International Journal *of* Designs for Learning
2018 | Volume 9, Issue 1 | Pages 135-148

THE EVIDENCE BASED CURRICULUM DESIGN FRAMEWORK: LEVERAGING DIVERSE PERSPECTIVES IN THE DESIGN PROCESS

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The ubiquity of touchscreen, mobile tablet technology has resulted in a plethora of "apps for learning" yet few leverage the learning sciences as a design driver. This paper describes our approach to integrating the learning sciences with best practices in app design: a design framework that involves researchers and developers in a co-development process to create apps based on research and evidence. Our framework centers around a learning blueprint which is intended to serve as a "boundary object." This boundary object facilitates a design process that allows the design team to focus on both children's engagement and learning. Here we describe the challenges that our project team encountered and our approaches to overcome those challenges on the Next Generation Preschool Math (NGPM) project, a development and research effort devoted to creating a supplemental preschool math curriculum supplement with integrated digital apps.

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INTRODUCTION

While app stores are overflowing with games and apps touted as educational, "only a handful of apps are designed with an eye toward how children actually learn," (Hirsh-Pasek et al., 2015, p. 5). While some of these apps are based on the learning sciences, such apps tend to reach fewer people (i.e. have fewer downloads), and thus have little impact on the commercial market (Guernsey & Levine, 2015). The goal of the Next Generation Preschool Math (NGPM) project was to create a set of preschool learning games that would be based on learning sciences principles, with the potential to have a significant impact in the market. To this end, our project engaged learning scientists and a professional game design and development team, as well as a set of expert advisors, partner teachers, and preschool children in a process of collaborative co-design (see Penuel, Roschelle, & Shechtman, 2007). All participants were committed to education and to reaching low-income and/or at-risk preschoolers with high-quality learning resources. While this collaboration was challenging in ways both foreseen and unforeseen, it resulted in a set of apps and associated classroom materials that have shown statistically significant learning gains in a randomized control trial while also reaching a considerable number of children as indicated through the number of downloads in the Apple App Store. In this article we report on our reflections from this endeavor, in particular the design process framework that emerged as well as the arguably necessary tensions that arose from assembling a collaborative team of learning science researchers and professional game developers and designers.

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https://doi.org/10.14434/ijdl.v9i1.23080

This is a particularly opportune time to investigate such collaborations, as they are likely to be more common moving forward. One reason is that the use of educational games and apps, both in and out of classrooms, has grown dramatically in recent years (Project Tomorrow, 2014). While there are many reasons for this growth, much of it is likely due to a variety of factors including increased grant funding for researching and developing educational games; the concomitant advances in the design of games for learning (Barab et al., 2009; Gee and Hayes, 2011); the increased ubiquity and accessibility of new forms of technology in the classroom, including touch-based tablet computers (Hu, 2014); the public acceptance of games as a legitimate learning activity (Van Eck, 2006); the increased sophistication of development environments that allow for more complex games to be created in less time than ever before (ESA, 2014); and market forces that pull developers toward making educational games to capitalize on (and then contribute to) the acceptance of games as a legitimate learning activity. Perhaps as a direct result of the popularity of educational games, coupled with expectations of measureable learning outcomes, all those involved—including educators, parents, learning scientists, policy makers, and other stakeholders—are now looking for increased evidence of quality learning experiences that produce measurable learning outcomes. But the current crop of games does not provide such evidence.

At the same time, traditional research-based funding organizations, such as the National Science Foundation, the Department of Education, and foundations are requiring that grantees no longer disseminate solely through traditional publications, but also take steps to have a larger societal impact. For instance, while the National Science Foundation's Discovery Research K–12 Request for Proposals (National Science Foundation, 2010) makes clear that research is paramount through statements such as, "Projects funded under this solicitation begin with a research question or hypothesis about how to improve preK–12 STEM learning and teaching," it also makes clear that large-scale impact is important by stating "… all proposals must explain how the work can lead ultimately to successful adoption of findings or products in the preK–12 enterprise on a national scale." As such, it is no longer enough for learning scientists to develop digital apps and games that are based on research and then publish research results; instead there is an additional expectation that the products should be accessible by the public and aim to have real impact in the world.

It is in this context that we undertook the NGPM project. Through a geographically distributed collaboration (across California, New York, and Massachusetts) between two research institutes, a well-established public media organization that produces educational content (including interactive media and games), and an external evaluator, we were able to build a set of high-quality, effective, and widely disseminated[1] educational games (Lewis Presser, Vahey, & Dominguez, 2015) that were built on both a deep knowledge of game design and knowledge generated from the learning sciences. In addition, an unanticipated but important outcome has been a new understanding of overall design considerations that we hope can inform the efforts of other cross-disciplinary collaborative teams.

PERSPECTIVES ON THE DESIGN OF EDUCATIONAL GAMES

Research into education and learning has resulted in great progress in researchers' understanding of how technology-based games can help children learn (Barab et al., 2009; Gee and Hayes, 2011). However, the impact of this research on the use of educational games for learning, both in and out of school, has been minimal, despite the large investment schools have made in technology (Mayo, 2008). While the reasons for this are complex, multifaceted and beyond the scope of this article, we wish to focus on addressing a need for research-based educational games by facilitating the interaction between game developers and educational researchers.

Traditionally, educational researchers have focused on designing game-based educational environments constructed around principles of the learning sciences, an interdisciplinary field committed to understanding learning itself and designing instructional experiences based on that knowledge (Carr-Chellman & Hoadley, 2004; Mayo, 2008). While game developers may be brought in as part of the team, their role has typically been to implement the vision of the research team, and any insights or suggestions that conflict with the research agenda are downgraded. This is to be expected, as the incentive system for most educational researchers is calculated as extent of impact in the research community as measured by grants awarded, learning gains in a limited research study, generating new knowledge about learning, and articles published. Having an impact on large numbers of students (by which we mean hundreds of thousands to millions of students) is, by itself, typically not rewarded. Hence, these products tend to not have the visual quality and appeal, intuitive usability (which helps to reduce cognitive load on the user interface of the game and help students focus sooner on the content topic), or level

[1] The project resulted in the *Early Math with Gracie & Friends* apps. "Birthday Cafe", the first app published, was featured in the Apple App Store's "education" and "kids" categories, was listed as one of the "Best New Apps and Games" in the Apple App Store's kids category, was named one of Common Sense Media Graphite's "Best Ed Tech of 2014" (https://www.graphite.org/top-picks/best-edtech-of-2014), and was listed first in the Graphite's "10 Best Math Tools for Elementary" (https://www.graphite.org/top-picks/10-best-math-tools-for-elementary). "Lemonade Stand" was named one of the "Best Learning Apps & Games of the Year" by Balefire Labs. All eight of the apps have been either Parents' Choice Recommended or Approved Award winners, and to date have together garnered over 1.67 million downloads across the globe.

of engagement found in commercially available games. Further, keeping design and production in-house (often by hiring graduate student programmers) is cost-effective, with the consequence of not having access to the experience required to produce competitive products in a highly commercial industry. The resulting lack of polish typically does not impede the research: When conducting relatively small-scale and classroom-based research studies, the threshold for students to engage with the game is simply that it is less boring than what is typical in school. However, such games do not lead to breakout successes in the market.

