Cyberchase Shape Quest: Pushing Geometry Education Boundaries with Augmented Reality

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ABSTRACT

Cyberchase Shape Quest is an augmented reality math app from PBS KIDS and THIRTEEN that exposes elementary-school children to three-dimensional immersive puzzle worlds, teaching geometry and engaging spatial cognition skills through the use of augmented reality (AR) technology. Designed for children 6-8 years old, the app features 3 games, *Patch the Path, Feed the Critters* and *Hide & Seek*. In *Patch the Path*, players to use a tablet device's camera and a printable game board to interact with 3D puzzles within five different virtual environments, over 30 different levels. While playing, children must engage their spatial memory, visualization, and planning skills to successfully complete each level of the game. In this demo, we focus mainly on *Patch the Path*, highlighting the game design and the roles of prototyping and formative research during development.

Categories and Subject Descriptors

H.5.1 [MULTIMEDIA INFORMATION SYSTEMS]: Information Interfaces and Presentation - Artificial, augmented, and virtual realities

General Terms

Design Human Factors

Keywords

Augmented Reality, Mathematics, Elementary Classroom, Pedagogy, Prototyping, Geometry, Game Design

1. INTRODUCTION

Augmented reality (AR) is a technology innovation that enables computer-generated imagery to be superimposed on a video-camera view of the real world. Augmented reality technology could bring many benefits to children, such as enhanced entertainment through whole-body interaction [1], and advancing education through in- situ interactive visualizations [2]. In the domain of learning, augmented reality has been shown to have measurable benefits over traditional approaches when experienced by K-12 students and adults [3]. National assessments show that over 60% of American students are performing below proficient levels in math and reading by the 4th grade, and this learning gap is even more pronounced for children from low-income families [4]. *Cyberchase Shape Quest* attempts to help close this achievement gap by leveraging the affordances of augmented reality technology for education, and bringing math-rich learning environments to the popular gaming platform of tablet mobile devices.

This demo will present the design and development of the *Cyberchase Shape Quest* game. This game was produced through a collaboration of PBS KIDS, THIRTEEN and Curious Media for the purpose of creating novel educational uses of augmented reality technology. The team included producers, game designers and developers, technology experts and educational specialists. The development was funded as part of the Ready To Learn Initiative developed by the Corporation for Public Broadcasting (CPB) and the Public Broadcasting Service (PBS), with funding from the U.S. Department of Education.[1] As a part of the Ready to Learn (RTL) Initiative, these organizations have pioneered strategies to design educational games, tools and resources for children, parents and educators.

This game represents an innovation in using tablet-based augmented reality for helping elementary-school children gain a better understanding of geometry and spatial thinking. Due to the scarcity of educational AR applications for children and the novelty of AR technology, multiple challenges had to be researched and overcome during the development process, such as: the lack of familiarity about AR technology among educational specialists and game developers, the lack of guidelines for how to design child-friendly interactions in tablet-based AR applications, and the lack of understanding of how to design spatially complex AR game environments that are appropriate for children's spatial cognitive skills. This paper will

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[1] However, the contents of this paper do not necessarily represent the policy of the U.S. Department of Education, and readers should not assume endorsement by the Federal Government.

discuss how we addressed some of these topics through the development process.

The *Cyberchase Shape Quest* app is freely available for camera-enabled Android, iOS and Kindle tablets [5]. In the first week of release, this application rose to be the #1 free iPad kids app on the iTunes App Store, and, so far, *Cyberchase Shape Quest* has been an official nominee of the Webby and iKids awards, and has been downloaded more than 500,000 times worldwide.

The application contains three games targeting elementary-school geometry topics (Figure 1). This demo will focus on the augmented reality game *Patch the Path,* which targets 3D geometry and spatial cognition. The application also contains two other non-AR games that target geometry vocabulary and spatial visualization. In the following sections, we describe the design and research-based development of the *Patch the Path* augmented reality game.

Figure 1: The three games contained within the *Cyberchase Shape Quest* application: *Hide and Seek* (top left), *Feed the Critters* (bottom left), and *Patch the Path* (right)

2. STORY AND GAMEPLAY

Cyberchase Shape Quest is part of the storyworld of *Cyberchase*, the math-themed, research-based animated series and trasmedia project for children 6-11 now in its 13th year on public television [6]. *Cyberchase* has 100 episodes on television (and streaming online and on mobile), more than 50 web games [7], another tablet-based game for iOS and Android devices (*Cyberchase 3D Builder* [8]), and a new season now in production.

