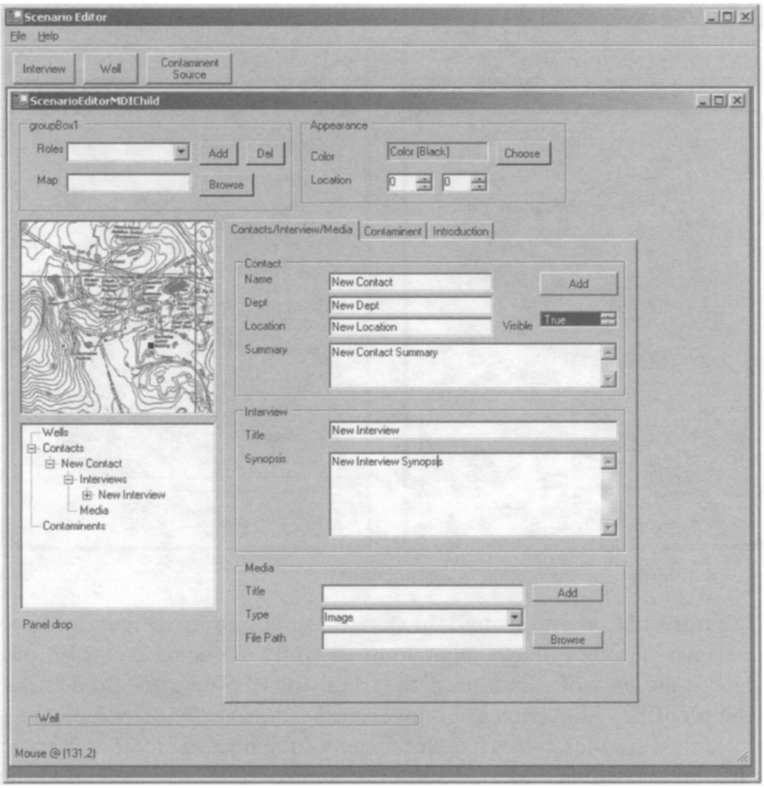

Fig. 3 Environmental Detectives Toolkit. This toolkit, which shows the map used in the farm scenario, was used to generate new game instantiations

For pedagogical and aesthetic reasons, we rewrote the story to tie it more specifically to the land. We rewrote the back story (which now concerned the health of the animals on the site), as well as all of the interviews to tie into local conditions. We also shot the video on site to tie the media to the physical geography, something that earlier students had requested. Since we were working with a younger group of students (high school juniors and seniors in from a suburban school), we simplified language and included additional background information to make the problem more tangible, such as pictures of the drill rigs that they would be using.

The physical space of the nature center was significantly larger than the original campus game site (Fig. 4). To help students navigate, we gave most groups walkie-talkies with which they could communicate. We also had a slightly improved GPS, which increase reliability at least 50% again. There were few technical difficulties—only one of the 12 groups was unable to navigate via GPS. The game also included enhanced multimedia, including video clips shot on site (Fig. 4).

There were many differences in the context between this version of the game and the previous ones. These students were younger, new to the site, more diverse in their academic capabilities, and playing on a larger, more difficult to navigate terrain. These factors combined to create a game experience entirely different from previous groups' experiences. These students were less inclined to collect primary data. Instead, they were driven to collect the interviews, although they had difficulty

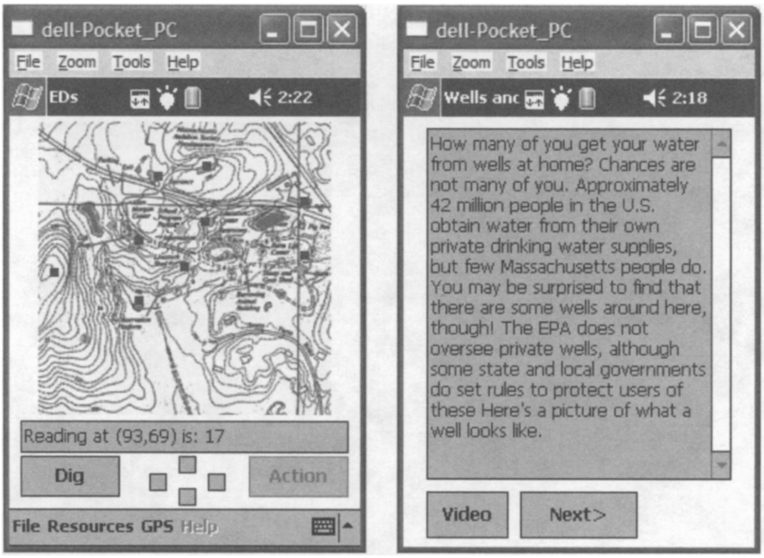

Fig. 4 Screenshots from the farm game implementation

interpreting information and using knowledge to plan an investigation. Instead the exercise became more of a scavenger hunt in which students could be overheard comparing the number of points that they had found. We attributed these differences to the identities of players as younger, less scientifically-oriented, and perhaps a strongly female gender bias (females in earlier games were found to be more focused on interviews than males—Klopfer & Squire, 2004). By the end of the game, most of the groups had insufficient data to identify the source of the chemical spill.