Conversely, while commercial game designers and developers have deep expertise in visual design, user experience, user engagement, and, of course, coding (Mayo, 2008), they typically do not have a deep background in the learning sciences. Educational researchers are typically brought into projects as initial consultants or as evaluators after the game is complete. As a result, the educational games created by many game designers are usually fun and engaging, but without a deep and robust link to research on how to best support learning. Such games give the user the (legitimate) impression of being "high-quality," yet the educational experience provided is often negligible.

While the description here is a stereotype that does not hold true in all cases (for instance, public media provides many examples of educational efforts based on research and designed to have broad impact, and a small number of educational games in app stores are based on learning sciences), it nonetheless holds true in the main: The games that are found to be effective in the research literature are not typically the educational games that are most popular, or even available, in the marketplace (Guernsey and Levine, 2015). There is reason to believe, however, that the bifurcation between the researcher and designer/developer communities may be diminishing: As the consumers of games demand more research evidence, there is an increasing pull for game designers and developers to collaborate with educational researchers, and as funding agencies demand more dissemination and impact, there is a concomitant pull for educational researchers to collaborate with game designers and developers to truly understand the requirements, criteria, and skill sets necessary for market competitiveness. Bringing together these different perspectives should be good news for the creation of educational games, as research shows that cognitive diversity (Page, 2008) leads to better design decisions when the design space is complex, and the design of educational games is indeed a complex undertaking.

While we can expect (and even hope for) more collaboration between educational researchers and game designers, we also can expect such collaborations to be challenging. As an illustration of such challenges, we describe the issues our own team grappled with, the Evidence-Based Curriculum Design (EBCD) Framework that we created to foster cross-disciplinary collaboration, and how these issues were aided not only by all participants having a deep commitment to learning and respect for each other's expertise, but also through use of that framework. Because the productive tensions we experienced together resulted in strong relationships within and between teams, we feel able to constructively critique specific challenges within the collaboration that stem from the identities of each group. Scrutinizing these tensions is not intended in any way to diminish the capabilities of one group or industry in preference to another, but is useful to identify nuances that might serve to more closely weave the values and contributions from partners who characteristically operate in different environments and with different expectations in terms of timelines, resources, and definitions of quality and success.

The organizations that form the "NGPM team" were the Education Development Center (EDC), SRI Education, WBGH Educational Foundation, and Education Design.

The "research team" was comprised of EDC and SRI. EDC's Center for Children and Technology (CCT) is located in New York City and has been at the forefront of creating and researching (with federal, state, foundation, and corporate funding support) new ways to foster learning and improve teaching through the thoughtful implementation of new educational technologies since 1981. The EDC team consisted of learning scientists, curriculum developers, technology specialists and early childhood experts to collaboratively drive the project's research-based approach to design. SRI is located in Menlo Park, California, and has over 200 researchers who conduct research for the U.S. and California Departments of Education, the National Science Foundation, state governments, and major foundations and corporations. The SRI team consisted of learning scientists, curriculum developers, early childhood experts, and assessment experts including four team members with PhDs and five team members with Master's degrees in Education.

The "design and development team" was entirely from WBGH Educational Foundation, located in Boston. WGBH is a non-profit public media station and a major producer of PBS content for TV, the Web, and apps, including popular children's shows *Arthur* and *Curious George*. The WGBH team consisted of producers, curriculum writers, programmers, and designers, with five of the team members having Master's degrees in Education.

The "evaluation team" was from Education Design. As external evaluator, Education Design engaged in an ongoing formative process with the team, bringing a neutral, dispassionate perspective to all discussions and decisions informed by site observations and sequential teacher interviews.

NGPM'S MATHEMATICAL FOCUS AND THEORIES OF LEARNING

The multi-institutional NGPM team came to agreement on many aspects of the design very early in the design process. We chose to focus on preschool mathematics learning because it is not only one of the strongest predictors of later mathematics achievement (e.g., Jordan, Kaplan, Ramineni, & Locuniak, 2009; National Association for the Education of Young Children [NAEYC], 2010) but is also significantly associated with literacy and school readiness more broadly (Claessens & Engel, 2013; Duncan et al., 2007). While research has shown that high-quality mathematics instruction can lead to improved mathematics outcomes for disadvantaged children, many teachers in public preschool programs feel ill-equipped or unprepared to teach mathematics (Ginsburg, Lee, & Boyd, 2008; National Research Council [NRC], 2011) and find it difficult to integrate mathematics into an increasingly crowded curriculum (NAEYC, 2010). As a result, many preschool programs do not provide young children with rich opportunities to learn the key mathematics concepts that play a crucial role in helping children develop early reasoning and critical thinking skills (e.g., Ginsburg, Lee, & Boyd, 2008).

Particularly important is improving children's understanding of sophisticated mathematics concepts, such as quantity and rational number reasoning. A focus on these concepts requires moving beyond typical, and highly recognizable, preschool mathematics activities that focus on skills such as counting numbers up to 20 or naming basic shapes (e.g., Clements, 2004; Ginsburg, Lee, & Boyd, 2008). In choosing to focus on sophisticated mathematics concepts, we deviated from most commercial app creators who, for market reasons, focus efforts on common activities, such as counting, shape recognition, and patterns. Instead, our commitment to advancing research and children's school readiness required that we focus on aspects of mathematics that are less well understood.

We leveraged research on preschool mathematics learning trajectories (Clements & Sarama, 2004; Clements & Sarama, 2009; Confrey, Maloney, Nguyen, Mojica, & Myers, 2009) when deciding on the particular content to be learned. We decided that one unit would focus on *subitizing* (quickly identifying the quantity of objects in a set—key to understanding the notion of quantity and cardinality) and one on *equipartitioning* (creating equal-sized groups from a collection or equal-sized pieces from a continuous whole—a precursor to division and proportional reasoning). For each unit, we agreed upon a set of research-based learning goals that would be the focus of our collaborative design process. This was a risky approach for a project that desired market impact, as preschool teachers are often unfamiliar with these topics or feel that these skills are too advanced for preschool children. For instance, in interviews with teachers after they implemented our units, they mentioned their initial reluctance to teach these topics through statements such as, "I have always thought doing it [equipartitioning and division in general] would be too advanced for the children, but they got it," and "[they were doing] division, which I didn't think was possible at this age ... I thought you needed numbers to divide."

