Journal of Research on Educational Effectiveness

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/uree20

Accelerating Early Math Learning with Research-Based Personalized Learning Games: A Cluster Randomized Controlled Trial

Khanh-Phuong Thai, Hee Jin Bang & Linlin Li

To cite this article: Khanh-Phuong Thai, Hee Jin Bang & Linlin Li (2022) Accelerating Early Math Learning with Research-Based Personalized Learning Games: A Cluster Randomized Controlled Trial, Journal of Research on Educational Effectiveness, 15:1, 28-51, DOI: 10.1080/19345747.2021.1969710

To link to this article: https://doi.org/10.1080/19345747.2021.1969710

JOURNAL OF RESEARCH ON EDUCATIONAL EFFECTIVENESS
2022, VOL. 15, NO. 1, 28–51
https://doi.org/10.1080/19345747.2021.1969710

INTERVENTION, EVALUATION, AND POLICY STUDIES

Accelerating Early Math Learning with Research-Based Personalized Learning Games: A Cluster Randomized Controlled Trial

Khanh-Phuong Thai[a], Hee Jin Bang[a], and Linlin Li[b]

[a]Age of Learning, Inc, Glendale, California, USA; [b]WestEd, San Francisco, California, USA

ABSTRACT

This study examines whether *My Math Academy*, a digital game-based learning environment that provides personalized content and adaptive embedded assessments, can improve math knowledge of Transitional Kindergarten and Kindergarten students. A cluster randomized study was conducted with 20 classrooms, 10 of which were randomly assigned to use *My Math Academy* for 12–14 weeks. Results of hierarchical linear models indicated that after using the app for about 5 hours, treatment students significantly outperformed the control group in math knowledge and skills as measured by TEMA-3. *My Math Academy* produced the greatest learning gains in students who began with a moderate level of math knowledge and on the most difficult skills assessed. Additionally, the more games students played, the greater the learning gains they experienced. Teacher surveys revealed that *My Math Academy* produced positive impacts on students' interest and self-confidence in learning math. Teachers also recognized *My Math Academy* as a user-friendly, valuable learning resource that they will continue to use. The study results will inform ongoing development of *My Math Academy*, including tools to enable teachers to help children with low levels of prior math knowledge.

ARTICLE HISTORY
Received 19 May 2020
Revised 11 March 2021
Accepted 23 April 2021

KEYWORDS
Math learning; game-based learning; adaptive instructional systems; personalized learning; early childhood education

Introduction

Students' proficiency in foundational mathematical skills is an important predictor of later academic success and preparedness for twenty-first century STEM careers (Chu et al., 2016). The latest results from the National Assessment of Education Progress (NAEP) show that only 41% of fourth graders are proficient in math (US Department of Education NCES, 2020), and the situation is worse for children from low socioeconomic (SES) backgrounds. Students with fewer resources at home begin school with significantly less math knowledge (Nores & Barnett, 2014; Starkey et al., 2004) and demonstrate clear, substantial gaps in the development of early math skills relative to

CONTACT Khanh-Phuong Thai kp.thai@aofl.com Age of Learning, Inc, Glendale, CA, USA.

their middle-class peers (Denton & West, 2002; Hecht et al., 2000; Lonigan et al., 1998; Nores & Barnett, 2014; Starkey et al., 2004). Consequently, many low-SES children are almost a full year behind their middle-class peers in math knowledge by the time they enter school (Nores & Barnett, 2014; Starkey & Klein, 2008). Left unaddressed, this gap persists and increases over time (Entwisle & Alexander, 1990; Morgan et al., 2009; Rathbun & West, 2004; Reardon, 2013).

Elementary schools are expected to align instruction with the higher learning expectations built into learning standards, despite the fact that many children enter school unprepared for math (National Research Council, 2009). Students who enter school with less proficiency in math and literacy are likely to disengage, which negatively affects their ability to benefit from instruction and predicts lower academic growth in elementary school (Bodovski & Farkas, 2007; Reyes et al., 2012). With students of varying degrees of readiness in their classes, teachers face challenges of appropriately personalizing and individualizing learning for each student in their class (Dixon et al., 2014; Goddard et al., 2015). Highly engaging educational technology innovations targeting early elementary grades have the potential to close the opportunity gap and prepare students for success in mathematics. In this paper, we operationalize mastery-based personalized learning as adaptation of learning content and difficulty level to individual student's readiness to tackle said content at a pace that is appropriate for the student. This concept is further elaborated below in Key Design Principles.

Objective

Despite the growing number of digital learning resources in recent years, there are few evidence-based, engaging resources to accelerate early mathematics learning. To address this need, a cluster randomized controlled study was conducted to evaluate the impact of a research-based, supplemental digital math learning resource called *My Math Academy* on kindergarten students' early number sense and operations and engagement in learning math. *My Math Academy* addresses most of the kindergarten level math standards in the Common Core State Standards (Counting & Cardinality, Operations & Algebraic Thinking, Number & Operations in Base Ten); it is designed to supplement core math curriculum that addresses other skills that also provide content on Measurement & Data and Geometry.

Studies have explored the benefits of game-based digital curriculum as one way to encourage learning and motivation in both formal and informal learning environments. Building on the theory of developmental psychologist, Lev Vygotsky, it has been suggested that *play* is an important element in game-based learning (Barab et al., 2005). Though research on game-based educational programs is still in its early stage, a number of studies have found positive impacts, including active involvement of the audience in the narrative, creation of a unified learning experience, improvement of the learning process by means of integrating knowledge and skills, and gains in student achievement (Andreu et al., 2012; Cohen et al., 2012; Gilardi & Reid, 2011).

Background

My Math Academy

My Math Academy is a game-based adaptive learning system designed to help young children build a strong understanding of fundamental number sense and operations. It includes 30 games with over 130 game-based activities, covering number sense and operations concepts and skills for pre-kindergarten through second grade. Topics range from counting to 10 to adding and subtracting three-digit numbers using the standard algorithm (see Appendix for list of games and learning objectives of this digital math resource). Each individual game activity maps to a learning objective and is supported by an interactive instruction level, as well as several layers of scaffolding and feedback. Within individual games and between games, built-in adaptivity provides scaffolding and adjusts difficulty based on the learner's performance. Across the system, this adaptivity gives learners a customized pathway between skills based on prior performance. Assessment is embedded throughout the play experience, including game-based pretests and final assessment tasks at a granular skill level. In addition, the game system as a whole uses cohesive narrative and interactive characters (embedded at the level of individual games) to support student engagement with the learning world. In sum, *My Math Academy* combines math curriculum with learning sciences, adaptive technology, and instructional design and production. With engaging characters and scenarios, individualized learning pathways, and continuous assessment built into every level of every game, *My Math Academy* aims to help students learn and make sense of math in an enjoyable way. *My Math Academy*'s design recognizes that children learn through play, and it builds upon the natural relationships between learning and children's daily life activities and experiences via game-based learning contexts, encouraging them to build connections between the math concepts and their developing world knowledge (more on this in Key Design Principles).

Throughout its design and production, My Math Academy applied "learning engineering," which is "*a process and practice that applies the learning sciences, using human-centered engineering design methodologies, and data- informed decision-making to support learners and their development*" (ICICLE, 2020). Originally coined by Herbert Simon (1967, cf. Carnegie Mellon University, 2020), learning engineering is gaining traction as a promising and innovative approach that uses evidence-based and iterative improvements in learning processes and outcomes to design educational interventions in real learning contexts (Hess & Saxberg, 2013; The Learning Agency, 2019). Learning engineering applies the learning sciences—informed by cognitive psychology, neuroscience, and education research on how people learn best (Willcox et al., 2016)—and engineering principles to create and iteratively improve learning experiences for learners (ICICLE, 2020). The design and development of *My Math Academy* leveraged human-centered design to guide design choices that promote robust student learning, and also emphasized the use of data to inform iterative design, development, and improvement processes (Age of Learning, Inc., 2020).

Key Design Principles

Theoretical foundations of learning sciences have been applied to inform *My Math Academy*'s content, pedagogy, and design for learning and engagement (Owen, in press; Age of Learning, Inc., 2020).

Learning Trajectories. Academic achievement involves accumulating and mastering new skills, while improving and building upon existing skills (Entwisle & Alexander, 1990). We adopted the following definition of learning trajectory: the learner's pathway through a hierarchy of goals and activities where each successive objective and interaction is designed to build on the understanding and mastery of previous objectives (Clements & Sarama, 2004; Sarama & Clements, 2004). Since all learners are different, multiple pathways are possible, and instruction is best when it is individualized. The Learning Trajectories approach depends on the learner's success with prior learning and uses that as a foundation for subsequent learning that is tailored to the individual child's needs (Clements & Sarama, 2004; Sarama & Clements, 2004).

