Math Readiness: Early Identification of Preschool Children Least Ready to Benefit from Formal Math Instruction in School

Anastasia Betts, University at Buffalo, United States
KP Thai, University at Buffalo, United States
Daniel Jacobs, University at Buffalo, United States
Linlin Li, WestEd, United States

The IAFOR International Conference on Education – Hawaii 2020
Official Conference Proceedings

Abstract
The math skills and knowledge measured at or near the beginning of school entry are most predictive of later school success. Unfortunately, deficits in math understanding can begin before students enter school, often due to home environments that lack sufficient mathematics enrichment. Moreover, the gap between students who begin school behind their more prepared peers only widens as students move through successive grades. As a result, developing ways to quickly assess and address gaps in students' mathematics foundations at school entry is critical to ensure future success in math. The present study presents findings from an evaluation study involving an adaptive digital mathematics program designed to assess and teach number sense skills to 292 low-SES children in 20 preschool classrooms in Southern California. The program consists of a set of research-based personalized learning games designed to address foundational number sense skills. Analyses revealed that preschool children with low prerequisite knowledge at the start of the school year were unable to progress effectively in the program. Results of this study confirm the need for the development of interventions that address early mathematics readiness skills for students, and call for educational programs that can quickly identify children who may not be ready to take full advantage of school mathematics instruction and to address their needs before the onset of formal schooling.

Keywords: mathematics readiness, early childhood, adaptive instructional system

iafor
The International Academic Forum
www.iafor.org

Introduction

The Importance of Early Childhood Mathematics

Research from the past couple decades has found that while math, reading, and executive functioning skills are important predictors for later school success, certain math skills and knowledge that is measured at or near the beginning of school entry, in particular, are most predictive of later school success (Duncan et al., 2007; Claessens & Engel, 2013; Nguyen et al., 2016). For example, Nguyen and colleagues (2016) followed a diverse sample of students from preschool through the end of 5^{th} grade and found that several preschool mathematics competencies are predictive of overall fifth grade mathematics achievement, with counting and cardinality competencies being the strongest predictors. They also found that certain advanced counting and cardinality competencies were much more predictive of later achievement than basic counting and cardinality competencies (Nguyen et al., 2016). This echoed earlier work of Claessens and Engel (2013) that also showed that key early math competencies such as count all, count on, count forward and backward from any number (within 10) were most predictive of later success in math.

It is evident that the development of key mathematical competencies early on leads to success in mathematics as students move forward in their schooling. However, not all children are able to master these key competencies during the critical window of early childhood, in preschool, or in Kindergarten (Claessens & Engel, 2013; Jordan & Levine, 2009). More importantly, these disparities appear to widen as children move on through schooling (Duncan & Magnusen, 2011; Seigler, 2009). Children who start with strong math knowledge and skills tend to attain higher levels of mathematics achievement as they move through school, while children who begin gaps tend to fall further and further behind (Seigler, 2009).

Differences in Mathematics Knowledge at School Entry

Children begin school with a wide range of mathematics knowledge and skills. Experiences in the child's home environment prior to the onset of formal schooling can provide a strong foundation for learning mathematics (Blevins-Knabe, 2016; Lee & Ginsberg, 2009). Conversely, a lack of enriching environments or experiences can result in gaps in children's mathematics foundation, causing them to be less prepared to take advantage of formal math instruction in school. As an example, consider that it can take a child a year or more to move from producing a set of one to producing a set of four (Wynn, 1992). If the child has not had enough exposure to counting sets of objects prior to beginning school, it is possible that she may not be able to master counting out a set of ten objects, a common kindergarten learning objective, within one year of schooling.

Designing a Mastery-Based Early Mathematics Program

Because children enter school with such varying degrees of prior mathematical knowledge and ability, it is vital to develop curricular programs that quickly assess and adapt to individual student needs. Advancements in technology and artificial intelligence (AI) have made it possible to develop highly engaging programs capable of individualizing the curriculum in real time and at scale, based on the ongoing data collection for each student, potentially closing the achievement gap and preparing students for success in mathematics.