The NGPM team agreed to think about our design in the context of a *curricular activity system* (Vahey, Knudsen, Rafanan, & Lara-Meloy, 2013), in which all aspects of the materials were complementary and designed to fit into a typical preschool context. The curricular activity systems approach calls for providing teachers with a complementary set of materials and supports. In the case of NGPM these materials included non-digital curricular resources and activities (such as paper-based activities, manipulatives, read-aloud books, and snack activities), and tablet-based games. Supports included face-to-face professional development, digital supports such as lesson plans, and an overall design that builds on what has been learned about designing educative materials (Davis & Krajcik, 2005). These were designed to improve preschool teachers' knowledge of mathematics and their comfort with using technology in their teaching, as well as facilitate seamless integration of the technology into the preschool classroom.

The NGPM team also agreed to take as our theoretical framework for materials design *joint media engagement* (JME), in which teachers and children engage together in repeated encounters with target ideas across multiple formats (Stevens & Penuel, 2010). Our notion of JME encompasses a range of interactive media applications, technologies, and forms of social interaction. Modes of JME include playing, searching, experimenting, augmenting, and creating with either interactive or traditional media. Materials intended to support JME must be designed and presented in ways that invite teachers to mediate this shared learning process. In addition to teacher engagement, parallel engagement with peers around content is also crucial to JME.

JME hypothesizes that these modes of learning, coupled with concurrent attention to the content from teachers and peers, can provide robust support for learning because they allow children to build meaningful connections among media representations, interests, and experiences. We also build on research that shows that social processes such as imitation, observation, and joint attention are fundamental to human learning from an early age (Meltzoff, Kuhl, Movellan, & Sejnowski, 2009). We designed our materials to include opportunities for teachers to mediate and facilitate children's interaction with the content, to allow for children to work together to engage in the content, and to enable children and teachers to review the outcomes of these activities in multiple ways. We also provided children with repeated encounters and opportunities to practice, as such

encounters with digital media have been found to enhance social interaction among peers and with teachers in early childhood classrooms (Sarama, 2004).

Finally, the team agreed on the broad strokes of the digital games. We agreed that each unit would include four digital games: two self-leveling games, one collaborative game, and one sandbox game. Each type of game has specific strengths and limitations. Our choice to include all three game types (as opposed to just one or two) allowed us to leverage the strengths of each and apply a broad set of findings from the literature on JME and learning sciences. The self-leveling games adapt to the individual learner, providing appropriate scaffolding catered to a child's challenge with, or mastery of, the content. Collaborative games allow for two players (peers or a child with a teacher) to jointly engage in the mathematics tasks, for children to take on various roles in their learning, and to engage in math talk together. The sandbox games allow children to engage in exploring the mathematical concepts as their interest and curiosity guides them. Overall, the suite of games allows for both individual and social gameplay/learning, integrate the mathematical content in a variety of ways to support a holistic understanding of the math concepts, build on developmentally appropriate uses of technology for the target age group (preschoolers), and support children's preferences for technology use and play.

DESIGN PROCESS FRAMEWORKS

As was appropriate, given our funding source and the required focus on research, we looked to the educational research literature for guidance on our design process. We chose to build on the Research-Based Curricula framework (Clements, 2007), which has commonalities with the Integrative Learning Design Framework (Bannan-Ritland, 2003). In these frameworks, one first makes explicit the *a priori* foundations of the work, including the content to be addressed and the general pedagogical and technological approach. Next, one determines the learning models to be used, and outlines the activities that fit these learning models (typically the design of these activities is based upon a specific theory of design). Once these aspects of design are decided upon, one engages in iterative design and initial evaluation of the specific activities, formatively testing components of the materials with small groups of children and focusing on the consonance (or lack thereof) between the child's actions and the learning model. At certain developmental milestones, one engages in formative research to test the materials in whole-class settings in a small number of classrooms. Finally, following a suitable round of analysis and revision after which children appear to be appropriately scaffolded and the materials appear to be having the intended impact on child behavior, comparative classroom research is conducted.

Our team recognized that these broad frameworks were most useful for an overview of how to conduct our design and analysis work, and that specific activity design would have to be augmented by more detailed design process frameworks. We chose the Design-Based Implementation Research framework (DBIR) (Penuel, Fishman, Cheng, & Sabelli, 2011) to guide our design and development. Following DBIR principles, we:

1. Involved multiple stakeholders (not only the NGPM team of researchers and game designers and developers, but also expert advisors, teachers, and children).
2. Engaged in rapid iterative design, with the research team focused on ensuring that the math learning goals were met and the design and development team focused on ensuring that the games were engaging, usable, used technology in the support of learning, and likely to result in children wanting to play each game multiple times.
3. Jointly ensured that (a) teacher, child, and researcher feedback from formative evaluations was thoughtfully integrated into the games with expert discretion; (b) we understood the environment for which the team was designing (specifically, the preschool classroom); and (c) we leveraged the unique affordances of technology.
4. Developed the capacity for change for the participants in the study, as well as supported the capacity for change for potential future users of the materials. We also developed the capacity within our research and design and development teams to understand the needs and limitations of designing tablet technology-based curricular materials for preschool classrooms.
5. Aimed to increase the field's understanding of best practices for the design and integration of interactive media and technology, in particular learning games on tablets, into preschool classrooms.

Building upon these process frameworks as well as on our collective experience and knowledge of best design practices, we generated the design and development process shown in Figure 1. While engaging in this process would prove to be a more intense, iterative, and collaborative process than any of us had ever undertaken before, we believed that such a detailed framework for collaboration would serve us well, as this was the first time the teams would truly co-design across disciplines, organizations, and learning cultures. In addition, the project was funded through an NSF grant, and did not have the typical funding and timing constraints found in commercial development (while we have found cross-disciplinary design teams to be effective for more traditional commercial efforts, they tend to work with abridged versions of this process).

