Designing Early Childhood Math Games: A Research-Driven Approach

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ABSTRACT
This paper describes the iterative research and development process used by the Next Generation Preschool Math project, which integrates content analysis, logic model processes, and iterative design and research approaches. An innovative aspect of this process is the inclusion of an adapted version of evidence-centered design—an approach traditionally used to create assessments—to align the mathematical goals with the design of instructional materials as well as with the assessment.

Categories and Subject Descriptors
C.5.3 Microcomputers- *portable devices.* D.2.10 Design- *methodologies.* K.3.1 Computer Uses in Education- *collaborative learning, computer-assisted instruction (CAI).*

General Terms
Design, Experimentation

Keywords
Early Childhood, Preschool, Mathematics, Technology, Design

1. INTRODUCTION
The Next Generation Preschool Math (NGPM) project is a collaboration between researchers and media developers to develop a two-unit preschool math curriculum supplement that supports young children's learning of subitizing and equipartitioning [2, 3]. Each unit combines digital games—including individual and collaborative games—and non-digital activities to support young children's learning.

The purpose of this paper is to delineate the design process utilized on the project, including the steps taken to ensure that the game activities are aligned with the research base on best practices in teaching the target mathematical concepts. We found that a co-design process that includes education researchers and media developers yields robust and promising design principles for creating classroom-based digital learning materials, and we posit that the use of this process can optimize the impact of digital designs for the teaching and learning of mathematics. In addition, the media developers worked closely with teachers to iteratively refine materials.

Our emerging design principles include user interface guidelines in designing tablet apps for preschoolers and best practices for developing software that increases the learning of mathematics.

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2. THEORETICAL FRAMEWORK FOR DESIGN
The project addresses the need for instructional materials that support the development of early rational number reasoning, a key goal of mathematics education reform [8]. The need for preschools to employ a challenging, research-based curriculum in early mathematics is supported by numerous organizations [4, 7]. In addition, research on the effectiveness of these mathematics curricula on early mathematics learning is promising [1].

Our NGPM materials currently focus on two mathematics topics, subitizing and equipartitioning. These topics receive little attention in the preschool years, even in most research-based curricula. Subitizing, or the ability to quickly determine the number of objects in a group without counting, was selected for unit 1 in order to support young children's growing understanding of number and quantity [2]. Equipartitioning, or the ability to create equal-sized groups of objects or equal-sized parts of one object, was selected for unit 2, as equipartitioning is foundational for more sophisticated rational number reasoning concepts, such as ratio and proportion [3].

We chose to use digital tablets (i.e., iPads) as the technology platform because tablets provide affordances, such as direct touch interfaces and easy portability, that support sustained practice and feedback. Subitizing tasks on the tablet allowed us to present preschool children with a set of objects in predetermined arrangements (e.g., in a line) for the appropriate amount of time (e.g., two seconds) before asking them to tap or drag objects to complete the task (e.g., choose sets of three objects). For example, in one game, groups of objects move across the screen as children tap to make a skateboarding character jump to select groupings that contain a specific number of objects. Equipartitioning tasks on the tablet allowed children to tap the screen and drag their finger to divide an object and share pieces of that object among a predetermined set of characters. For example, one game required children to use a finger to "cut" a watermelon into pieces and then drag pieces to the characters so that each character had the same

amount of watermelon. While the tablet allowed for more repetition and feedback on performance than could reasonably be expected from a classroom teacher, it also allowed children to use more natural gestures and movements than would be possible using a traditional computer and mouse [10].

2.1 Preschool Classroom Context

We designed our materials to integrate with existing structures and routines in preschool classrooms (i.e., whole-class circle time, small group center-based play, and individual or paired computer time). Much of the learning children do in a preschool classroom is social, and working with technology is no exception. Social processes such as imitation, observation, and joint attention are fundamental to human learning from an early age [4]. Thus, we created games for individual and collaborative play, so that children can build skills individually and collaboratively with peers and teachers.

2.2 Mathematical Content Alignment

Our framework for aligning the game activity to learning goals is based on a modified version of Evidence Centered Design (ECD) [6] and was developed to ensure that the evidence gathered is consistent with the underlying knowledge that an assessment is intended to address. While there are significant differences in the development of assessments and learning activities, NGPM leveraged key aspects of ECD in the design of our games, as discussed in Section 3.

3. METHODS

We employed a design-based research approach that showcases how learning is deepened through successive interactions with specific concepts and skills across media, with adult- and peer-mediated discussion becoming richer with each subsequent interaction [9]. During our design process, there was extensive interplay between educational researchers and the media production team across several phases of work (Figure 1).

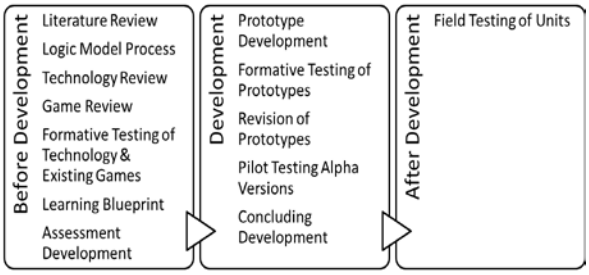

Figure 1. Phases of Development and Research

- *Literature Review*: The process started with a literature review covering those topics we identified as being core to designing effective early childhood technology-based environments. They include key curriculum areas and frameworks, designing for collaborative learning, teaching with technology, the use of joint media engagement, and professional development materials.