This study explores a mastery-based early mathematics program called ABCmouse Mastering Math™ , developed by Age of Learning, Inc. (see Figure 1 for examples). Mastering Math is a game-based adaptive learning system designed to help young children from preschool to 2nd grade build a strong understanding of fundamental number sense and operations. Mastering Math is available as an app for smartphones and tablets and in both English and Spanish.

The development of Mastering Math was based on years of research, user-testing, iteration, and proto-type development, designed by a team working in fields of learning sciences, educational research, curriculum, game design, art, engineering, and data science. Throughout its design and production, the team employs learning engineering, "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" (ISLS, 2019).

Theoretical foundations of learning sciences have been applied to inform Mastering Math's content, pedagogy, and design for learning and engagement (see also Owen, in press; Betts, 2019; Goodell & Thai, in press). The curriculum was built upon Benjamin Bloom's (1968) model of Mastery Learning and Simon's (1995) theory of Hypothetical Learning Trajectories. Similar to the beliefs of early learning theorists such as Piaget and Vygotsky, Bloom believed that learning occurred as a sequence of experiences, each building on the knowledge of prior experiences. In Bloom's Mastery Learning model, all skills and knowledge to be learned are organized by expert teachers into hierarchical learning "trajectories" that provide a pathway for students to master earlier skills before moving on to later skills (Bloom, 1968). Simon (1995) furthered this idea through the concept of hypothetical learning trajectories. Hypothetical Learning Trajectories (HLT) describe student pathways through a specific set of activities that lead to mastery of various learning objectives. While there is perhaps a single hypothetical learning trajectory that describes a typical learner's pathway through the universe of learning objectives that comprise a topic, there are an infinite number of learning trajectories that different students may take as they master the content. This is because the best or most efficient way through the content is likely to be different for each learner, and is based on many factors, including the student's prior knowledge, learning pace, the quality of the planned activities, as well as the teacher's expertise and knowledge.

The focus of this paper is on the curriculum coverage of Mastering Math. For theoretical foundations underlying of the design and development of other aspects of Mastering Math, see Owen (in press), Owen & Hughes (2019), and Betts (2019).