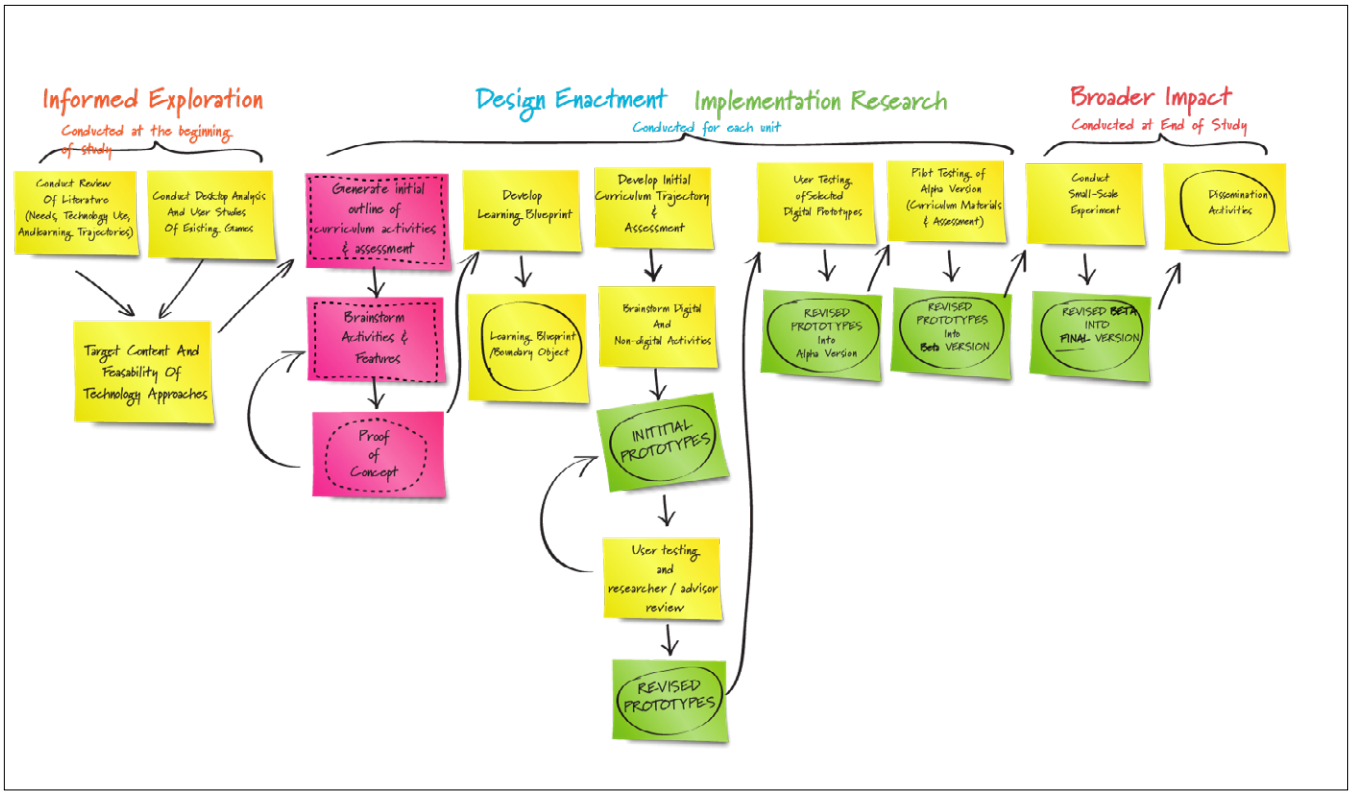

FIGURE 1. Initial Design Process Overview, which included the early creation of prototypes and specifications

INSTANTIATING THE DESIGN PROCESS

Generating Learning Goals

As shown in Figure 1, the first step in the design process was to conduct a literature review with the goal of creating a shared understanding of the learning goals. Members of the research team conducted this literature review and generated a four-page summary for each of the two primary math concepts—subitizing and equipartitioning. Each of the summaries included the justification as to why the concept was important, a definition of the concept, and the learning goals situated in a learning trajectory that research posits would be a productive path through the concept (including example tasks for key points in the learning trajectory). For each concept, the summaries were distributed to all NGPM team members, all team members (including designers and developers) read the materials, and any questions that arose were e-mailed to the group. There was then an all-team videoconference in which the documents and questions were reviewed. Once there was agreement over the goals by all members, the design and development team turned to creating prototypes for the full team to review. (This process was conducted in parallel with an analysis of existing games, which will not be discussed in this article.)

Creating and Evaluating the Prototypes

As the design and development team began to create and share prototypes, it soon became evident that, even following our agreed-upon design processes, there was not general agreement on the overall approach to the prototype design. The design and development team began to generate prototypes to explore the affordances of the new technology. This included testing various game mechanics, considering novel forms of interacting with the technology, and observing the level of interaction and engagement with the technology to determine the boundaries, expectations, and desires of preschoolers. This can be considered creating and testing with a goal of "finding interaction opportunities," and the design and development team generated dozens of low-fidelity prototypes to this end. Each prototype was only loosely tied to a learning goal, with the design and development team expecting to test out potential uses of the technology for finding optimal mechanics for mathematics teaching and learning, and then later implementing the concrete learning goals and trajectories once a game mechanic direction was chosen. This was part of the innovation and design process that was ideal for the development team, but had not been articulated to the research team. Meanwhile, the research team expected the design and development team to be prototyping game experiences based on obvious and measureable connections to the mathematics learning goals. Upon viewing the prototypes, the research team found the prototypes to be unexpectedly removed from the learning goals. Just as surprising to the research team, the prototypes often foregrounded challenging game mechanics that made the mathematics seem deprioritized and

potentially difficult to perceive and understand. These differences in expectations led to significant misunderstandings and tensions within the project. For instance, one of the initial prototypes had children tilt the tablet to move ice cubes around the screen. In this prototype the ice cubes were hard to control (even for adults), it was not clear to the research team what benefits there were to tilting the tablet (instead of, say, dragging onscreen elements with your finger), and it was difficult for the research team to ascertain the mathematical goal of the activity. Later in the paper we will report on how this prototype evolved into one of our more popular games.

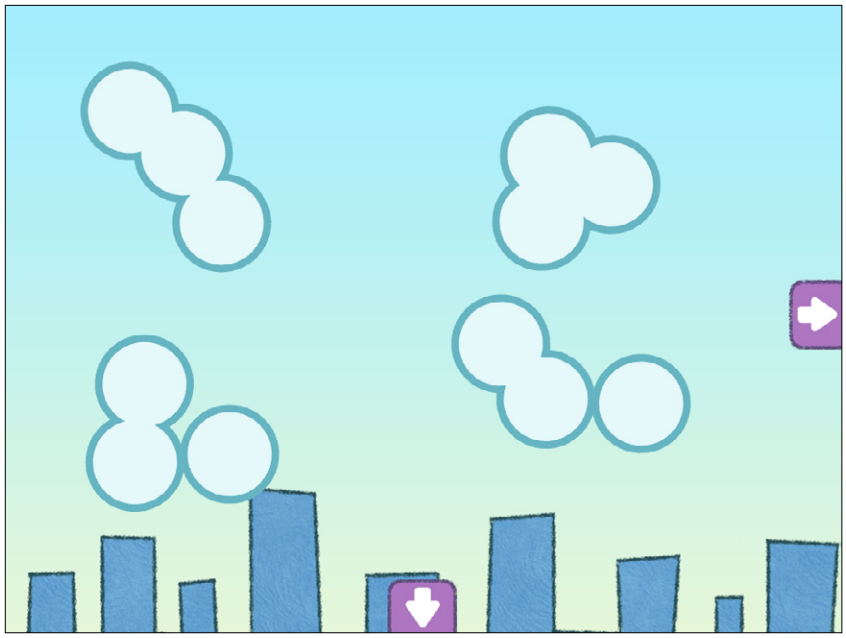

FIGURE 2. Example of Prototype (Bubble Clouds) Not Meeting Learning Goals.