Students in this game also had difficulty navigating the physical space. This was a large space and some sections contained few identifying marks. This difficulty in navigation parallels the difficulties that novices often face in virtual environments. Still, students were able to think across their virtual resources and physical space with ease. For example, students on the edge of a field nearly climbed over a barbed wire fence to get to the "next" interview on the other side until they looked at the map and found another way around. The virtual cues gave them strong motivation for taking physical actions.

In general the students had difficulty with the subtlety of the investigation, indicating that the game play may have been too difficult for this age without additional scaffolding. Students were unable to interpret the clues within the interviews to inform them as to where to go next. Many of the clues were tentative, forcing them to evaluate the authority of the person speaking to them and weigh that against other evidence that they had collected. The problem itself, to identify the source of the contamination and come up with an appropriate plan of action, was not well enough defined for them to know how to proceed. The solutions that students presented suggested that they were looking for someone that would give them the answer, rather than them having to construct their own answers from the data that they collected, which is consistent with typical school-based pedagogies. This calls into question their previous experience in collecting and interpreting data and has led us to better understand relationships between previous scientific investigation experience and game play strategies. Whereas the college student groups did not find it unusual at all to be doing an open-ended investigation, high school students framed the game as a scavenger hunt activity whereby the goal was to find the correct answer.

Students rated the experience of interacting with the technology and investigative experiences very highly. They unanimously requested more time for their investigation, suggesting that some of the seemingly haphazard decisions that they made were as a result of time pressure. Students also requested further direction in their investigation—which could be done either through up front directions, or additional scaffolding built into the software.

This run also contained some experiments in group collaboration. First, most of the pairs of students were given walkie-talkies with which they could communicate with each other. Students were rarely heard sharing clues, but they did discuss technical issues. Even when students requested instructions from one of the facilitators, those instructions could be heard by the entire group. Second, while each pair of students was given a Pocket PC, two pairs of groups were told that they should play as a collaborative team and design appropriate strategies. While the students responded that this was a positive aspect of the game, students did little more than share data in the end.

Phase seven: customized dynamic events

The scavenger hunt tactics of the fourth group suggested that the game design and presentation lent itself to a haphazard disconnected approach to untrained audiences. In short, for many groups, the game became a scavenger hunt rather than a simulation. Indeed, in this generation the game itself was quite static; outside of a few timed events, nothing in the game changed in response to a player's actions, the actions of other players, or even time. To a student who is totally unfamiliar with this kind of investigation the game appears as a web page on which you can click on specific links to get the information by visiting a particular site, but links are only one layer deep. This caused us to redesign the core engine and provide a more robust authoring tool for subsequent generations.

The goal of this process was to explore how dynamically generated events might lead to more engaging game play and deeper problem solving. For the current generation (Klopfer & Squire, 2004; Squire et al., 2004), we sought to provide a more dynamic and responsive environment by borrowing additional tactics from games. These new elements consisted of:

Time dependence—The interviews that are given to players by non-player characters can change over time. The game is divided into several time intervals (usually 3–5) and each character can change what they say based on the current time period. Similarly, samples that are taken from the environment can change over time. This feature both creates a feeling of a more dynamic game world and requires deeper problem solving from players as they must adjust strategies to emergent data.

Cascading events—When a player interview non-player characters, information about previously unknown characters can be given and shown the game screen. This connects players' actions to consequences in the game world. For example, speaking to the head of facilities might reveal several facilities workers with both useful and distracting information. Adding new elements in the course of game play requires players to adjust their plans on the fly, moving the game away from a scavenger hunt experience and toward one of problem solving.

Distinct, differentiated roles—Players take on distinct roles that change their capabilities and the information that is given to them by the non-player characters. For example, a student who is feeling sick might give a player in the role of nurse different information than they would give to the detective. This feature was designed to promote collaboration across players, as no one player would then have access to all the needed information.

These different capabilities can also be connected allowing for a much greater sense of a dynamic world in which actions have consequences and collaboration is a key to success. In one situation a character reveals information to the detective about a student who has fallen ill. The detective must share that information (via infrared beaming) with the nurse, so that the nurse can interview the player and get at the specific symptoms and what might be causing them. These differentiated roles force students to consider what information is needed, articulate what they have learned, and work together to synthesize understandings, a pedagogical technique common to problem-based learning and contemporary gaming alike (e.g., Savery & Duffy, 1995).