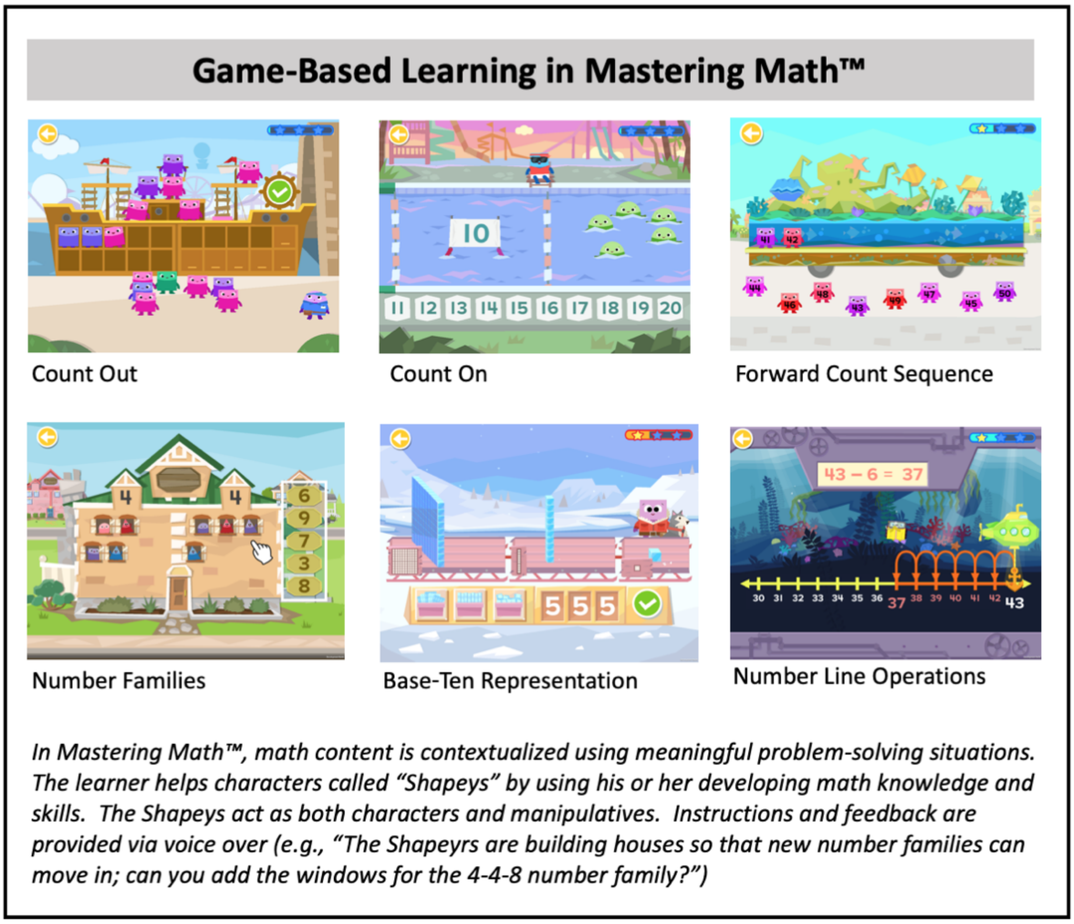

Figure 1: Sample screenshots and a brief description of Mastering Math games.

The primary goal of Mastering Math is to ensure that every learner masters key early mathematics competencies in order to progress forward without gaps. The underlying pedagogy is founded on the idea that all precursor learning objectives should be mastered before moving on to successor learning objectives (Bloom, 1968; Simon, 1995). As such, the Mastering Math development team created a hypothetical learning trajectory (Simon, 1995), detailed in an extensive knowledge map that defines the principles, concepts, skills, and data that a learner must master in the domain of early number sense (See Figure 2).

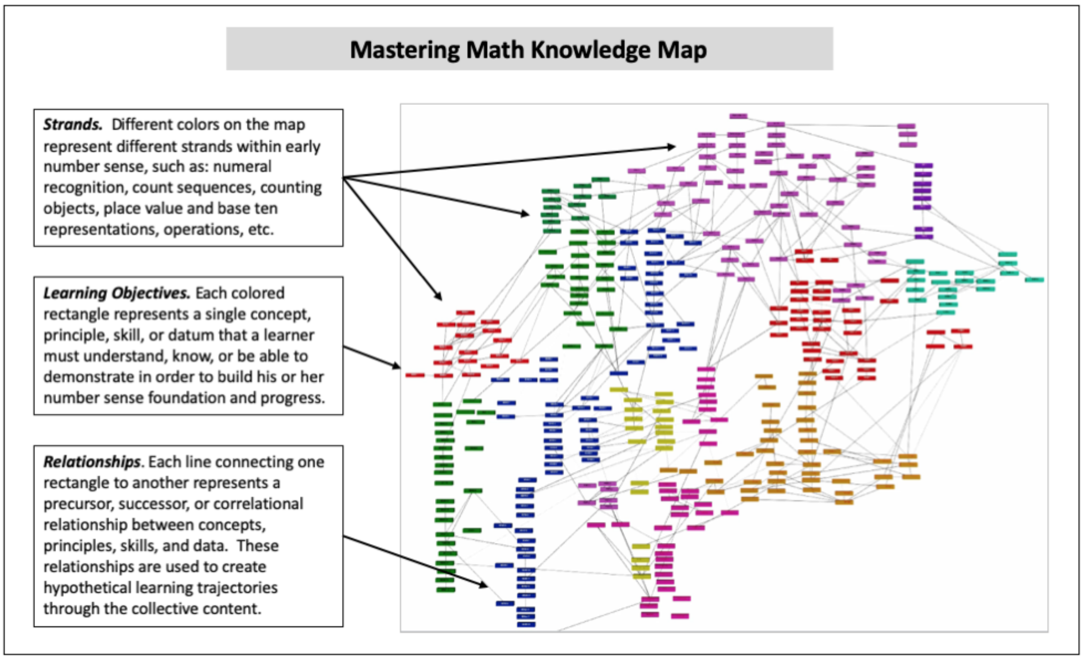

Figure 2. The Mastering Math knowledge map.