In retrospect, we believe that our over-dependence on one form of literature (in this case, the educational research literature) was an inherent weakness in our design process: The processes we relied on had assumed a relatively homogenous team who had a common vocabulary and understanding of the issues and processes surrounding the design of a learning technology. However, a common vocabulary and understanding was not the case: The design and development team's process and approach to prototyping was not articulated to the research team, nor was the research team prepared to evaluate prototypes that did not directly relate to the expected learning goals. Once the team agreed on the purpose of the initial prototypes, we worked together to better understand how the prototypes could evolve to more full-featured games.

Game Play and Learning Goals

As the prototypes evolved into games, there were still many instances in which the research team and the design and development team had different expectations. To provide an example, the design and development team prototyped an activity called *Bubble Clouds* (see Figure 2).

Bubble Clouds was created as an open-ended "sandbox" activity that would encourage children to equipartition a large group of bubbles by dragging bubbles together to create clouds. The goal was to have children create clouds each with the same number of bubbles. While this activity was fun and enjoyable to children (four year-olds love bubbles in all their forms!), they did not approach the game with the goal of engaging in equipartitioning. While the design and development team saw the children in the formative testing phase as having fun while playing in a way that *could* result in them spontaneously engaging in equipartitioning, the research team saw the children as engaging in non-mathematical play. Adding to the research team's concerns, the children did not engage in equipartitioning even when asked to and, perhaps just as disconcerting, clouds of the same number of bubbles were unlikely to have the same area, obstructing the mathematical idea of equipartitioning as resulting in equal quantities. As the formative testing continued and the design and development team could not articulate or provide solid evidence that use of the game supported mathematics learning for the majority of children, the NGPM team collectively decided that the *Bubble Clouds* prototype should not be part of the final game set.

Bubble Clouds is one example of an activity that was fun, but was unlikely to result in the target learning or show measurable learning gains. As such examples became apparent, the team began to struggle with an important question: Is there a tradeoff between a "fun" activity (that is, an activity that is fun enough that children will spontaneously ask to play it multiple times) and an activity that will lead to rigorous mathematical learning? This is not to say that the design and development team did not want mathematical rigor, or that the research team did not want high affect. However, the viewpoints and approaches often differed, resulting in passionate discussions. While, of course, the goal for any educational game should be both fun and rigorous, and it is easy to say, "of course the goal should be both," the realities of game design made this difficult. How could we create activities that were novel, fun, and in which children would want to repeatedly engage, even after experiencing failure, while also being based on detailed learning progressions, providing contexts in which the mathematics was the driving force, and providing activities that would likely result in learning gains on an assessment of preschool mathematics content (the stated main outcome of the project)? This remained a tension for some time, and was only resolved

when the team reflected on our design process and created the learning blueprint, as described later.

Iterating on the Games

As we began to iterate on the games we also discovered differences in expectations about the iteration timeline. All team members agreed that the design would benefit from having user testing with children and teachers. While both teams agreed on the need for fast iteration cycles, the researchers expected to engage in rounds of systematic analysis, and wanted time between each revision to (1) analyze game elements and their consonance with the learning goals, and (2) analyze responses from diverse sets of children to determine (a) what aspects of the activity resulted in behavior consistent with learning the target mathematics and (b) if there were differences based on children's background (e.g., language or home culture). Understanding the need for rapid iteration, even when doing systematic analysis, the research team was able to provide the design and development team with a detailed set of integrated feedback often within one week from receipt of a new set of prototypes. The research team considered that almost recklessly fast, given that each cycle required learning about the new prototypes (typically provided Monday morning), modifying the protocols (Monday afternoon), running multiple user sessions over two days in multiple locations (Tuesday and Wednesday), writing up each user session (also Tuesday and Wednesday), finding commonalities and differences across the sessions (Thursday), determining which aspects of interactions came to the level of being reported to the design and development team (Thursday), and then generating an integrated document that summarized the findings of the user tests (Friday morning, to be reported Friday afternoon). However, this pace seemed almost glacial to the design and development team, who tended to base revision on impressions from their own formative testing, reacting more quickly during the prototyping phase and often making changes and modifications to prototypes within a day of testing with two classrooms of preschoolers. As a result, the design and development team often already had undergone internal revision cycles by the time the research team developed and presented its feedback, sometimes rendering the research team's comments outdated and, occasionally, completely obsolete.

A NEW DESIGN FRAMEWORK AND THE NEED FOR A BOUNDARY OBJECT

Once these collaboration difficulties were identified, we determined that a key impediment was that different team members had very different understandings of what it means for a game or activity to address a mathematical learning goal. We also realized that this went beyond simply explicating a set of high-level learning goals, as all team members could agree to the learning goals yet still not agree on the approach for how an activity should address a specific learning goal. To deal with this difficulty, we created a learning blueprint (Table 1): a "boundary object" (Wenger, 1988) that detailed not only specific learning goals

DETAILED LEARNING GOAL (developmentally appropriate to already know or to learn the following)	**TASK** (instructional or assessment)	**WAYS TO VARY DIFFICULTY**	**POSSIBLE SCAFFOLDING ACTIVITIES** (if not successful in original activity)	**SUGGESTIONS GOING FORWARD**
Identifying collections as equipartitioned or not equipartitioned	Show a child two small collections of objects (e.g., coins) and ask them if they each have the same number of objects	Varying size of collection (generally increase in size more difficult; however this gets complicated as you introduce variation in receivers) Varying number of receivers (easiest case is 2 receivers; then 2^n; then 2n and finally odds, starting with 3)	Afterward: Promote checking by counting (either matching or comparing magnitude)	This could be built into the introduction (to be used as a training space) e.g., show how-to, have children decide whether next character carried it out correctly, then move into having the children do their own (next rows in this spreadsheet…) Or if children are not able to perform their own equipartitioning, have the identification as a lower level

TABLE 1. Learning Blueprint Excerpt.