- *Logic Model Process*: The project team engaged in a logic model process to confirm our learning theory. This resulted in a final version of the logic model (Figure 2).

- Technology Review: The media development team reviewed existing tablet technology and operating system options for development. Three tablets were selected for review—Apple's iPad2 and the Android Galaxy Tab 10-inch and 7-inch—and the team conducted user studies to investigate technology features that facilitated or hindered young children's learning.

- Game Review and Formative Testing: The team reviewed existing apps for early childhood mathematics and field-tested three in order to understand game mechanics that facilitated or hindered young children's learning. This phase of formative testing involved approximately 30 children playing digital games on the iPads in two geographic locations.

- Learning Blueprint: Using the literature review, the research team created a learning blueprint using a modified evidence-centered design approach (ECD). This resulted in a chart linking the activities produced to (1) the mathematical learning goals of the unit, (2) the prerequisite skills children required for success, (3) actions that provide evidence of achieving the learning goals, and (4) task features that modify task difficulty. This blueprint is intentionally created to be agnostic as to key aspects of gameplay. While the initial use was for the researchers to indicate what is important to the game designers, it is also used by the game designers in discussing potential design tradeoffs, by the assessment team in the creation of assessments, and by our evaluation teams in the creation of observation protocols.

- *Prototype Development:* After reviewing the literature, technology, and existing math-based games for preschoolers, the NGPM team entered an extensive prototyping phase. During this phase, a variety of prototypes were built to test a range of user interface questions (e.g., size of hotspots, use of the accelerometer for children this age), to investigate collaborative gaming modes, and to consider any tradeoffs between math learning and game-play learning. Researchers and expert content advisors gave feedback on prototypes; prototypes were iteratively revised, and then tested in the field with children. Formative testing included observation of gameplay, as well as interviews with children and teachers. The learning blueprint provided the basis for observation categories and analysis. These activities were then further refined until we were able to collect evidence that children were, indeed, engaged in the target mathematics. Emerging design principles were identified during this prototyping phase, leading to guidelines for the next development phase, Alpha development. Finally, prototypes were solidified into Alpha versions that comprised robust, multi-level games with supportive feedback.

- *Assessment Development:* An individual assessment was created that aligned with the unit content. This assessment was used as a pre- and post-assessment of preschool children's understanding of the content during the pilot study.

- *Alpha Pilot Study:* NGPM is currently conducting a pilot study of the two units in multiple classrooms (three classrooms, approximately 50 children). Each classroom is implementing both the digital and non-digital activities in sequence, incorporating the activities into the existing structures of the preschool classroom (e.g., circle time, free choice time). In addition to observations of classroom implementation, teachers

provided direct feedback to researchers about the games and non-digital classroom activities.

- *Concluding Development and Field Testing:* Results from this pilot test will inform changes to the final set of games and non-digital activities. Upon completion of the units, the educational research team will conduct a larger field trial that includes more teachers, and will rigorously evaluate learning outcomes.