My Math Academy's highly detailed scope and sequence were informed by research on hypothetical learning trajectories (Simon, 1995); the learning trajectories approach for early math (Clements & Sarama, 2014); literature on math interventions (e.g., the internationally recognized Math Recovery program); as well as state and national standards frameworks such as the CCSS-M and the National Council of Teachers of Mathematics' Standards and Principles for School Mathematics. The scope and sequence capture the entirety of the concepts, principles, and skills involved in early number sense and operations for kindergarten through second grade, focusing on the most challenging areas of early math and the hidden concepts and skills that drive children's misunderstandings. Each standard is unpacked into learning objectives that articulate fundamental concepts, procedures, and skills that underpin the standard. Figure 1 shows an example of a CCSS-M kindergarten standard that is unpacked into 13 distinct learning objectives.

In a *My Math Academy* game targeting the standard shown in the table, children help Shapeys (game characters and manipulatives) compare and sort toys and packages in order to move them through a factory. Figure 2 provides a screenshot of the game. This game involves the student counting each toy in each bin (one-to-one correspondence), comparing the total number of toys across two bins, and determining whether

Common Core Kindergarten Standard:

Identify whether the number of objects in one group is greater than, less than, or equal to the number of objects in another group, e.g., by using matching and counting strategies.

Concepts:

- *Student understands that when counting, each object is counted only once (1:1 correspondence)*
- *Student understands that different groups of objects can have different amounts (compare)*
- *Student understands that one group of objects can have more than another group of objects (greater than)*
- *Student understands that one group of objects can have less than another group of objects (less than)*
- *Student understands that one group of objects can have exactly the same number of objects as another group of objects (equal to)*
- *Student understands that when counting, the last object counted represents the total number of the set (cardinality principle)*
- *Student understands that numbers higher in the count sequence represent larger quantities than numbers lower in the count sequence (hierarchical principle)*

Procedures/Skills:

- *Student can count objects in the group counting each only once*
- *Student can correctly label the group with the last object counted*
- *Student can match objects in one group with objects in another group using a 1:1 strategy*
- *Student can compare groups of objects to see which group has more or less using a matching strategy*
- *Student can compare groups of objects to see which group has more or less using a counting strategy*
- *Student can identify groups with the same number of objects as equal*

Figure 1. An example of a Common Core Kindergarten standard and the granular learning objectives in *My Math Academy* that underpin the standard.

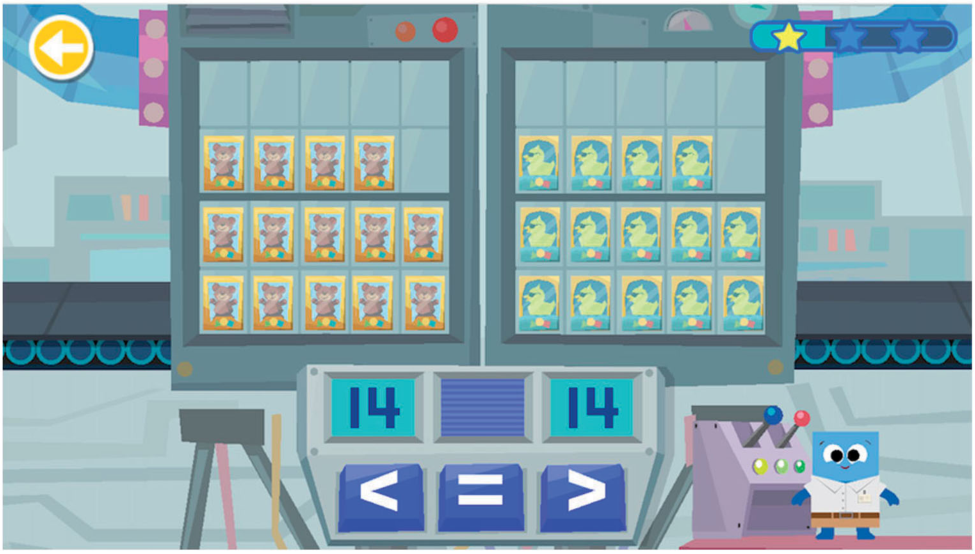

Figure 2. *My Math Academy* Screenshot of a game (Toy Factory).

one bin has more or fewer number of toys than the other bin (greater than, less than). It is important to note that the fundamental concept (e.g., one-to-one correspondence, cardinality, and hierarchical principles) and procedural skills outlined in the table are addressed in earlier games leading up to the one addressing the standard on comparing numbers. Students must apply the concepts they learned previously (one-to-one correspondence and cardinality, counting objects, and numerals between 1 and 20) to count the totals of two separate sets of objectives and exercise their understanding of the hierarchical principle as they learn to compare groups of objects using a one-to-one strategy, matching strategy, or a counting strategy. Since conceptual understanding is built through exposure to a mathematical idea and working with it in various contexts, *My Math Academy* guides players through counting in different scenarios (e.g., counting Shapeys to go on balloon or rollercoaster rides with designated numbers of seats, placing Shapeys onto horses in the correct count sequence in order for them to put on a show, counting the number of prizes in different boxes), reinforcing the one-to-one correspondence, cardinality, and count sequence principles.

Based on the detailed scope and sequence, the team produced a knowledge map of fine-grained, measurable learning objectives, their prerequisite relationships, and pathways toward the development of early number sense. *My Math Academy* embodies the Learning Trajectories approach as it uses this knowledge map of learning objectives and adaptive algorithms to determine what the child knows, does not know, and is ready to learn next. The built-in, adaptive Personalized Mastery Learning System aims to place the child in game-based activities appropriate for the child's anticipated zone of proximal development, adjusting to the child's needs based on ongoing interactions and game-play (Dohring, Hendry, Gunderia, et al., 2018). Consequently, each child experiences a unique learning trajectory, based on her prior knowledge, experience, learning ability, and agency within the game.

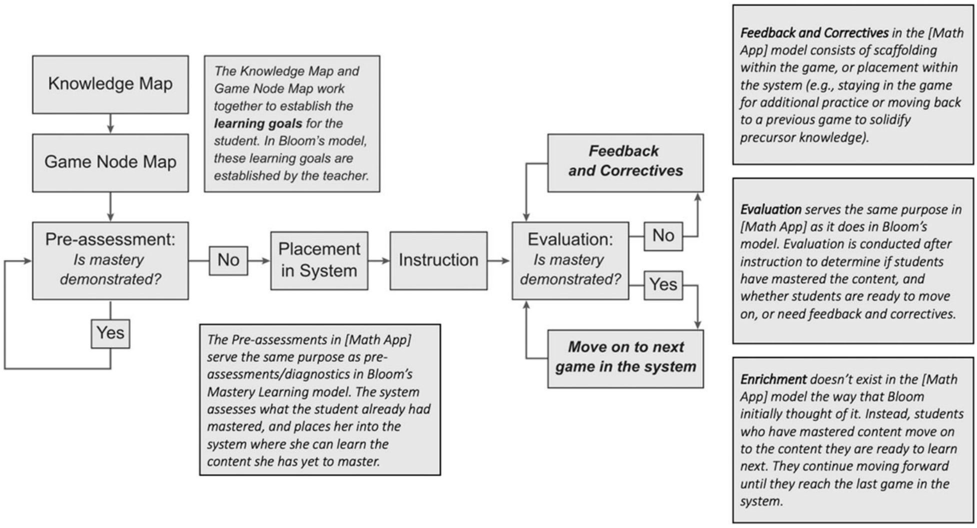

Figure 3. *My Math Academy* Personalized Mastery Learning Model (from Betts, 2019).

Mastery-Based Learning. Bloom's (1968) seminal Mastery Learning theory posits that all students can learn given needed time and appropriate instruction. One-to-one tutoring produces the largest learning gains when tutors adjust their teaching to keep the learning matched to the individual students' needs. Tutors deliver ongoing *assessment, feedback, correctives, enrichment,* and *alignment* of the instructional components to engage learners in their zones of proximal development (Vygotsky, 1978), where they can reach their potential with guidance. The *My Math Academy* personalized learning model (Figure 3) uses initial diagnostic assessments to place each student onto the knowledge map and provides dynamically modified instruction and practice by varying the scaffolding, feedback, and content based on the learner's performance.

Each game play starts with a teaching portion that provides a brief overview of the game, the problem-scenario, and instructions on the mathematics content needed to successfully solve the problem or complete the presented task. The teaching portion explains the content and tells students which actions to take. Next, the student moves onto the actual game, where scaffolding is provided only as the student demonstrates the need for help. The levels of scaffolding translate into measures of mastery and struggle that determine what the student sees next. A student may pass, stay, or fail back in a game (go to an easier level), and the various adaptivity and scaffolding mechanisms enable each student to have a completely personalized experience, tailored precisely to his or her "ready to learn" math level and learning pace.

Data-Driven, Evidence-Based Design. The design of *My Math Academy* integrates principles of evidence-centered design to clearly connect learning objectives with specific digital interactions designed to elicit evidence of student knowledge and abilities (e.g. Mislevy, 2011). As an approach to game design process, evidence-centered design affords a principled alignment of the knowledge, skills, and abilities a game is designed to teach with evidence of learning and task design (Clarke-Midura et al., 2012; DiCerbo et al., 2015; Shute, 2011). This principled alignment was established for each of the games in the *My Math Academy* system, each with a highly granular learning objective related to foundational number sense. Game designers worked closely with curriculum experts to generate a core design template aligning each game's learning objective, in-game task design, and resultant evidence of knowledge, skill, or ability gain. They used these game-based evidence-aligned tasks to build meaningful contexts for learning, which are crucial to authentic assessment and game play immersion. By adopting the evidence-based approach utilized in *Balanced Design* (Groff et al., 2015), the creator of the game used evidence of learning to drive the design, ongoing assessment of student skill, and real-time scaffolding and personalization of learner pathways.