(e.g., partition groups of objects into smaller, equal groups of objects), but also gave generic instances of activities that instantiate those learning goals (e.g., given a small collection of objects and people to whom to distribute the objects, children equipartition/distribute the same number of objects to each person), appropriate ways to vary the difficulty of the activities (e.g., varying size of the collection), and appropriate scaffolds for those instances when children were not able to achieve success with an activity (e.g., promote checking by counting). While the need for such a boundary object seems obvious in retrospect, we note that none of the design process articles we have reviewed mentions the importance of creating a boundary object that can be used cooperatively by educational researchers and game designers. We believe that, as more projects engage in this type of cross-disciplinary co-design, the need for such a boundary object will become more evident. We incorporated this boundary object into what we call the *Evidence-Based Curriculum Design Framework*.

The Evidence-Based Curriculum Design Framework borrows heavily from the notion of Evidence Centered Design (ECD) (Mislevy & Haertel, 2007) and includes components of ECD design patterns, such as (a) clearly articulated target knowledge, skills, or abilities (which we refer to as learning goals), (b) consideration of additional knowledge, skills, or abilities required to engage in an assessment task (or in our case in learning activities), and (c) potential observations or work products needed to assess learning (or in our case to promote learning; Mislevy et al., 2003). While ECD focuses on designing *assessment items*, Evidence-Based Curriculum Design focuses on designing *learning activities*. These differences are not trivial: In the design of assessments, the focus is on validly and reliably determining the level of competence a test-taker has exhibited with respect to a particular learning goal. This is in contrast to the design of curricular activities, in which the focus is on providing the learner with an interaction that will allow that learner to advance his or her knowledge.

Once the team developed the notion of the evidence-based curriculum design framework, significant development of activities was put on hold while the research team developed the first iteration of the learning blueprint based on the subitizing trajectory outlined by Clements and Sarama (2009).

With the learning blueprint in place, the teams again began rapid cycles of iterative design that included content analysis by the research team, as well as user testing by the research and design and development teams. The result was a modified design and development process (see Figure 3), in which the creation of a learning blueprint is before the creation of proofs of concept or prototypes.

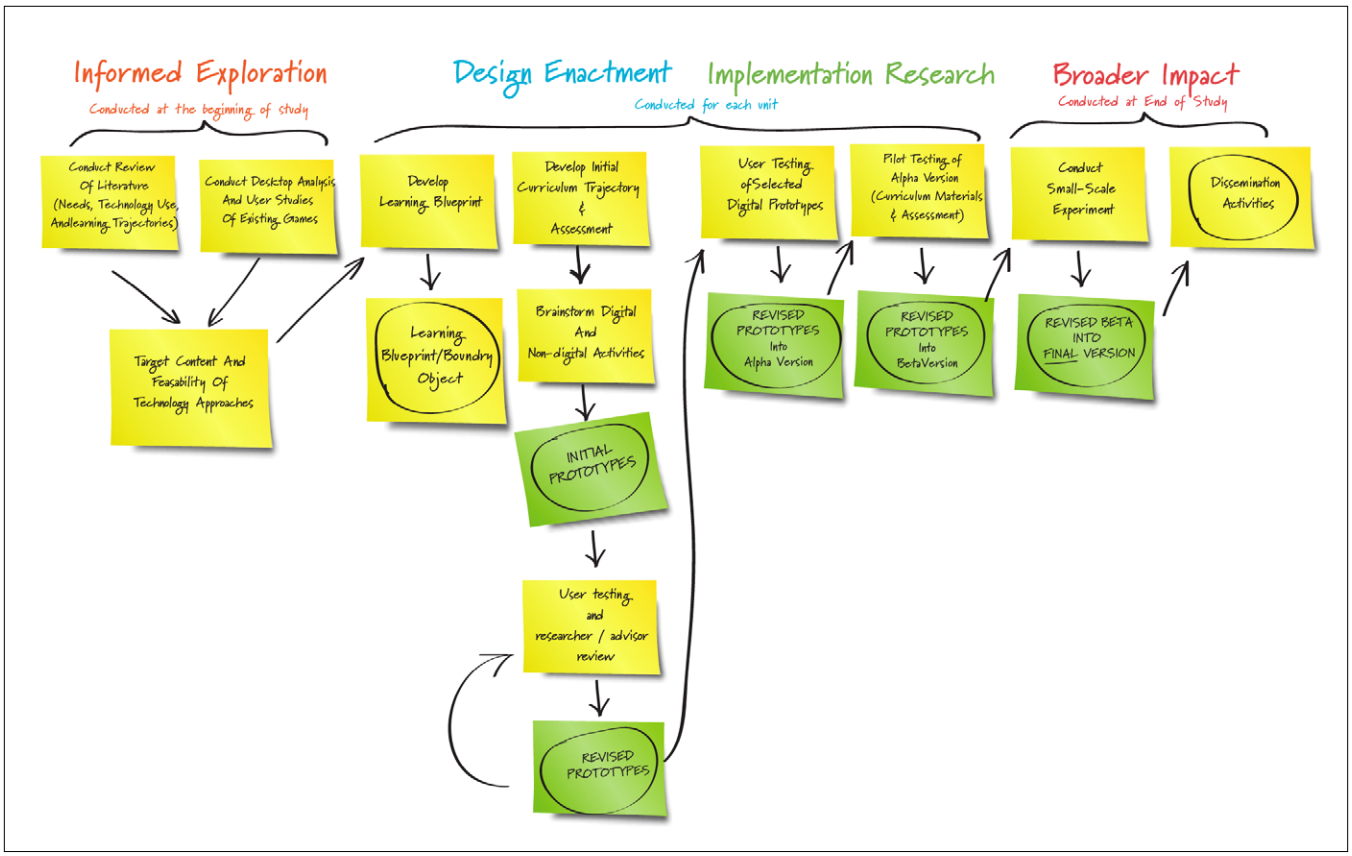

FIGURE 3. Modified Design and Development Process Overview.

The modified design process starts with the *informed exploration* phase, in which we conduct a literature review and conduct an analysis of existing studies and games, which lead the team to target the content and technical approach. In the second phase, *design enactment,* we develop the learning blueprint that serves as a boundary object, then develop an initial curriculum trajectory (and assessment if needed), brainstorm activities (digital and non-digital), create proofs of concept, conduct user testing, and then continually revise prototypes based on additional user testing and review by researchers (and advisors). Phase 3, *implementation research,* proceeds with another round of user testing before creating an alpha version to be used in a larger pilot study and revising the activities into beta version. Finally, phase 4 focuses on *broader impacts,* during which the research team conducts a small-scale experiment, revising the beta into a final version for public release, and disseminating both the activities and research findings.