The knowledge map informs both the development of highly engaging math games, and AI algorithms that analyze the players' clicks, taps, drags, and more to evaluate whether the player has (1) mastered the objective, (2) needs additional help or scaffolding, (3) needs reteaching, or (4) should pursue a different objective altogether. As the learner plays the games in the system, the system uses the data being gathered to create hypothetical learning trajectories that are completely unique to each learner. These individualized learning trajectories adapt real-time to new information as it is gathered about each learner's performance. Figure 3 shows examples of four different learner trajectories though a portion of learning content (games) in the system.

Each individual game maps to a learning objective and is supported by an interactive instruction level, as well as several layers of scaffolding and feedback. In addition, the Mastering Math system uses cohesive narrative and interactive characters (embedded at the level of individual games) to support student engagement with the learning world. Within individual games and between games, built-in adaptivity provides scaffolding and adjusts difficulty. 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 sum, Mastering Math 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, Mastering Math aims to help students learn and make sense of math in an enjoyable and highly effective way.

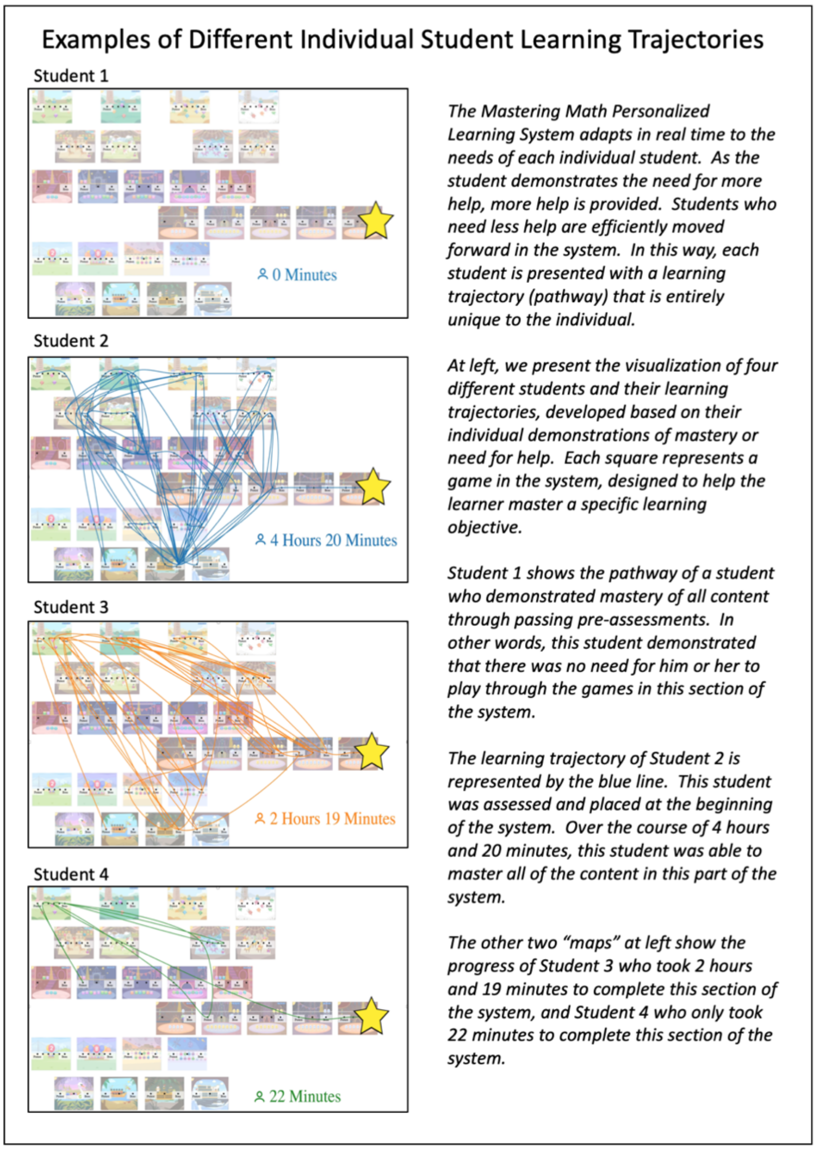

Figure 3: Sample individual student learning trajectories.