Game-Based Engagement. Play is an important element in game-based learning (Barab et al., 2005). Since Vygotsky (1978), *play* has been construed as a context for children to explore action and meaning in ways that can liberate them from many social constraints in which the child's behavior usually occurs. Barab et al. (2005) argue that designers of game-based learning have a unique opportunity to leverage play in their designs by fostering engaging, *meaningful interactions* to students, which sit at the core of well-designed environments for teaching and learning (Hirsh-Pasek et al., 2015; Rothschild, 2015). Moreover, play specifically has been lauded for its ability to foster discovery learning (Burton & Brown, 1979), implying self-regulated, engaged learning in game worlds (Rieber, 1996). Game-based learning, when well-designed, has been shown to sustain engagement and motivation across time via ongoing feedback, interactivity, and adaptive challenges (Bransford et al., 2000; Gee, 2003; Rupp et al., 2010; Shute, 2008). Games can support growth in STEM education (e.g., McLaren, Adams, Mayer, & Forlizzi, 2017; Plass et al., 2009), literacy (e.g., Steinkuehler & King, 2009), self-regulated learning, and higher-order thinking skills (e.g., Rieber, 1996; Squire, 2006; Steinkuehler & Duncan, 2008). They can further promote perseverance by encouraging students to embrace challenges and use mistakes to learn, making them a perfect mix of desirable difficulties that seek to maximize long-term retention (Kornell & Bjork, 2008).

Learning in Context. Understanding the context of a math problem allows students to make concepts and operations more meaningful and provides a framework for understanding what the student is expected to do, and why (Sullivan et al., 2003). The story context requires students to identify known and unknown information and develop what in Common Core is called a "solution pathway" (Flynn, 2017). Story lines in game-based learning activities help all students, including struggling readers, gain access to the math and make sense of math problems in a story context, as Fisch's Capacity Model (2000) posits that learning content integrated within narrative contexts creates a mediated environment in which the narrative does not compete for limited cognitive resources. Story contexts can also help students transfer skills learned in games of the abstract and into the world. In *My Math Academy*, learners are engaged with problem solving within a story context, which serves as both an engagement tool and a core part of the instructional method. The learners help "Shapeys"—characters and manipulatives in the games—in specific story contexts by using their developing math knowledge and skills. For example, the Shapeys might need help lining up in numerical order for a parade (see Figure 4).

Figure 4. *My Math Academy Sample game: Shapeys lining up for a parade (Forward Count Sequence).*

Formative Assessment. A major feature of *My Math Academy* that aims to sustain engagement and foster learning is formative assessment. Integrated, formative assessment provides useful feedback *during* the learning process, in contrast to a summative assessment conducted at the end of an instruction sequence to evaluate cumulative learning (Shute & Kim, 2014). *My Math Academy* games present players with a series of well-ordered problems and provide just-in-time information and feedback to support mastery (Gee, 2005). Formative assessment enables ongoing feedback cycles and customized player difficulty levels (Shute & Kim, 2014); the just-in-time feedback may change behaviors that is fed into the next round of formative feedback (e.g., Ke et al., 2019).

For example, in the Forward Count Sequence game in Figure 5, the learner can drag any Shapey that is on the street to the float, but only the correct Shapey will be able to stand on the float without falling. If the learner drags the correct number 65–70, she proceeds to the next set of numbers (i.e., 71–80, 81–90, 91–100). If the learner makes a mistake, she receives increasing levels of scaffolding based on her performance (listed below), each of which is informed by research on how children learn the target skill. In this particular example of counting forward from 61, the scaffolding ranges from reminding the learner of the count strategy starting from 61 to aligning 1–10 above the count sequence to help highlight for learners the similarity in numerical pattern.

Attempt 1: The incorrect Shapey sits down and is no longer available to choose, and the voiceover feedback indicates, "That's not the next number. What comes after 64?" (the 64 Shapey waves its hand).

Attempt 2: If the learner again submits an incorrect answer, she hears "Uh oh! Try counting forward from 61 to find what number comes next," and the learner is forced to count all of the Shapeys on the float; each Shapey shouts out its number when the learner clicks on each Shapey.

Figure 5. *My Math Academy Sample game: Reference Shapeys (1–10) in the round where learner is practicing the sequence 61–70.*

Attempt 3: If the learner still makes a mistake, she hears, "That's not the next number. Let's look at the number pattern. [Shapeys with 1-10 on them appear above the upper deck of the float (Figure 5).] When we start counting from 1, we count … ." The learner sees Shapeys count off their numbers, while their 1 s place highlights as they count (1–10 Shapeys' ones places highlights followed by the Shapeys' ones place in the current sequence she is working on, i.e., 61–70) so that both rows highlight the 1–10 pattern.

Attempt 4: After failing again, the highlighting is cleared, and the number pattern highlight sequence repeats. The only difference at this point is that the correct answer Shapey is revealed at the end, and the learner is asked to place it on the float.

Robust cognitive science principles for long-term retention and transfer were applied to develop algorithmic recommendation of activities designed to support desirable difficulties (Bjork & Yan, 2014), such as retrieval practice (Roediger & Karpicke, 2006) and distributed practice over time (Bahrick et al., 1993; Ebbinghaus, 1964). Within games, other proven research-based instructional principles were also used, including techniques like immediate feedback (Anderson et al., 1995), hints, and scaffolding sequences (McKendree, 1990). The presentation and language used in these communications were frequently tested via user testing to maximize their appropriateness and effectiveness for target learners.

Developmentally Appropriate Interactions. Research in human cognition and development informed various aspects of the interaction design of *My Math Academy*. Frequent user testing and application of design research practices (Design Based Research Collective, 2003; Laurel, 2003) informed insights that drove design iterations. With user interface design, for example, cognitive load—the amount of working memory used in a given context was a large consideration. Research on cognitive load (e.g. Sweller, 1988) informs how visual and audio elements must be implemented so as not to overwhelm the learner nor to distract them from the core learning interactions. Deliberate decisions were made to include a minimal number of elements on screen required for each learning game. Furthermore, motor skill considerations shaped specific interaction design, iterating with user testing data to support tap, drag, and drop interactions calibrated to the target age group for each game. In tandem, executive function capability was considered in the design of the complexity of games and activities—with layers of instruction, visual and verbal cues, and well as problem-solving steps kept to a level appropriate for early learners.

Methods

Design and Participants

This study used a blocked cluster random assignment design, which randomly assigned 20 kindergarten (K) and transition kindergarten (TK) classrooms ($n = 453$ students, 50.7% female) at four Title I elementary schools in urban Southern California. These schools were ethnically diverse (76% Hispanic, 22% African American), with 100% of students qualifying for free lunch. None of the schools had a standard curriculum nor assessment in place for early mathematics. Comparisons of baseline data across groups showed that there were no statistically significant group differences in attrition ($p = .54$), age, gender ($p = .15$), or pretest language ($p = .44$). There was no cluster-level attrition, and at the student level, the attrition rate was only 4.9% in treatment (12 students) and 6.3% in control (13 students), making the overall attrition rate 5.5%. Table 1 displays the participant demographic information by group.

Procedure

Prior to the start of the study, classrooms within each school were randomly assigned into the treatment group or the control group. Each school housed four to six participating classrooms. Prior to implementation, treatment teachers received a one-hour training on

Table 1. Participant demographic information by condition.

	Treatment	Control	Total percent (%)	*p*-Value
Attrition	12 (4.9%)	13 (6.4%)	5.5	.54
No posttest	12	12		
Cluster change	0	1		
Analytic sample	233 (95.1%)	195 (93.8%)	94.5	
Gender				.15
Female	126 (54.1%)	91 (46.7%)	50.7	
Male	107 (45.9%)	104 (53.5%)	49.3	
Pretest assessed language				.44
English	224 (96.1%)	182 (93.3%)	94.6	
Spanish	8 (3.4%)	11 (5.6%)	4.4	
English/Spanish	1 (0.4%)	2 (1.0%)	0.7	

how to operate the tablets and use *My Math Academy*. This training provided an overview of the curriculum scope and sequence; the learning objectives and standards addressed in the program; how the program assesses students and places them on their individual learning pathways; and the kinds of strategies and scaffolding provided for each student. Teachers also received suggestions for using the program as a supplement to their core mathematics program. Each treatment classroom received six tablets with access restricted to *My Math Academy* and teachers were asked to implement the app in the classroom in small groups for 15 min per day, 3 days per week, for 12–14 weeks in fall 2017. Students took turns using the tablets in groups of six, each student working independently on his/her tablet, while the teacher worked with the rest of the class. Teachers did not have a role in determining students' pathways through the app; each student progressed at his or her own pace. All classrooms had some math instruction daily (approximately 30 minutes), and treatment teachers received weekly email reminders of usage and summary of student usage during the week. Control classrooms did not receive *My Math Academy* access and conducted business-as-usual instruction. There were no mandated math curriculum or assessment that treatment or control teachers were required to use, and the instructional software that control classroom teachers used included ST Math, My Math, Starfall, Mis Matemáticas, as well as online videos.