Designing with the Learning Blueprint to Enhance Communication

With the new design framework—and, most notably, the learning blueprint/boundary object—in place, the teams again engaged in rounds of iterative design. The use of the learning blueprint had several implications for the design process. The first, and perhaps most important, was that the design and development team and the research team had a common artifact and vocabulary. In addition, because the learning blueprint had example tasks and suggestions for varying the difficulty of tasks, the design and development team was more attuned to the researchers' needs and expectations and, just as importantly, was able to describe the design choices made in terms that the research team could understand. It also imposed the requirement that the research team pre-specify, as much as possible, what the detailed learning goals were. This ensured that the design and development team could have confidence that their designs were addressing the full set of learning goals. Likewise, the learning blueprint was revised based on feedback from the development team.

Another implication is that it lessened (but did not eliminate) the mismatch in timing expectations. While the research team still required a week before providing feedback, it was clearer what aspects of the games would be the focus of that feedback. That allowed the design and development team to focus their rapid iterations (multiple versions per week) on those aspects of the game that were less directly related to the learning, such as detailed game mechanics and usability.

The third and final implication we discuss in this article is how using the learning blueprint as a boundary object changed the *nature of disagreements* between the research and the design and development teams. In particular, it provided the design and development team with the backing it needed to include features that increased affect, so long as those features did not detract from the math learning. As one example, the design and development team prototyped a collaborative game in which the children took pictures of each other, and those pictures then became part of the gameplay. The research team was concerned that, while children found the photo taking fun, user testing found that it could be difficult and time consuming for young children. However, the design and development team pointed out that this feature did not *detract* from the learning goals found on the learning blueprint and that whatever difficulty there was or whatever time was spent on photo taking was more than made up for by the increased gameplay and willingness to collaborate the children showed when their faces were part of the game. (Note that this feature made it into one of the collaborative and more popular games, called *Photo Friends*.)

The game *Lemonade Stand* provides another example of how the learning blueprint provided backing for the design and development team to include features with which the research team initially disagreed, and it highlights the issue of the apparent tradeoff between an engaging game and mathematical rigor. *Lemonade Stand* is an equipartitioning game, built upon the ice sliding game described previously. In *Lemonade Stand* children tilt the tablet to slide equal numbers of ice cubes into cups (see Figure 4). The game starts with just ice cubes and cups, but as the game progresses there are challenges such as straws and lemon slices (which

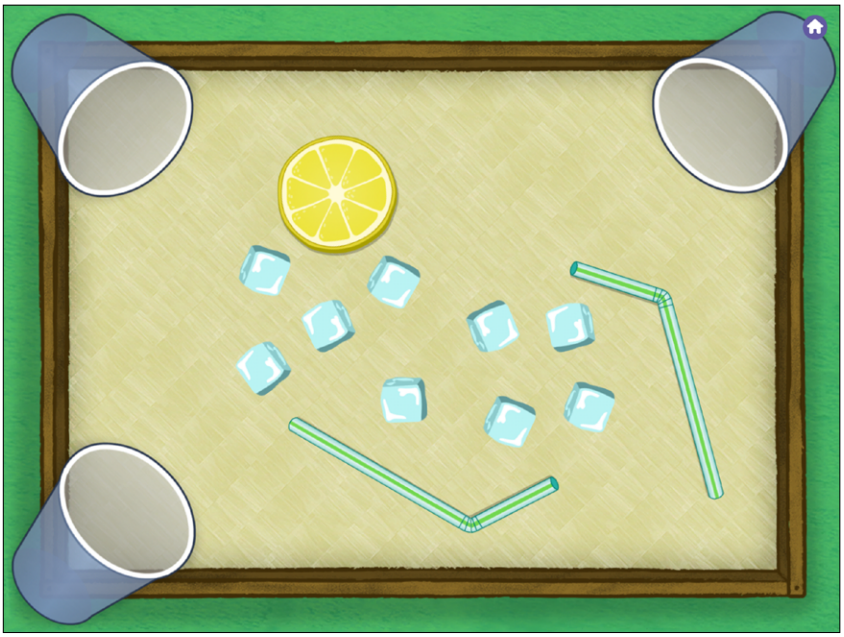

FIGURE 4. Example of *Lemonade Stand* Prototype.

do not move when the tablet tilts, but which can divert the ice cubes), holes (through which ice cubes can slide, ending the level), and ladybugs (if a ladybug slides into a cup, the level ends).

The researchers were concerned that the obstacles would be so challenging that it would take the focus away from the target mathematics or would be so frustrating that children would stop playing the game. However, the design and development team felt that the challenges increased affect and that leveling the game purely by the math difficulty would result in a game that would quickly become boring, as sliding ice cubes around without any other obstacles would become repetitive. After user testing[2] the design and development team was able to argue that the challenges did not detract from the math, but the research team highlighted one exception: The higher levels of math achievement were also associated with the more difficult obstacles, and a significant number of children got frustrated and stopped playing the game when the most difficult obstacles were introduced. The research team considered this an equity issue: Many children stopped playing before they had the opportunity to experience the higher-level mathematics. The final compromise was to leave in the obstacles, but those obstacles that user testing showed to be the most difficult (e.g., ladybugs and holes in the sides) were reserved for levels that *repeated* the highest levels of math: That is, children could experience all of the math content (in levels 1–11) without having to completely master the game mechanics. (The more difficult game mechanics were introduced in levels 12-20.)

An important aspect of all these uses of the learning blueprint was the collaborative engagement throughout the design process. That is, the learning blueprint was *not* designed for a smooth handoff, say from the researchers who specified the learning goals to the developers who then created the games. Instead, it was designed for iterative design, where the teams kept coming back to the document and, in some cases, revised the document where clarifications or additions were needed. This is critical to note, as the project itself was first and foremost about answering our research question (which required measuring gains in children's learning), with the research team being the lead on the grant and the design and development team being a sub-awardee. The power dynamic could easily have been uneven, and in fact early in the project it felt uneven—to *both* teams. But the learning blueprint empowered *both* teams to articulate their expectations, desires, needs, observations from user testing, feedback, and decisions thus ultimately providing a common language and understanding across teams. Better communication and therefore better processes and products resulted, and both teams felt as collaborative partners.

[2] Due to built-in tracking data, we were able to determine where the big "drop offs" were in terms of level failure and link those to newly introduced game mechanics.