The current game features two characters from the TV show – bumbling bots Buzz and Delete. We chose them because they're best friends, they're funny and children like them. They also need a lot of help to figure stuff out – so children are playing *with* them, and helping them save the day. The game *Patch the Path* follows the adventures of Buzz and Delete, who encounter baby animals that have gotten lost and need to be returned home. On their way returning the animals home, Buzz and Delete encounter gaps in their path, which players must patch up by solving 3D geometry puzzles.

The game is played by pointing the tablet device at a special paper marker image, which then becomes augmented with the 3D game world (Figure 2). The device functions as both a controller and a camera, tracking the paper so that the 3D game world always appears on top of the paper. As the player moves the device around the paper, or up and down, her/his perspective will shift, just as in real life. Informed by our research, we designed the game interface to be usable for young children who require both hands to hold tablet devices. The player aims with the center of the screen, and can interact with virtual objects by using touchscreen buttons on the sides of the screen. Through these interactions, the player can pick up, rotate, and drop the virtual objects in order to solve the 3D geometric puzzles.

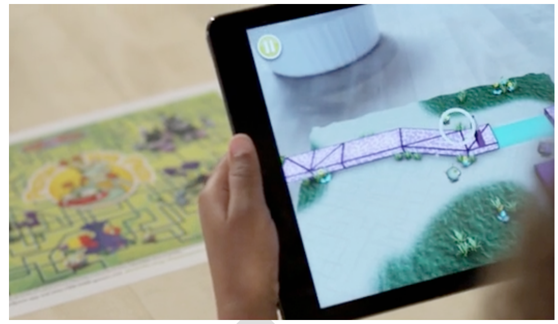

Figure 2. The *Patch the Path* game is played by pointing the camera at the paper.

The game features five worlds, with six geometric puzzles in each, for a total of thirty puzzles. In each puzzle, players are given a 3D path with one or more gaps in it. The game builds in difficulty and complexity as player gains mastery. In the beginning, the puzzles are relatively easy, and the pieces are low-height 3D shapes: one gap, one shape to fill it. Later, they become more challenging: two or three gaps with two or three shapes needed to complete each. Then, the shapes gain more height, and the player needs to be aware of patterns on the sides of the shapes (Figure 3).

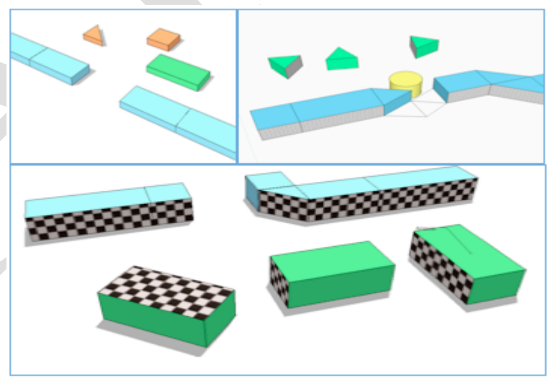

Figure 3. Design of level progression: Low-height shapes, one per gap (top left); taller and multiple shapes per gap (top right); patterned shapes (bottom).

In each puzzle, there are several 'pieces' to choose from to fill each gap: the correct pieces plus a few 'distractors,' which resemble the correct pieces in one or more ways, but ultimately do not fit. For example, in one puzzle, players are given a variety of triangles of similar size, but different shape, and must determine which ones will best fit the gaps.

Solving the puzzles requires children to use spatial thinking and visualization in order to reason about the properties of shapes. To encourage this type of thinking, there are several factors we required players to consider when they are solving the puzzles: Does the overall shape fit the gap? Are the sides of the shape equal to the sides of the adjacent shape? And, in higher levels, are the colors on the sides of a shape the same as the colors on the sides of the adjacent shape?

Based on observations regarding our users' developing spatial and motor skills, we designed the game pieces to snap together like magnets if their edges are fit for connection. The core idea of the game is to encourage children to engage in spatial thinking in a fun game environment, while leveraging the familiarity of playing with real physical blocks, and providing the benefit of scaffolding clues and offering feedback on player actions.