Materials and Data Sources

1. **Test of Early Mathematics Ability, third edition, or TEMA-3:** TEMA is a standardized and nationally norm-referenced measure of mathematics performance of children between the ages of 3 years 0 months and 8 years 11 months (Ginsburg & Baroody, 2003), and it was used as the primary measure of children's mathematics knowledge. In this study, a modified assessment was created using a subset of 19 out of 72 items from Form A that best represented the numeracy skills covered by *My Math Academy*. No *TEMA-3* items were identical to the questions asked in *My Math Academy*, and some TEMA-3 item required students to extend their knowledge beyond *My Math Academy*.
2. ***My Math Academy* Usage Data:** Usage data was gathered from the *My Math Academy* which logs each student's event-stream data (i.e., all user interactions within the app) and includes when the student accessed the app, which game they played, and their performance on each activity.
3. **Teacher Survey:** Teachers were asked to rate the impact of *My Math Academy* (for treatment group) or another math educational technology resource (if applicable, for control group) on students' early math learning.

Results

My Math Academy *Usage*

Treatment students spent 5.22 h on average ($SD = 2.97$ h) or between 28 and 35 min/week on *My Math Academy* and completed nearly 79 activities on average ($SD = 40.93$). On average, they started 11.5 games ($SD = 6.12$) and completed 2.21 games ($SD = 5.10$)

by passing the mastery levels. Forty-five students (20%) reached end-of-experience by demonstrating mastery on all 29 games that were available at the time of the study.

Overall Impact

To control for students' performance at pretest, we used a 3-level hierarchical linear model (HLM) to account for differences by students based on their pretest score, group assignment, and school. This allowed us to compare the treatment group's posttest outcomes against the control group after adjusting for differences in baseline scores. Although the intraclass correlation coefficient (ICC) was 0.10, indicating a low variation across classrooms, we used HLM to control for the variability that may exist across schools (ICC = .03).

In the model below, subscripts *i*, *j,* and *k* denote student, teachers, and schools (blocks), respectively; *Math* represents student achievement in math; *PreMath* represents the baseline measure of math performance; *TREAT* is a dichotomous variable indicating student enrollment in a classroom that has been assigned to the treatment condition. $\boldsymbol{r}_{jk}$, and $\boldsymbol{e}_{ijk}$ represent the random effect of teacher and student, respectively. μ_{00k} are fixed effects associated with each school mean, constrained to have a mean of 0; and μ_{01k} are fixed effects associated with each treatment-by-school interaction, constrained to have a mean of 0. In this model, the intervention effect is represented by β_{01k}, which captures treatment/control differences in changes in the outcome variable between pretest and posttest.

$$\text{Level 1}: \; Math_{ijk} = \pi_{0jk} + \pi_{ijk} PreMath_{ijk} + e_{ijk}$$
$$\text{Level 2}: \pi_{0jk} = \beta_{00k} + \beta_{01k} TREAT_{jk} + r_{0jk}$$
$$\text{Level 3}: \; \beta_{00k} = \gamma_{000} + \mu_{00k}$$
$$\beta_{01k} = \gamma_{010} + \mu_{01k}$$

Results indicate that *My Math Academy* produced significantly higher gains in children's knowledge and skills in mathematics when compared to business-as-usual instruction as measured by the selected TEMA-3 items. The treatment group exceeded the control group by 5.71 points, and this difference was statistically significant at alpha = .05 after controlling for differences in pretest ($p = .034$; effect size = 0.228, see Table 2). Table 2 displays the pretest and posttest percent correct by experimental conditions, and Figure 6 displays the percent gain on the assessment by treatment and control groups. The effect size of baseline difference between treatment and control groups is 0.14. According to What Works Clearinghouse (2020), effect size between 0.05 and 0.25 standard deviations is in statistical adjustment range to meet the baseline equivalence requirements.

Table 2. Impact analysis on student outcome.

	Adjusted mean (SD)				
	Treatment ($n = 233$)	Control ($n = 195$)	Adjusted mean difference[a]	*p*-Value	Effect size
Pretest % Correct	43.56 (25.21)	40.07 (24.80)	3.49	0.33	0.14[b]
Posttest % Correct	62.15 (24.61)	56.44 (25.06)	5.71	0.03	0.23[c]

[a]Pretest difference is in adjustable range. The adjusted mean reflects the adjustment of baseline measures and characteristics, as well as the nesting of students in classrooms and classrooms in blocks.
[b]Effect size was calculated by dividing the adjusted mean difference by the full sample unadjusted standard deviation of the pretest.
[c]Effect size was calculated by dividing the impact estimate by the full sample unadjusted standard deviation of the outcome variable.

To examine the robustness of the findings, models were estimated with different combinations of baseline covariates (see Table 2 for sensitivity analyses). The inclusion of covariates in the impact analysis model should theoretically have consequences for the precision of the impact estimate, but not for the point estimate. Changes in point estimates resulting from the inclusion of different sets of covariates could arise because of baseline differences in characteristics across treatment and control groups. As presented in Table 3, *My Math Academy* impacts were estimated based on regression models using the following combinations of covariates: baseline percent of correct answers on TEMA only (Model A, 2-level HLM); randomization strata/block and baseline percent of correct answers on TEMA (Model B, 3- level HLM); baseline percent of correct answers on TEMA, gender, baseline assessment language, and baseline age (Model C, 2-level HLM); and baseline percent of correct answers on TEMA, gender, baseline assessment language, baseline age, and randomization strata/block (Model D, 3- level HLM). The results indicated that the impact estimates were similar when different combinations of covariates are included in the models.

Impact by Prior Knowledge

Using Model B 3-level HLM specified above, further analyses were conducted to determine the impact of *My Math Academy* by students' prior knowledge. Results indicated that *My Math Academy* produced the greatest learning gains in students who scored in the middle third on pretest ($n = 150$, point of estimate = 7.28, $p = .04$, effect size = 0.46)

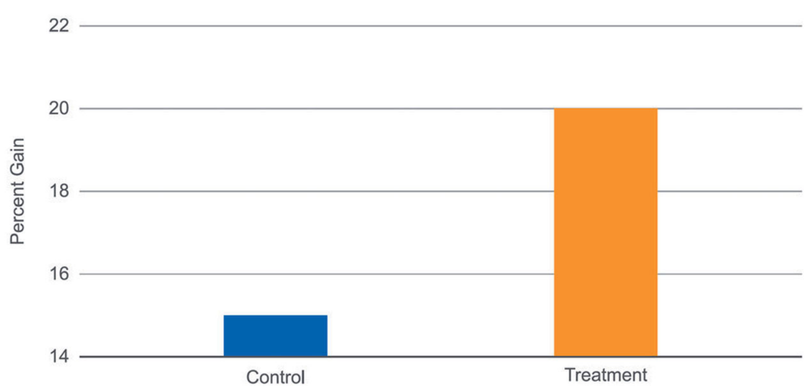

Figure 6. Percent gain in TEMA-3 math scores by treatment group students who used *My Math Academy* ($n = 233$) and control group students who did not ($n = 195$, $p < .05$, effect size = 0.23).

Table 3. Sensitivity analysis on student outcome.

Models		Adjusted Mean (SD) Treatment ($n = 233$)	Adjusted Mean (SD) Control ($n = 195$)	Adjusted mean difference	p-Value	Effect size
A	Posttest % Correct	62.23 (24.61)	56.45 (25.06)	5.78	0.025	0.231
B		62.15 (24.61)	56.44 (25.06)	5.71	0.034	0.228
C		62.24 (24.61)	56.41 (25.06)	5.83	0.031	0.232
D		62.17 (24.61)	56.40 (25.06)	5.77	0.041	0.231

[a]Effect size was calculated by dividing impact estimate by the full sample unadjusted standard deviation of the outcome variable.

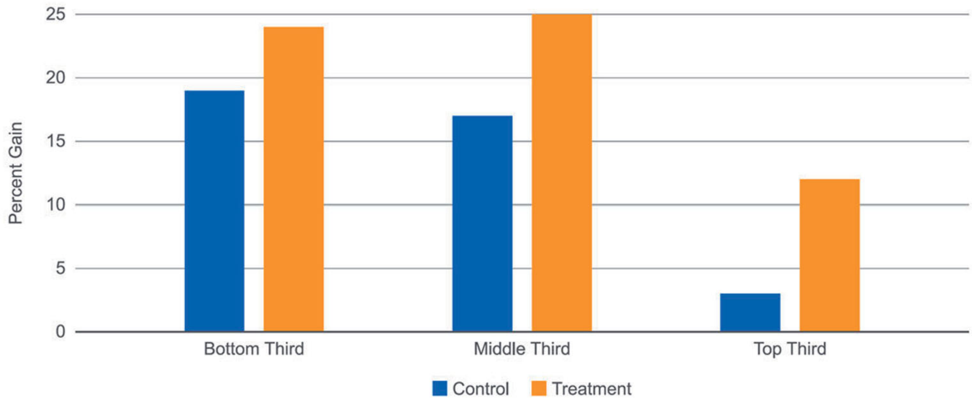

Figure 7. Percent gain in TEMA-3 math scores based on prior knowledge for treatment and control group students based on top, middle, and bottom thirds at pretest (p <.04, effect size = 0.46). Cutoffs were as follows: top third TEMA-3 score > 50% correct (control $n = 67$, treatment $n = 82$); middle third <= 50% correct and > 23% correct (control $n = 70$, treatment $n = 80$); bottom third <= 23% correct (control $n = 58$, treatment $n = 71$).