GOING TO MARKET: DESIGN TENSIONS AND DECISIONS MADE

So far in this article we have discussed our design frameworks, specific examples of the ways in which game designers and educational researchers differed in design expectations, and the importance of the learning blueprint. In this section we review other design tensions that arose as we undertook the steps necessary to move from a relatively small research project to a suite of popular published tablet apps, and our reflections on this experience.

Final Design Cycles

Earlier, we discussed the mismatch in expectations related to the time between iterative cycles of design, where the research team wanted more time between design cycles than the design and development team thought was reasonable for rapid prototyping iterations. There was a symmetrically opposite tension in the time it took to go from the final prototype to the finished product available on the Apple App Store. That is, as the research team engaged in the final set of research activities in the experiment, they observed several aspects of the games that they thought could be improved. As these requests were months before the suite of final apps would be available on the App Store, it seemed logical to implement these suggestions (especially given the blazing turn-around time during the initial prototype iterations). This, however, was unrealistic from the perspective of the design and development team: Finalizing the app for publishing included creating the final voiceovers, final graphics, and final code, conducting final quality assurance, and implementing necessary bug fixes. Any additional iterations or wish-list items were considered only if they resulted in minimal changes and testing that could fit into the scope, time, and budget constraints.

Context of Use

Because the NGPM project was funded by the National Science Foundation to investigate the efficacy of tablet-based games for teaching math in preschool classrooms, the research team considered the classroom to be the primary context of use. The design and development team were also cognizant of the fact that ultimately the games would be released on the Apple App Store and, as such, the games would have to be attractive to anyone who was looking for preschool math apps. Due to the requirements of our funding, the team decided that decisions would be made from the classroom-first perspective, but use outside of the classroom would be part of the design considerations.

We made several decisions about the games based on this choice. For instance, when designing for classroom use, it is important that the teacher have at least minimal control over what game the children are using, because the games were designed to link to other activities planned for that day.

For this reason, we made eight games total—four subitizing and four equipartitioning. This allowed the teacher to launch the day's game, and easily tell the children what game to be playing. If the games were designed primarily for home use, we may have taken a different approach to the suite of apps, possibly be creating fewer or designing a longer play experience. The existing NGPM apps were designed for 15-minute classroom experiences (this was what teachers reported being realistic for preschool classroom use, for example during learning center time, and what we confirmed through classroom observations), and we likely would have made different design decisions and engaged in different forms of user testing if we were focused on home use. Comments on the App Store and other forums share that some NGPM games are repetitive, which was actually by design for the classroom so that children can build up their skills over several short play periods and better understand and reinforce the math learning based on the learning blueprint.

Supports Beyond the Apps

We found that releasing the final products—which included the eight iPad apps (available on the Apple App Store under the overall heading of Early Math with *Gracie and Friends*™), a digital teacher's guide, and a set of non-digital materials designed to integrate into the preschool classroom—did not fit into existing structures of any of our organizations. The research teams typically produced papers, and in those cases where classroom-ready materials were produced, they were not in the form of tablet apps. Tablet apps must be updated and maintained over time, and research project funding typically does not cover ongoing maintenance and upgrades. The design and development team was experienced in creating and supporting apps and educational materials, but this tablet-based formal preschool curriculum that included teacher materials was a new approach to development that comes with a larger vision. In addition we were committed to all materials being available for free, with future support primarily being based on additional grants.

In the end, the design and development team created a new faction within their organization entity, First 8 Studios, which links to the App Store and houses the online teacher guide, the print materials, and research findings. As the full NGPM team continues to work together (currently on preschool science and more math apps for home use), first8studios.org will house these hybrid materials.

REFLECTIONS ON THE DESIGN

From this experience we learned that our team could not just have strong researchers and strong game designers and developers each "doing their job." The team must operate in an environment that consciously allows for collaboration, communication, and negotiation. There also must be agreement from the outset on the focus of the project (in our case, it was increasing children's mathematics learning while adding to the research base). In a review of trends in educational gaming, Young, et al. (2012) discuss the need to encourage collaborative partnerships among commercial game companies and educational researchers, since it is unlikely game companies will either undertake the research or risk manipulating their content for research purposes. The authors continue with a recommendation to ensure game objectives and learning objectives correspond, something the NGPM team achieved via the learning blueprint. We also have learned to adhere to a design plan that includes negotiating roles, a learning blueprint necessary to guide research and design, and a process of iterative design that allows for input from different perspectives and for dispute among participants. In today's increasingly crowded marketplace for early educational digital products, many developers are citing probable educational impact as a result of use. Guernsey and Levine (2015) suggest that if one is claiming a game's educational impact, it would be helpful to know on what basis that claim is being made. Acknowledging the complementary roles of research and game design, and defining the rules for iteratively negotiating between the roles, led us to a stronger collaboration and, ultimately, to a stronger product.

We understand that the process described in this paper may be considerably more time-intensive and costly than is possible for commercial products. This is due in part to the nature of a project funded under the auspices of a research agency. We do not advocate that all educational game development follow the full set of processes described here. We do, however, advocate that an object similar to a learning blueprint be created that allows team members with different perspectives to agree on a set of detailed learning objectives as well as the means to achieving those objectives.

CONCLUSIONS

We have discussed critical tensions between the design and development team and the research team, as well as the ways in which these design tensions were addressed. Key to these was the creation of a boundary object that was a shared artifact between the researchers and designers. In our case the boundary object was a learning blueprint, which was a living document that was able to take into account input from the research team and the design and development team. A result of using the learning blueprint was the collaborative engagement throughout the iterative design process, where teams participated in recurring modifications of the document.

We recognize that our boundary object was created based on an explicit theory of learning, and we believe that if another boundary object with a different focus were used, the design could have led away from the science of learning

mathematics and toward, say, affect being paramount. It is not clear to us that an "unbiased" boundary object (and hence design process) is possible, or even desirable.

While our design process was biased toward the sciences of learning mathematics, we have shown that the process allowed for tremendous latitude throughout the development and design periods. We have seen how, in NGPM, the importance of acknowledging, navigating, and mediating the complex relationships between research design and game design resulted in productive tensions, as well as in games that, we all agree, were better than if we had not had all the different perspectives.

Through our design process, decisions were made that were faithful not only to the initial project intent, which was primarily to explore innovations in early mathematics teaching and learning, but also to the secondary goal of having large impact. The contributions to the field of this work will ultimately lie in mathematics research, which in this case undergirds the design and development decisions, including usability, engagement, appeal, and even marketability.

ACKNOWLEDGMENTS

We would like to thank the contributions of the extended NGPM team, as well as the teachers and children who enthusiastically participated in the project. This material is based upon work supported by the National Science Foundation under Grant No. (DRL-1119118). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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