3. DESIGN PROCESS

The development of *Cyberchase Shape Quest* employed an iterative design process that involved a high degree of user research, due to the novelty of working with AR technology for children. Incorporating formal and external formative evaluation into several of the design cycles proved to add significant value during game development because it helped reduce the uncertainty around a large number of unknowns—AR is a relatively new technology and unfamiliar to young children, as well as to game designers and educational specialists.

In working with an evolving technology, prototyping at key stages in early development was crucial. Prototypes were created and informally tested at several key decision points.

3.1 Choosing the Math Topic

Early prototyping discussion helped determine which math topic was best suited for an AR mobile game. The topics considered for a potential AR game included tessellations, fractions, nonstandard measurement, and spatial reasoning.

Our team of producers, game designers, technology experts and educational specialists, discussed these topics while exploring high-fidelity prototypes. These early prototypes gave us a feel for potential games, and the types of puzzles we could build within the current limitations of AR technology. The concept for *Patch the Path* was chosen because we decided it best used the affordances of AR to develop children's understanding of geometry and spatial reasoning, and because it had the lowest risk of usability issues.

3.2 First Evaluation Phase

There are many unknowns in trying to use a novel technology such as augmented reality in an educational game for children. For example, we didn't know how young kids would react to our game interface, and we didn't know if/how children would be able to solve the problems we were planning to give them. Through the different phases of formative evaluation, we answered multiple questions, and this evaluation helped to guide our design process.

We used two types of formative evaluations with children: paper prototyping and alpha testing. These evaluations were integrated into a process of iterative design, where the team had frequent discussions, ensuring all our expertise was pooled into the design process. This was particularly useful in our case because we were generating a novel type of product.

Once the main math topic was chosen for the game, many new questions arose. The team was faced with a large number of decisions, such as the design of levels and of user interface controls. Rather than make decisions based on limited knowledge of how children would react to the game concept, the team turned to a round of formative evaluation to guide the design.

3.2.1 Paper Prototype Testing and Game Mechanics Testing

The formative evaluation used a two-part approach in order to address the large number of questions regarding appropriate game design, focusing on questions related to level design and game controls.

The team first designed a series of possible level configurations that used a variety of spatial skills, were developmentally appropriate, and which progressed in difficulty. Researchers then constructed 13 tangible block-and-tile versions of the levels (Figure 4). These physical versions of the puzzles were used in a variation of paper prototype testing. The goal of this prototype testing was to collect data on the difficulty of the different types of spatial reasoning problems, document the problem-solving strategies children used to solve the problems, and document the scaffolding techniques used by in-person adult facilitators.

The second part of this formative evaluation was to collect data on the usability of different types of game controls. There is little published data on the usability of AR games for children. Rather than spending resources on developing high-fidelity game interfaces, the team opted to test a variety of controls (e.g., pressing buttons with thumbs, shaking the tablet, ability to maintain AR tracking) from a collection of commercially-available AR and non-AR tablet games. Seven children ages 6-9 (3 boys and 4 girls) participated in the formative evaluation. The paper prototype testing and the game mechanics testing each took 30 minutes, with the order of tests counterbalanced across participants. All sessions were video recorded and analyzed.

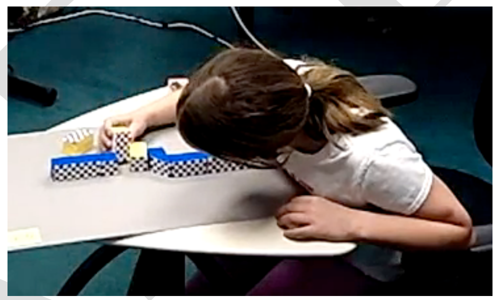

Figure 4. A child tests the cognitive difficulty of a level, by using physical paper blocks representing the level.