(Figure 7). Students who scored in the top third at pretest also showed statistically significantly greater gains than similarly scoring peers from the control group ($n = 149$, point of estimate = 5.87, $p = .01$, effect size = .37).

Engagement

In addition to early math skills, another important outcome of interest was students' engagement in learning math. Therefore, descriptive analyses were conducted, which revealed that the more games students started in *My Math Academy*, the greater their learning gains, $r = .19$, $p < .01$. For children who have completed at least one mastery level, there was a significant correlation between the number of games mastered (by completing the mastery level) and learning gains, $r = .38$, $p < .01$.

Figure 8 shows that for nearly all students, the longer they are in the system, the higher their rate of mastery becomes ($r^2 = .40$). A personalized learning system is expected to adapt to each student's pace by delivering appropriate instruction and practice when they are most needed. This enables continuous learning progress as students spend time in the system. One way of evaluating in-game learning in relationship to game play is by estimating the rate of mastery.

Passing in-game boss level is an in-game demonstration of skill mastery, and the learning activities completed on that skill can be thought of as each student's learning pathway toward that skill. Thus, rate of mastery can be thought of as the total boss levels passed divided by total activities completed. We should expect that within a personalized learning system, the longer students spend in the game, the mastery rate should increase. While this relationship between time in the system and learning is not causal, as this relationship can be influenced by other factors (e.g., motivation), it suggests that time in system is associated with personalized learning.

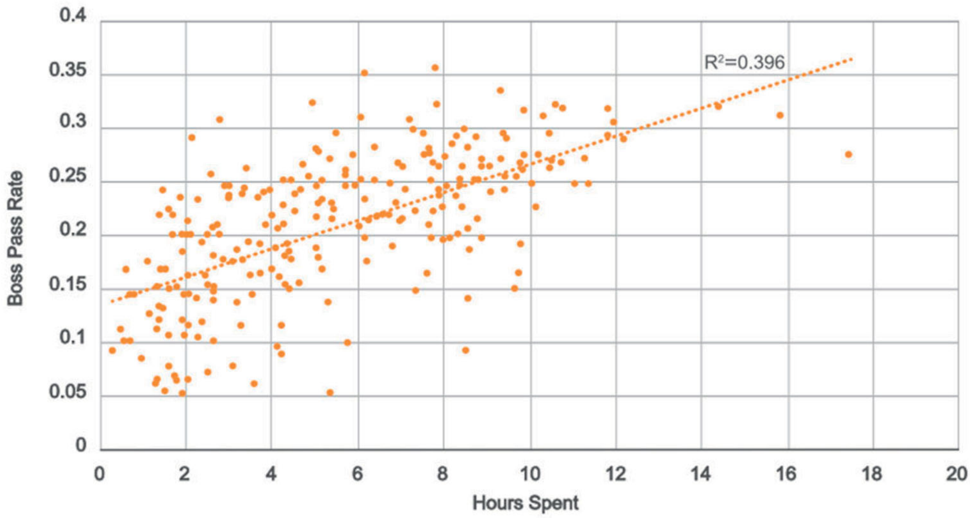

Figure 8. Relationship between total number of hours spent using *My Math Academy* and the rate of mastery in the program.

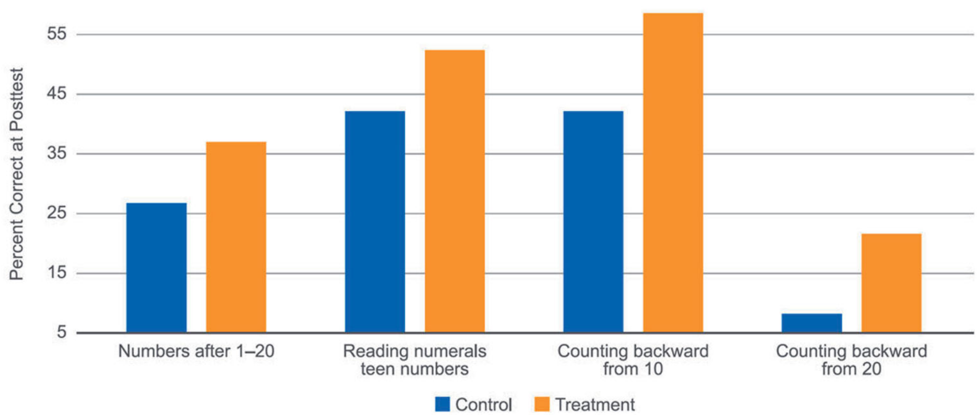

Figure 9. Percent correct on the most difficult TEMA-3 items at posttest for treatment and control groups (n's for students correctly answering each item varied between 48–132 for treatment and 16–81 for control, p's $<=.05$).

Analyses of Specific Skills

Among the skills addressed by the TEMA-3, *My Math Academy* appeared to have produced the greatest gains on the most difficult skills. The four most difficult skills (counting backward from 20, identifying numbers after 10 (up to 20), reading teen numbers, and counting backward from 10), as evidenced by the lowest percent correct at pretest, had the greatest effect size difference at posttest between the treatment and control groups (Figure 9). It is also plausible that these skills, which are explicitly addressed in *My Math Academy* may not have been addressed as prominently in the curricula used by the control group teachers.

On numbers greater than 10, there were no significant differences between treatment and control groups at pretest, but at posttest, 36% of treatment and 26% of control were able to name the numbers (10-20, X^2 [3, N = 428] = 10.65, $p = .05$, effect size = .33), and 53% of treatment and 42% of control were able to read teen numerals (X^2 [3, $N = 428$] = 11.96, $p = .03$, effect size = .27).

On verbally counting backward, there were no significant differences between treatment and control groups at pretest, but at posttest, 57% of treatment and 42% of control were able to correctly count backward from 10 (X^2 [3, $N = 428$] = 13.64, $p = .05$, effect size = .25), and 21% of treatment and 8% of control were able to correctly count backward from 20 correctly (X^2 [3, $N = 428$] = 15.64, $p = .02$, effect size = .54).

Teachers' Perceptions of Impact

Following the implementation, all teachers were asked to respond to a post survey on the impact of educational technology on students' early math learning. While these are self-reported data, and treatment teachers' perceptions may have been positively biased due to their access to a novel resource, notably greater proportions of treatment classroom teachers reported that the *My Math Academy* had a positive impact on the learning outcomes in various areas (e.g., counting, writing numbers) than the programs that their control group peers reported using in their classrooms.

Among the treatment group teachers, 100% reported a positive or highly positive experience using *My Math Academy* in their classroom. In response to, "How would you rate the positive impact in each of the following area as a result of *My Math Academy*?" on a scale from 1 to 4 (1 = no impact, 2 = low impact, 3 = medium impact, and 4 = high impact), 90% reported a meaningful (medium or high) impact of *My Math Academy* on math learning overall. As shown in Figure 10, 100% reported meaningful (medium or high) impact on their students' counting skills and identifying numbers. 80% reported meaningful impact on addition and subtraction skills, and 70% reported meaningful impact on writing numbers. 100% of teachers reported meaningful impact on their students' interest in learning math, self-confidence on learning math.

Teachers were also asked to rate the extent to which they agree and disagree with statements regarding their *My Math Academy*. As seen in Figure 11, 100% of teachers

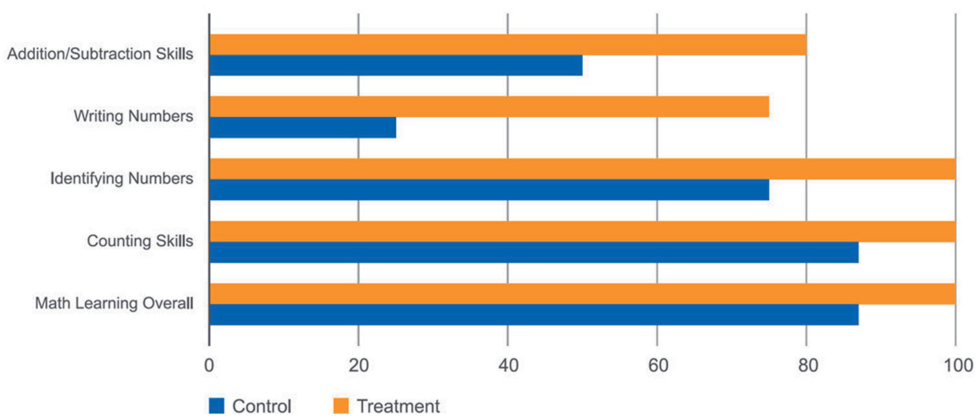

Figure 10. Percent of teachers reporting positive impact on their students' learning outcomes as a result of the educational software they used in math instruction.