Pilot studies indicate that these features may be effective at fostering collaboration, which in turn scaffold a more authentic investigation process. The fact that sharing information could reveal new information, encouraged frequent digital exchanges, which were accompanied by pertinent discussions of game progress. The cascading events require students to delve deeper into interviews as they looked for clues that might point them in the right direction for finding another, currently hidden, piece of information. These additions do require more sophisticated authoring tools. The current authoring tool supports the integration of all three of the aspects of the new game. New visualizations that show information by time and role allow authors to be able to explore this much richer play space and create games that take advantage of these tactics.

Conclusions

This paper explores the design experiment of Environmental Detectives, presenting a rapid prototyping approach to designing software platforms, and serving as a narrative case study of a design experiment in action (Barab & Squire, 2004; Brown, 1992; Hoadley, 2002). We narrate our development process across four case studies involving four instructional contexts with two different populations of users. We found this rapid prototyping approach useful in articulating the design features of location-aware, augmented reality games, and demonstrating that such applications could be successful in formal learning environments. This approach allowed us to get user data quickly; only six months after our initial brainstorm we were working classes of students using the program. This case suggests the value in quickly coding solutions to technical, user, and educational unknowns before over-designing software and instruction.

Pedagogical conclusions

Across all four cases, we saw two different ways of playing the game, which map directly to the two kinds of investigation strategies that our environmental engineers reported using in the field. First, many students saw the problem as a mathematical sampling problem whereby the goal was to map how the contaminant (TCE) spread through the environment, ignoring the social problem of what might have caused the spill or what remediation strategies should be used to solve it. Students adopting this approach were largely unsuccessful in identifying the contaminant, chasing down numerous "dead-end" leads. The second approach, collecting interviews, also resembled a scavenger hunt activity, whereby students thought that the game would be won by talking to the right expert who would then give them the exact location to drill. Students adopted the language of the scavenger hunt quite plainly, talking across groups about "who collected the most interviews."

The most successful groups approached the activity as inquiry, negotiating multiple forms of data, much as the designers and environmental engineers hoped they might. These groups tended to have multiple strong personalities who each argued for a different approach (quantitative sampling vs. qualitative observations). Often, these playing tendencies fell along gender lines, with men preferring sampling strategies and women preferring to interview others.

Across cases, few groups ultimately designed satisfactory solutions. Most groups could either locate the general area of the toxin or some basic remediation strategies, but none of the groups had a coherent plan that showed where toxins came from, drew data from previous investigations provided in their library, and then created a suitable remediation plan. In fairness, the challenge behind Environmental Detectives was an open-ended challenge; while the exact location of the initial spill could be pinned down, there was no one ideal remediation plan. Good solutions, however, would account for the different remediation options and understand the strengths and drawbacks of each approach. Most students opted for politically easy answers, such as "plant some trees to help remediate the problem [phytoremediation, a legitimate, but inadequate strategy] and monitor the situation."

Teachers responded to this shortcoming by having students present their remediation plans before their peers and then discuss as a group potential causes and remediation plans. Some classes voted on which group had the best solution; others compiled their data into one or two ideal solutions. Across all implementations how the teacher framed collaboration and competition had an effect on the ensuing behavior; some teachers wanted groups to collaborate, others allowed them to go alone and encouraged competition among groups. These results remind us that it is not only the game itself that determines how a game is played, but the encompassing culture (whether it be a community of game players or a classroom context) that determines many of the game-play practices (Squire et al., 2003). As we engage in future development, we are paying more attention to what kinds of scaffolds we can build into the program or framing of the problem to support collaboration and competition among groups.

Technological/design methodology conclusions

When developing new genres of educational technology, rapid prototyping with multiple sets of users can lead to new insights about not only interface issues, but core functionality. These descriptive case studies allowed us to see what kinds of experiences worked in the medium, and then invest more energy in them. In these cases, two features typified this pattern: (1) cascading events and (2) multi-media cover stories. Cascading events arose after watching students use the program which suggests that, consistent with situated theories of instructional design (i.e., Streibel, 1995), there is value in using observations of learners' interactions with the medium as material for creating new designs. Involving users in usability testing or design groups processes is an increasingly accepted component of instructional design, but these cases suggest that systematic study of users in naturalistic contexts may be useful in situations where the goal is to develop new goals and functions for the software system.