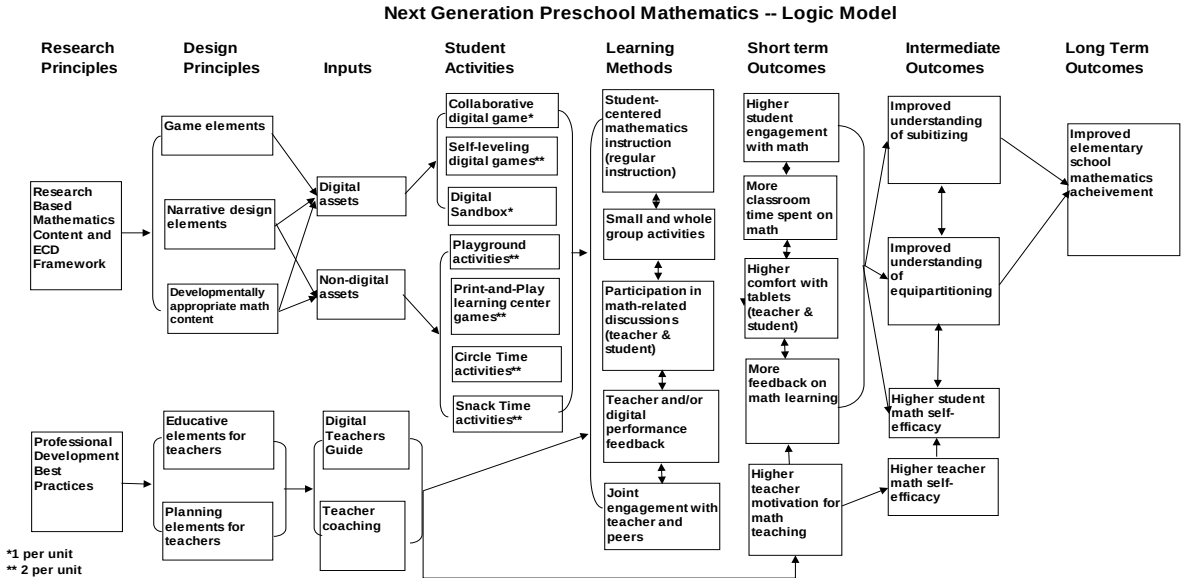

Figure 2. Logic Model

4. DESIGNING EDUCATIONAL GAMES FOR YOUNG CHILDREN

NGPM provides both a design process and design principles for developing educational games for young children. A number of design principles for media designers were documented throughout the development process, begining with the initial literature review. Many of these principles resulted from formative research on the game prototypes, including direct observations of children's gameplay and interviews. This section discusses our game design principles and the larger design principles for the project.

1. *Multiple opportunities to learn across games*. To target a particular content area (i.e., subitizing, equipartitioning), it is important to create a suite of tasks or games to provide multiple opportunities to learn. The benefits of this are twofold: (1) each child has multiple entry points into difficult topics, and (2) one game may not fit all children, particularly young children, equally well; allowing for different experiences provides a greater chance of meeting the needs of each child.

2. *Multiple opportunities to learn within a game*. Within one game, young children often need the same information presented in multiple ways. This can help children make connections, and leverages the fact that young children come to the game with a wide range of skills. For example, a task requiring children to select groups of two might have to show the numeral, show characters modeling the number with their fingers, and provide audio instructions.

3. *Carefully select visual objects*. Young children in general are limited in the amount of visual information to which they can attend, and this is particularly salient when the information is presented with digital screens. Each object on the screen should have a purpose, and the child's task should be clearly defined through clear cues that indicate what she or he should touch (e.g., bouncing or glowing objects). For example, when tappable objects appear quickly onscreen, children often will tap everything rather than selectively tap based on the task's purpose; thus, the number of active objects should be considered carefully.

4. *Limit audio cues*. The early childhood classroom is often an active and loud learning environment, so games should be designed with minimal audio cues, as they are often difficult to hear. Audio cues should include short words or phrases that refer to things that designers want children to act on or repeat aloud. Games should be playable without reliance on audio cues.

5. *Provide opportunities to learn the game mechanics*. New mechanics must be modeled and scaffolded for children through demonstrations and step-by-step instructions, as well as in onscreen introductions to games. This should be done in an intuitive way before gameplay, i.e., as the initial round of the game.

6. *Consider the impact of game mechanics on pace*. Game mechanics can have a large influence on the effective pace of the game. For example, dragging slows the pace (but movement is deliberate) and tapping maintains a fast pace (but children tap everything). For young children, it is helpful to build moments of slower gameplay even into an otherwise fast-paced game in order to keep children from becoming overstimulated or frustrated. Slower game mechanics also allow for more think time, and allow children to reflect on difficult topics.

7. *Allow touch responses with a wide range*. Game mechanics should match levels of physical ability as well as cognitive ability. For dragging objects, the touch points that allow objects to snap into place should have a wide area that is distinct from

other, similar touch points. This helps children with limited motor ability to succeed at the task.

8. *Carefully select feedback.* Feedback in response to gameplay can impact what young children will focus on. In order to make cause and effect explicit and keep children focused on learning goals, provide clear positive feedback for correct responses. Feedback for incorrect responses should indicate that the response was not correct, and should not include engaging material, such as characters making funny faces or sounds, that could be misconstrued as a reward (or simply be fun to watch). Further, feedback for incorrect responses should ideally include a strategy for solving the problem correctly.

9. *Selectively integrate physical movement into games.* Children enjoy games that involve some physical movement, but games should not be too physically taxing.

10. *Level games to match children's growing competence*. Young children enjoy persisting at challenging activities and can learn to be very good at tasks that they initially found difficult; however, game levels should increase in difficulty slowly, in order to build competence with both the game mechanics and content understanding.

11. *Provide compelling game context*. Children enjoy games that employ contexts with which they are familiar with, such as serving food at a restaurant, or serving familiar foods such as fruit or waffles. This not only supports engagement but also enables transfer from the game into real-world environments, and vice versa.

5. SIGNIFICANCE

The goal of this paper is to share our emerging design process and principles in an effort to help others' efforts to design tablet games that preschoolers can easily interactive with and learn from. In addition, the process of development, as well as these design principles, could be adapted for use beyond the domain (mathematics) and age group (preschool children) of this project. This will support the creation of digital learning opportunities that are driven by a clear delineation of the content areas and the way learning typically occurs in that domain, as well as consideration of the actual game mechanics and technological affordances.

This development and research approach to designing games seeks to ensure that games, or learning activities more broadly, are aligned to target concepts and learning goals. In addition, this framework can facilitate successful partnerships between educational researchers and game developers. Such partnerships are becoming more common, and are required to make real educational impact. It is imperative that we find productive processes that focus on children's learning, and that we have agreed-upon methods to investigate and assess learning.

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