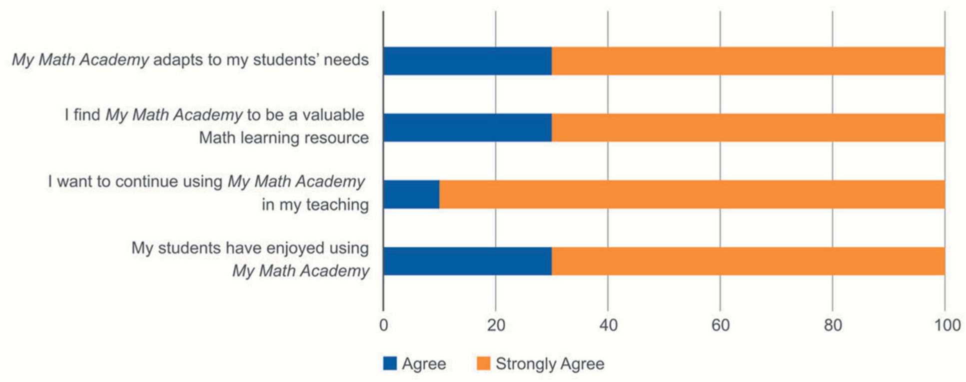

Figure 11. Teacher perceptions of *My Math Academy*.

agreed or strongly agreed that *My Math Academy* adapts to their students' needs, that they find it to be a valuable math learning resource and want to continue using *My Math Academy* in their teaching, and that their students have enjoyed using *My Math Academy*. While these survey responses are subjective evaluations of teachers who used a new resource, they are meaningful given the implementation in real classroom settings and teachers' recognition of *My Math Academy* as a tool that can provide personalized learning experiences for each student.

Discussion

In alignment with a joint position statement of the National Association for the Education of Young Children and the Fred Rogers center for Early Learning and Children's Media at Saint Vincent College (National Association for the Education of Young Children & Fred Rogers center for Early Learning & Children's Media at Saint Vincent College, 2002), this study provides supporting evidence for how developmentally appropriate, individually appropriate, and linguistically appropriate game-based curriculum can meet individual students' math learning needs.

My Math Academy is a mastery-based personalized learning system developed with learning engineering practices. It is grounded in learning sciences research, incorporating key design principles such as mathematical linear trajectories (Clements & Sarama, 2004), formative assessments (Gee, 2005), evidence-based design (Mislevy, 2011), into game-based learning (Barab et al., 2005) contexts that are developmentally appropriate for young children. Study results confirmed that, overall, students who used *My Math Academy* in fall 2017 outperformed their control group peers on selected *TEMA-3* items by 5.71% at posttest (effect size=.23). The treatment group students used *My Math Academy* for 5.2 hours in total, averaging about 30 minutes/week, during fall 2017. This finding was especially notable given that treatment teachers were not provided with comprehensive training on *My Math Academyi* nor were they informed of their students' in-app performance during the study.

Additional analyses revealed that the impacts of *My Math Academy* were greatest for those students who have some prior, basic number sense (i.e., in the zone of proximal development) and/or for those who were more engaged in using the app. These results point to the need for developing supports for children with the lowest level of prior math knowledge as well as instructional materials and tools that enable teachers to effectively intervene in helping these children learn.

Importantly, *My Math Academy* appeared to have the greatest impacts on the most difficult, and most likely to be overlooked by teachers, math skills for young learners. Research suggests that kindergarten teachers spend most of their time on basic math skills of simple counting and shape recognition and tend not to cover more advanced skills such as counting backwards or skip counting even though the vast majority of children enter kindergarten having already mastered these basic skills and could benefit from being exposed to more advanced content (e.g., Engel et al., 2013). This points to the importance of personalized learning and the value of *My Math Academy* as a tool that can provide more advanced content for children who are ready for the challenge, children who may be overlooked by teachers whose resources and attention may be demanded by children who are struggling to master the basics.

Lastly, teachers recognized the value of *My Math Academy* as a resource to personalize learning and one that they want to continue using. Teachers had a positive perception of the program's ability to differentiate and meet students at their current level of understanding. They were impressed with the extent to which *My Math Academy* could adapt based on each student's zone of proximal development, and students could navigate largely independently through the program once they got started. This also enabled the teachers to conduct other instructional activities or provide targeted instruction to small groups of students.

Limitations and Directions for Future Research

While this study provides us with some insights about the extent to which a set of personalized game-based digital learning games can be effective in helping young children develop foundational math skills, it would have been strengthened if the study design had included classroom observations and interviews with teachers in both control and treatment groups. Classroom observations would have provided more in-depth descriptions about how *My Math Academy* and other mathematics curricula were implemented, and teacher interviews would have offered opportunities to better understand how teachers complemented or supplemented *My Math Academy* as well as the extent to which they intervened or supported individual students while they were using the program. Understanding variations in how teachers implemented *My Math Academy* would better inform potential users of the necessary conditions for successful implementation. Another study limitation was the teacher survey which included questions focused primarily on the impact of *My Math Academy* on instruction and student learning.

Future studies on *My Math Academy* should include observations and interviews as well as additional survey questions about the math skills teachers covered during the study period, in addition to other constructs that could have affected teachers' implementation of *My Math Academy* such as their comfort level with technology, math self-efficacy, and attitudes toward technology-based educational interventions. Additionally, a study examining the impact of *My Math Academy* over a longer period of time than

12-14 weeks would offer opportunities to examine cumulative impact of *My Math Academy* usage and the extent to which children's engagement with the program is enduring.

Further analyses of the study data are also warranted, given the large-scale data streams that were designed with *My Math Academy*, which generated comprehensive click-level data, consistent across all 30 games within the app. These data are structured around clear milestones in game play, learning performance results, and all interactions in the context of specific game levels and learning objectives. Such data can be used to generate insights for ongoing *My Math Academy* refinement, improved personalization of the in-app experience, as well as information that educators can use to plan their instruction.

Conclusion

This study provides evidence that a supplemental mastery-based personalized math learning program designed and developed with a research-based and data-informed learning engineering process can significantly improve young learners' foundational math skills while keeping them engaged. Such evidence is crucial as interest in digital game-based learning increases and educators evaluate the utility of tools that students can use independently to learn whether they are in the classroom or at home.

The findings from this study will inform ongoing refinements to *My Math Academy*, such as the creation of activities to develop math readiness in very young learners, with the goal of providing frequent, varied exposure to basic math concepts such as quantity, count sequence, and numerals. These math readiness activities will provide a strong conceptual foundation on which to build subsequent skills in *My Math Academy*. Furthermore, given teachers' recognition of *My Math Academy* as a valuable learning resource especially due to its ability to adapt to each student's needs, this study provides support for the development of specific educator resources that would enable teachers to further tailor instruction for students outside of the app. Future efficacy studies of *My Math Academy* will examine the impact of these new resources and build on the evidence base for how *My Math Academy* can be successfully implemented in typical classroom settings.

Open Scholarship

This article has earned the Center for Open Science badges for Open Data and Open Materials through Open Practices Disclosure. The data and materials are openly accessible at https://data.mendeley.com/datasets/gf9dc6zxdx.

References

Age of Learning, Inc. (2020). *My Math Academy: A research-driven design approach to personalized learning for young children*. https://www.ageoflearning.com/research/MM%20Development%20Process.pdf.

Anderson, J. R., Corbett, A. T., Koedinger, K. R., & Pelletier, R. (1995). Cognitive tutors: Lessons learned. *Journal of the Learning Sciences*, *4*(2), 167–207. https://doi.org/10.1207/s15327809jls0402_2

Andreu, L., Marti, J., & Aldas, J. (2012). The use of digital transmedia storytelling for case studies in marketing education. *INTED2012 Proceedings*, 1406–1414.

Bahrick, H. P., Bahrick, L. E., Bahrick, A. S., & Bahrick, P. E. (1993). Maintenance of foreign language vocabulary and the spacing effect. *Psychological Science*, *4*(5), 316–321. https://doi.org/10.1111/j.1467-9280.1993.tb00571.x

Barab, S., Thomas, M., Dodge, T., Carteaux, R., & Tuzun, H. (2005). Making learning fun: Quest Atlantis, a game without guns. *Educational Technology Research and Development*, *53*(1), 86–107. https://doi.org/10.1007/BF02504859

Betts, A. (2019). Mastery learning in early childhood mathematics through adaptive technologies. In *The IAFOR International Conference on Education–Hawaii 2019 Official Conference Proceedings* (pp. 51–63).

Bjork, R. A., & Yan, V. X. (2014). The increasing importance of learning how to learn. In M. McDaniel, R. Frey, S. Fitzpatrick, & H. L. Roediger (Eds.), *Integrating cognitive science with innovative teaching in STEM disciplines [E-reader version].* Washington University Libraries. https://doi.org/10.7936/K7QN64NR

Bloom, B. (1968). Learning for mastery. *Evaluation Comment*, *1*(2), 1–5.