3.2.2 Contributions to Later Iterations

Researchers analyzed the video data in order to establish the relative difficulty of the different puzzle levels based on the number and age of students who completed each level, the time needed to complete each level, and the amount of scaffolding needed. The video data was further analyzed to generate detailed data on children's problem-solving strategies, the amount and type of scaffolding required for students to complete each level, children's ability to use different games' controls, ability to maintain AR tracking, and the amount of fatigue encountered by children. As a result of this first round of formative evaluation, our team was able to determine which styles of puzzle levels were too easy for the target age group and which styles were too difficult. We were also able to use the scaffolding interactions from the paper prototype testing as models for the scaffolding algorithms into the game. Specifically, the paper testing informed the timing of scaffolding, the progression of scaffolding (e.g., moving from general to specific hints), the wording of scaffolding (sometimes using exact words captured during the study), as well as the modality of scaffolding (e.g., what types of verbal and visual hints to include and when to deploy each type of hint). In addition, the formative evaluation determined that the most usable approach to game control was to have children hold the tablet with both hands and have UI buttons on the edge of the screen. It was also determined that children lose the AR tracking frequently, so providing adequate support for avoiding and recovering from tracking loss was a critical element for game usability.

3.3 Second Evaluation Phase

Following the first round of formative evaluation, the team continued iterating on the game design and produced an Alpha version of the tablet game that underwent another cycle of formal formative evaluation. This cycle of formative evaluation was guided by the following research questions: 1) What usability problems did the participants encounter when playing the game? 2) Is the difficulty of the levels appropriate for the participants and do the levels build in difficulty? 3) What would teachers change about the game to improve the instructional content?

Seven children ages 6-10 (3 boys and 4 girls) tested the game. Additionally, three teachers who currently work with the children's age group tested the game and provided feedback about the game's efficiency as an instructional tool. Each participant played *Cyberchase Shape Quest* for 30-40 minutes, with a break in the middle (Figure 5). Game play was followed by a post-interview to obtain participants' feedback. Observers took note of usability and pedagogical issues that arose during game play. Researchers debriefed after each session to synthesize what they observed in context of the research questions. Observations, interview responses, and researcher debriefs were transcribed and qualitatively coded.

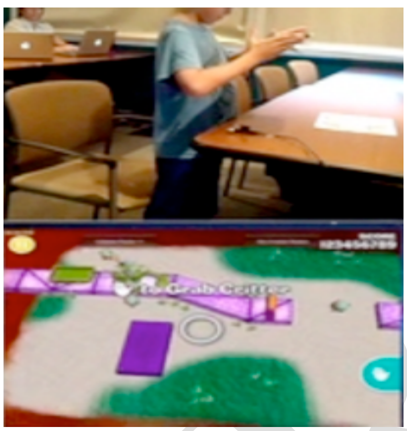

Figure 5. A child tests the Alpha version of the game while the game's screen is remotely recorded.

3.3.1 Contributions to the Final Game

The evaluation confirmed that the game is generally usable and fun, that kids can persist through multiple levels of the game at a time, and that the game is interesting and valuable to teachers. We also uncovered several usability issues that were particularly critical to address in the final game. Specifically, users had major problems with understanding the mechanics of AR and perceiving the 3D space. This led the developers to create a "tutorial" level that trained children to physically move, and made them sensitive to the 3D depth of the game. This also led the creative team to amplify perceptual cues in the game (adding shadows, making shapes bounce around, etc). In addition, children struggled to understand the scaffolding provided by the game. As a result, the development team adjusted the scaffolding wording and visuals to be simpler and more direct, as well as adjusting the algorithms for triggering the scaffolding. Finally, having teachers participate in the evaluation enabled the team to identify more teaching opportunities in the game.

4. Recommendations and Conclusions

We have the following recommendations for designing high-quality educational games based on novel technologies: 1) Expect to have many unanswered questions early in the design process, when dealing with bringing technology into a new domain. 2) Explore unknowns by incorporating formal formative evaluation into an iterative design process. 3) Involve different stakeholders and domain experts (game developers, researchers, content area experts) early in the development process, and keep them involved throughout. 4) Conduct testing early and often, as it is not necessary to have a playable game for testing to add value, and be sure to include teacher participants in the testing of educational games.

Cyberchase Shape Quest is available for camera-enabled iOS, Android, and Kindle HD tablets [5]. As of February 2015, it has been downloaded more than 500,000 times. The game also boasts 50,000 educational downloads for classroom use, and a user base that's 47% international. The top three countries for downloads are United States (268,628), China (104,545) and Canada (21,439).

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