Local classroom cultures and contexts played a profound role in shaping how the software was used, suggesting the importance of varying implementation contexts when designing new platforms for broad audiences. Unlike any previous case, the high school students we studied took the game and turned it into a scavenger hunt activity where the goal was to collect as much information as possible in the allotted time. These observations caused us to make several design changes, including more implementations of cascading events, more timed events, and generally speaking, more efforts to represent the game as a dynamic system. More "traditional" evaluation techniques would have limited us to looking for specific variables a priori, and thus, we maintain that responsive, descriptive approaches are useful and perhaps necessary when dealing with innovative programs (c.f. Stake, 1995). In short, because the game experience is a function of the classroom culture and context plus the software, it is critical that as designers we use methodologies that account for these interactions.

Implications

Pedagogical implications

There is a saying in the games industry that good games are easy to learn and difficult to master. We found that Environmental Detectives was relatively easy to learn, and at least for these students, not masterable in 90 minutes. Failure, a hallmark of the game play experience and in many psychologists' eyes, a key precursor to learning (e.g. Schank, 1994), occurred often in this game. Building such failure into the broader pedagogical model is one area to explore further. One can imagine students playing the game multiple times, iteratively playing, debriefing, and trying new strategies on new maps or with different contaminants. In addition to helping students succeed, allowing them to build strategies and then using success as one form of feedback indicating their success, multiple iterations might help produce transfer across contexts, as students build understandings that are not tied to one particular situation but are developed across multiple cases (Bransford et al., 1999). Unfortunately, none of the teachers we worked with were able to deploy multiple iterations of the game. One can imagine students trying the investigation once, debriefing, and then trying again on a new map.

Roschelle and Pea (2002) argue that a challenge for handheld developers will be in managing tensions between power and information flows. Leveraging what Jenkins and Squire (2002) call contested spaces, we find that power and information flows make good focal points for handheld games. In Environmental Detectives, students had incentive to share information, in that no two students could cover the entire field at once. In future iterations, we hope to leverage these design tension further, pitting different groups against one another so that they will have to critically evaluate the quality of information that they are giving away. Students will need to decide if the location or value of an interview is sensitive information which can be given away, or if it should be kept. We believe that the most powerful applications of handheld computers may be in exploiting these design tensions between power and information flows and embedding them as core components of the educational experience. Restated, if a core feature of handheld computers are their ability to allow different players to function as interacting components of a dynamic system, then educational software designers might think of applications where students have to critically consider when to share information within the broader system and when to opt out and act independently.

These cases also show the critical role that *space* or *locale* plays in augmented reality games. In the cases with the college students, we saw that the fact that the toxin was spreading in their own community was a strong motivator, whereas the students visiting a field trip were much less emotionally engaged in the problem.[1] Both the emotional resonance of the space and students' prior knowledge of the locale mediated students' experiences. High school students turned the game into a scavenger hunt, building on an activity common to fieldtrips. These findings reinforce our commitment to creating a software platform whereby teachers and students can create and customize their own game scenarios. Further, it suggests that *a mature theory of augmented reality software may require a more robust theory of how space connects to previous understandings and future learning trajectories.*

Technological implications

Educational technologists might also benefit by noting how rapidly handheld hardware technologies are developing. In the 12 months while this paper was in review for publication, the accuracy of GPS devices increased three or fourfold without any increases in price. The cost and power of Pocket PCs themselves changed, as costs nearly fell in half and units became more powerful and efficient. We believe that the next 12 months will see similar increases in both GPS devices and Pocket PC technologies, suggesting that projects such as this, which may appear to be "boutique" projects out of the range of most schools may in fact be widely available within 3–5 years.

The hardware and software infrastructure for running Augmented Reality games on handhelds has reached a maturity that now positions us to distribute the underlying engine, and reasonably expect end users to be able to reliably run their own games. Recently, a third party successfully designed and implemented a game using these tools with success on every machine. The technology that supports the effective use of Augmented Reality learning environments must not be thought of as simply what players hold in their hands. Authoring scenarios that employ the many available game elements appears to be critical. Thus, in many ways, the authoring tool (being distributed soon) is perhaps the key advance this project has led to. Scaffolding the construction of new scenarios by designers instead of developers will open up new possibilities for this platform.

[1] This was not a clean comparison as there were several other mitigating variables, including age, level of commitment to the domain, and so on.

Anticipating this more ubiquitous use of handheld computers, we have advocated the development of a handheld augmented gaming platform, which may be used to allow students and teachers to create customized, location-specific games. Already we have created a rudimentary toolkit and a second game iteration. Working with this toolkit, we have students building murder-mystery games and virtual tours which are pushing the boundaries of this system. We have also begun work on indoor positioning via wi-fi, which allows for an entirely new breed of game to emerge.

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