Bodovski, K., & Farkas, G. (2007). Mathematics growth in early elementary school: The roles of beginning knowledge, student engagement, and instruction. *The Elementary School Journal*, *108*(2), 115–130. https://doi.org/10.1086/525550

Bransford, J., Brown, A., & Cocking, R. (2000). *How people learn: Brain, mind, experience, and school* (Expanded ed.). National Academies Press.

Burton, R. R., & Brown, J. S. (1979). An investigation of computer coaching for informal learning activities. *International Journal of Man-Machine Studies*, *11*(1), 5–24. https://doi.org/10.1016/S0020-7373(79)80003-6

Carnegie Mellon University (2020). *Reinventing education based on data and what works, since 1955*. https://www.cmu.edu/simon/what-is-simon/history.html

Chu, F. W., vanMarle, K., & Geary, D. C. (2016). Predicting children's reading and mathematics achievement from early quantitative knowledge and domain-general cognitive abilities. *Frontiers in Psychology*, *7,* 775. https://doi.org/10.3389/fpsyg.2016.00,775

Clarke-Midura, J., Code, J., Dede, C., Mayrath, M., & Zap, N. (2012). Thinking outside the bubble: Virtual performance assessments for measuring complex learning. In M. C. Mayrath, J. Clarke-Midura, D. H. Robinson, & G. Schraw (Eds.), *Technology-based assessments for 21st century skills: Theoretical and practical implications from modern research* (pp. 125–148). Information Age Publishing.

Clements, D. H., & Sarama, J. (2004). Learning trajectories in mathematics education. *Mathematical Thinking and Learning*, *6*(2), 81–89. https://doi.org/10.1207/s15327833mtl0602_1

Clements, D. H., & Sarama, J. (2014). *Learning and teaching early math: The learning trajectories approach*. Routledge.

Cohen, J., Ducamp, G., Kjellstrom, W., & Tillman, D. (2012). What happens when children encounter the T-book?: The potential for transmedia books in teacher education. *Society for Information Technology & Teacher Education International Conference*, *2012*(1), 1033–1040.

Denton, K., & West, J. (2002). *Children's reading and mathematics achievement in kindergarten and first grade*. National Center for Education Statistics, Office of Educational Research and Improvement, U.S. Department of Education.

Design Based Research Collective. (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher*, *32*(1), 5–8.

DiCerbo, K. E., Bertling, M., Stephenson, S., Jia, Y., Mislevy, R. J., Bauer, M., & Jackson, G. T. (2015). An application of exploratory data analysis in the development of game-based assessments. In C. Loh, Y. Sheng, & D. Ifenthaler (Eds.), *Serious games analytics* (pp. 319–342). Springer. https://doi.org/10.1007/978-3-319-05834-4_14

Dixon, F. A., Yssel, N., McConnell, J. M., & Hardin, T. (2014). Differentiated instruction, professional development, and teacher efficacy. *Journal for the Education of the Gifted*, *37*(2), 111–127. https://doi.org/10.1177/0162353214529042

Dohring, D., Hendry, D., Gunderia, S., Hughes, D., Owen, V. E., Jacobs, D. E., Betts, A. & Salak, W. (2019). *U.S. Patent No. 20190236967 A1.* Washington, DC: US Patent and Trademark Office.

Ebbinghaus, H. (1964). *Memory: A contribution to experimental psychology*. Dover. (Original work published 1885; translated 1913).

Engel, M., Claessens, A., & Finch, M. A. (2013). Teaching students what they already know? The (mis)alignment between mathematics instructional content and student knowledge in kindergarten. *Educational Evaluation and Policy Analysis*, *35*(2), 157–178. https://doi.org/10.3102/0162373712461850

Entwisle, D. R., & Alexander, K. L. (1990). Beginning school math competence: Minority and majority comparisons. *Child Development*, *61*(2), 454–471. https://doi.org/10.2307/1131107

Fisch, S. M. (2000). A capacity model of children's comprehension of educational content on television. *Media Psychology*, *2*(1), 63–91. https://doi.org/10.1207/S1532785XMEP0201_4

Flynn, M. (2017). *Beyond answers: Exploring mathematical practices with young children*. Stenhouse Publishers.

Gee, J. P. (2003). What video games have to teach us about learning and literacy. *Computers in Entertainment*, *1*(1), 20–20. https://doi.org/10.1145/950566.950595

Gee, J. P. (2005). Learning by design: Good video games as learning machines. *E-Learning and Digital Media*, *2*(1), 5–16. https://doi.org/10.2304/elea.2005.2.1.5

Gilardi, F., & Reid, J. (2011). E-learning through transmedia storytelling: How the emerging internet-based participatory cultures in China can be co-opted for education. *Global Learn Asia Pacific*, *2011*(1), 1469–1474.

Ginsburg, H., & Baroody, A. (2003). *TEMA-3 examiners manual* (3rd ed.). PRO-ED.

Goddard, Y., Goddard, R., & Kim, M. (2015). School instructional climate and student achievement: An examination of group norms for differentiated instruction. *American Journal of Education*, *122*(1), 111–131. https://doi.org/10.1086/683293

Groff, J., Clarke-Midura, J., Owen, V. E., Rosenheck, L., & Beall, M. (2015). *Better learning in games: A balanced design lens for a new generation of learning games [white paper]*. MIT Education Arcade and Learning Games Network. https://www.media.mit.edu/publications/better-learning-in-games-a-balanced-design-lens-for-a-new-generation-of-learning-games/.

Hecht, S. A., Burgess, S. R., Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (2000). Explaining social class differences in growth of reading skills from beginning kindergarten through fourth-grade: The role of phonological awareness, rate of access, and print knowledge. *Reading and Writing*, *12*(1/2), 99–127. https://doi.org/10.1023/A:1008033824385

Hess, F. M., & Saxberg, B. (2013). *Breakthrough leadership in the digital age: Using learning science to reboot schooling*. Corwin Press.

Hirsh-Pasek, K., Zosh, J. M., Golinkoff, R. M., Gray, J. H., Robb, M. B., & Kaufman, J. (2015). Putting education in "educational" apps: Lessons from the science of learning. *Psychological Science in the Public Interest: a Journal of the American Psychological Society*, *16*(1), 3–34. https://doi.org/10.1177/1529100615569721

IEEE IC Industry Consortium on Learning Engineering (ICICLE) (2020). https://sagroups.ieee.org/icicle/

Ke, F., Shute, V., Clark, K. M., & Erlebacher, G. (2019). *Interdisciplinary design of game-based learning platforms*. Springer. https://doi.org/10.1007/978-3-030-04339-1

Kornell, N., & Bjork, R. A. (2008). Learning concepts and categories. *Psychological Science*, *19*(6), 585–592. https://doi.org/10.1111/j.1467-9280.2008.02127

Laurel, B. (2003). *Design research: Methods and perspectives*. MIT Press.

Lonigan, C. J., Burgess, S. R., Anthony, J. L., & Barker, T. A. (1998). Development of phonological sensitivity in 2- to 5-year-old children. *Journal of Educational Psychology*, *90*(2), 294–311. https://doi.org/10.1037/0022-0663.90.2.294

McKendree, J. (1990). Effective feedback content for tutoring complex skills. *Human-Computer Interaction*, *5*(4), 381–413. https://doi.org/10.1207/s15327051hci0504_2

McLaren, B. M., Adams, D. M., Mayer, R. E., & Forlizzi, J. (2017). A computer-based game that promotes mathematics learning more than a conventional approach. *International Journal of Game-Based Learning (IJGBL)*, *7*(1), 36–56. https://doi.org/10.4018/IJGBL.2017010103

Mislevy, R. J. (2011). *Evidence-centered design for simulation-based assessment (CRESST Report 800)*. University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).

Morgan, P. L., Farkas, G., & Wu, Q. (2009). Five-year growth trajectories of kindergarten children with learning difficulties in mathematics. *Journal of Learning Disabilities*, *42*(4), 306–321. https://doi.org/10.1177/0022219408331037

National Association for the Education of Young Children & Fred Rogers Center for Early Learning and Children's Media (2012). *A framework for quality in digital media for young children: Considerations for parents, educators, and media creators*. http://cmhd.northwestern.edu/wp-content/uploads/2015/10/Framework_Statement_2-April_2012-Full_Doc-Exec_Summary-1.pdf

National Research Council (2009). *Mathematics learning in early childhood: Paths toward excellence and equity*. National Academies Press.

Nores, M., & Barnett, W. S. (2014). *Access to high quality early care and education: Readiness and opportunity gaps in America (CEELO Policy Report)*. Center on Enhancing Early Learning Outcomes.

Owen, V. E. (in press). Learning science in data-driven adaptive design for young children. In *To appear in proceedings of the 3rd international conference on artificial intelligence and adaptive education*.

Plass, J. L., Homer, B. D., & Hayward, E. O. (2009). Design factors for educationally effective animations and simulations. *Journal of Computing in Higher Education*, *21*(1), 31–61. https://doi.org/10.1007/s12528-009-9011-x

Rathbun, A., & West, J. (2004). *From kindergarten through third grade: Children's beginning school experiences (NCES 2004–007)*. U.S. Department of Education, National Center for Education Statistics. U.S. Government Printing Office.

Reardon, S. F. (2013). The widening income achievement gap. *Educational Leadership*, *70*(8), 10–16. https://pdfs.semanticscholar.org/20db/9981d4b87a9635c41976922d68c7b617e99b.pdf.

Reyes, M. R., Brackett, M. A., Rivers, S. E., White, M., & Salovey, P. (2012). Classroom emotional climate, student engagement, and academic achievement. *Journal of Educational Psychology*, *104*(3), 700–712. https://doi.org/10.1037/a0027268

Rieber, L. P. (1996). Animation as feedback in a computer-based simulation: Representation matters. *Educational Technology Research and Development*, *44*(1), 5–22. https://doi.org/10.1007/BF02300323

Roediger, H. L., & Karpicke, J. D. (2006). Test-enhanced learning: Taking memory tests improves long-term retention. *Psychological Science*, *17*(3), 249–255. https://doi.org/10.1111/j.1467-9280.2006.01693.x

Rothschild, M. (2015). *Two-way play: Early learners' experiences with bidirectional television* [Doctoral dissertation]. Retrieved from ProQuest. (3722845).

Rupp, A. A., Gushta, M., Mislevy, R. J., & Shaffer, D. W. (2010). Evidence-centered design of epistemic games: Measurement principles for complex learning environments. *Journal of Technology, Learning, and Assessment*, *8*(4), 4–47. http://www.jtla.org.

Sarama, J., & Clements, D. H. (2004). Building blocks for early childhood mathematics. *Early Childhood Research Quarterly*, *19*(1), 181–189. https://doi.org/10.1016/j.ecresq.2004.01.014

Shute, V. J. (2008). Focus on formative feedback. *Review of Educational Research*, *78*(1), 153–189. https://doi.org/10.3102/0034654307313795

Shute, V. J. (2011). Stealth assessment in computer-based games to support learning. In S. Tobias & J. D. Fletcher (Eds.), *Computer games and instruction* (pp. 503–524). Information Age Publishers.

Shute, V. J., & Kim, Y. J. (2014). Formative and stealth assessment. In J. M. Spector, M. D. Merrill, J. Elen, & M. J. Bishop (Eds.), *Handbook of research on educational communications and technology* (4th ed., pp. 311–323). Lawrence Erlbaum Associates, Taylor & Francis Group.

Simon, M. (1995). Reconstructing mathematics pedagogy from a constructivist perspective. *Journal for Research in Mathematics Education*, *26*(2), 114–145. https://doi.org/10.2307/749205

Squire, K. (2006). From content to context: Videogames as designed experience. *Educational Researcher*, *35*(8), 19–29. https://doi.org/10.3102/0013189X035008019
Starkey, P., & Klein, A. (2008). Sociocultural influences on young children's mathematical knowledge. In O. Saracho & B. Spodek (Eds.), *Contemporary perspectives on mathematics in early childhood education* (pp. 253–276). Information Age Publishing.
Starkey, P., Klein, A., & Wakeley, A. (2004). Enhancing young children's mathematical knowledge through a pre-kindergarten mathematics intervention. *Early Childhood Research Quarterly*, *19*(1), 99–120. https://doi.org/10.1016/j.ecresq.2004.01.002
Steinkuehler, C., & Duncan, S. (2008). Scientific habits of mind in virtual worlds. *Journal of Science Education and Technology*, *17*(6), 530–543. https://doi.org/10.1007/s10956-008-9120-8
Steinkuehler, C., & King, E. (2009). Digital literacies for the disengaged: Creating after school contexts to support boys' game-based literacy skills. *On the Horizon*, *17*(1), 47–59. https://doi.org/10.1108/10748120910936144
Sullivan, P., Zevenbergen, R., & Mousley, J. (2003). The contexts of mathematics tasks and the context of the classroom: Are we including all students? *Mathematics Education Research Journal*, *15*(2), 107–121. https://doi.org/10.1007/BF03217373
Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, *12*(2), 257–285. https://doi.org/10.1207/s15516709cog1202_4
The Learning Agency (2019). *Learning engineering: It's a game changer*. https://www.the-learning-agency.com/insights/a-game-changer-lets-talk-about-learning-engineering
U.S. Department of Education, National Center for Education Statistics. (2020). *The Condition of Education 2020 (NCES 2020-144), mathematics performance*. https://nces.ed.gov/programs/coe/indicator_cnc.asp
Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Harvard University Press.
What Works Clearinghouse (2020). *What works clearinghouse standards handbook, version 4.1*. U.S. Department of Education, Institute of Education Sciences, National Center for Education Evaluation and Regional Assistance. https://ies.ed.gov/ncee/wwc/Docs/referenceresources/WWC-Standards-Handbook-v4-1-508.pdf
Willcox, K. E., Sarma, S., & Lippel, P. H. (2016). Online education: A catalyst for higher education reforms. *MIT Online Education Policy Initiative*, 1–56. https://sites.nationalacademies.org/cs/groups/pgasite/documents/webpage/pga_171687.pdf

Appendix

Games and Learning Objectives Addressed by My Math Academy.

Grade Level	Topic	Game	Lesson
2	Fact Families	Pyramids	Make fact families using proportional blocks, using number bonds, using number families
PreK-K	Numeral Recognition	Shapey Tag	Find the number you hear (1–5, 6–10, 11–15, 16–20)
PreK-K	Count Sequence	Tightrope	Count from 1 to 5, from any number to 10, from any number 11 to 20, from 11-20
PreK	Counting	Prize Store	Count from 1 to 20
PreK	Counting	Balloons	Count 1–5 or 6–10 objects
PreK-K	Count Sequence	Horses	Fill in the missing number (1–5, 6–10, 11–15, 16–20)
PreK-K	Counting Out	Boats	Count out a number of objects (1–5, 6–10, 11–15, 16–20)
K	Counting	Rollercoasters	Count objects (11–15, 16–20)
K	Counting Sequence Backward	Swingy Rings	Count backwards from 5 to 1, from 10 to 1, 20 to 11, from any number 20 to 11.
K	Count All, Count On	Waterslides	Count the total of two groups (1–10), Count on from one quantity to a total (1–10)
K	Number Composition/ Decomposition	Airshow	Select parts to make a total (1–10, 11–20); break a total into two parts (1–10)

(*continued*)

Continued.

Grade Level	Topic	Game	Lesson
K	Comparison with Objects	Toy Factory	Make a quantity that is more, less, or the same; compare numbers (1–20)
K	Count Sequence	Parade	Count from 21 to 60; count from 61 to 100.
K	Numeral Recognition	Camping	Find the number you hear (10–100, 21–29, 30–49, 50–100, 10–100).
K	Skip Count Sequence	Drumline	Count backwards and forwards by tens; count forwards by fives; count forwards by twos
K	Hundred Charts	Hundred Chart Harvest	Find numbers on a Hundred Chart by counting forward / backward across rows and columns; find numbers on a Hundred Chart within a row / column.
1	Concept of Subtraction	Dance Party	Take a number of objects away from a set of objects (1–10)
1	Number Families	Houses	Find the missing total / part in a number family; create number families when given the total
1	Number Sentences	Market	Represent addition number sentences; write addition number sentences; represent subtraction number sentences; write subtraction number sentences
1	Modeling Math Facts	Ancient Puzzle	Represent addition facts that are doubles / near doubles / equal to 10
2	Fact Families	Pyramids	Make fact families using proportional blocks, using number bonds, using number families
1	Fact Fluency	Rafting	Practice addition facts that equal 10; practice addition facts with doubles / near-doubles; practice subtraction facts, subtracting from 10; practice subtraction facts with doubles / near-doubles
1–2	Base Ten Blocks	Ice Castles	Count base ten blocks representing a 2-digit number; show 2-digit numbers with base ten blocks; count base ten blocks representing a 3- digit number; show 3-digit numbers with base ten blocks; show 3-digit numbers with base ten blocks
1–2	Place Value	Rockets	Find the tens or ones place; identify the value of a digit in a 2-digit number; find the hundreds, tens, or ones place; identify the value of a digit in a 3-digit number
1	Comparison with Numerals	Shipping	Compare numbers (21–99)
1	Number Line Operations	Scuba	Add 1-digit numbers on a number line; subtract 1-digit numbers on a number line
2	Base Ten Addition	Mining	Use base ten blocks to add 2-digit numbers with regrouping; use base ten blocks to add 3-digit numbers with regrouping
2	Base Ten Subtraction	Island	Use base ten blocks to subtract 2-digit numbers with regrouping; use base ten blocks to subtract 3- digit numbers with regrouping
2	Standard Algorithm Addition / Standard Algorithm Subtraction	Arcade	Use an algorithm to add without regrouping; use an algorithm to add with regrouping in the tens / ones / tens and ones places; use an algorithm to subtract without regrouping; use an algorithm to subtract with regrouping in the tens / hundreds places
1–2	Adding Numbers by Place Values	Waterworks	Break apart 2-digit numbers / 3-digit numbers by digits to add without regrouping