Mastering Math Efficacy Studies

Mastering Math efficacy studies provide insights into what is working about the system and to inform what can be improved. In setting out to address the foundational math competencies, it is important that we evaluate how well Mastering Math can address the needs of the targeted age groups in both prekindergarten and kindergarten. The goal of this paper is to illustrate the need for development of interventions that address math readiness skills.

The first iteration of Mastering Math, which included games that targeted the mastery of prekindergarten and kindergarten number sense learning objectives, was released in the spring of 2017. At that time, Mastering Math contained 29 games addressing granular skills within number recognition, forward and backward counting, and counting from 1 to 20. Each game included up to six learning activities at various difficulty levels, including a pretest and an in-game mastery check called the "boss" level. Students were able to demonstrate mastery by passing the pretest, passing the boss level (after failing a pretest), or getting placed out of a skill by passing a more advanced skill. If students demonstrated mastery of all skills in the app, they received practice boss levels on high level skills.

During the fall of 2017, researchers and developers at Age of Learning partnered with independent researchers at WestEd to conduct two efficacy research studies. The first was conducted on Kindergarten students (Thai, Schachner, & Li, 2019), which is summarized briefly below, and the second on Pre-Kindergarten students, which is the focus of this paper.

The Kindergarten Study

This randomized controlled trial involving 453 students from 20 kindergarten (K) and transitional-kindergarten (TK) classrooms at 4 Title I elementary schools in urban South Central Los Angeles, California. Prior to the start of the study, half of the classrooms were randomly assigned to the treatment group to implement Mastering Math for 15 minutes per day, 3 days per week, for the fall semester. The control group did not receive Mastering Math access and conducted business-as-usual instruction. For the implementation period, each treatment classroom received six tablets with access restricted to Mastering Math for implementation in small groups. Control classrooms did not have tablet access. Before and after implementation, both groups were tested with selected items from the Test of Early Mathematics Ability, Third Edition (TEMA-3; Ginsburg & Baroody, 2003), a standardized and nationally normed reference assessment of mathematics performance of children ages 3 to 8 and 11 months.

These pretest and posttest scores were used in a three-level hierarchical linear model accounting for differences by students based on their pretest score, group assignment, and school. This enabled the comparison of the treatment group's posttest outcomes against the control group after adjusting for differences in baseline scores. Results showed that the treatment group outperformed the control group by 5.71 percentage point at posttest (Treatment M = 62.15, SD = 24.61, Control M = 56.44, SD = 25.06), and this difference was statistically significant after controlling for differences in pretest ($p = .03$, effect size = .23). The difference between the two groups at pretest was not statistically significant (Treatment M = 43.56, SD = 25.21; Control M = 40.07, SD = 24.80; $p = .33$, effect size = .14). Mastering Math produced 36% greater gains in treatment children's mathematics knowledge and skills than control children. Treatment students on averaged spent 5.22 hours (SD = 2.97 hours) on Mastering Math, an average of 28-35 minutes per week over the course of 12-14 weeks. They completed on average 79 learning activities (SD = 40.93), started 11.5 games (SD = 6.12) and acquired mastery on 2.21 skills (SD = 5.10) that they have not demonstrated mastery for during in-game pretests. The more students used Mastering Math and completing more games, the greater their learning gains ($r = .19$, $p < .01$, and for those completed at least one boss level, $r = .38$, $p < .01$).

These results are encouraging, suggesting that a research-based, developmentally appropriate, individually appropriate, culturally and linguistically appropriate game-based curriculum can meet individual students' math learning needs. This result is particularly notable because the treatment teachers were not provided with comprehensive training on Mastering Math prior to the study nor were they informed of their students' in-app performance during the study.

Additional analyses from this study revealed an interesting impact of Mastering Math based on pretest score, as measured by the TEMA-3. The greatest learning gains from Mastering Math were most notable in children who scored in the middle third at pretest (Figure 4, n = 150, point of estimate = 7.28, p = .04, effect size = 0.46). Students who scored greater than 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). This suggests that the impact of Mastering Math were greatest for those with some prior, basic number sense. This result begins pointing 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.

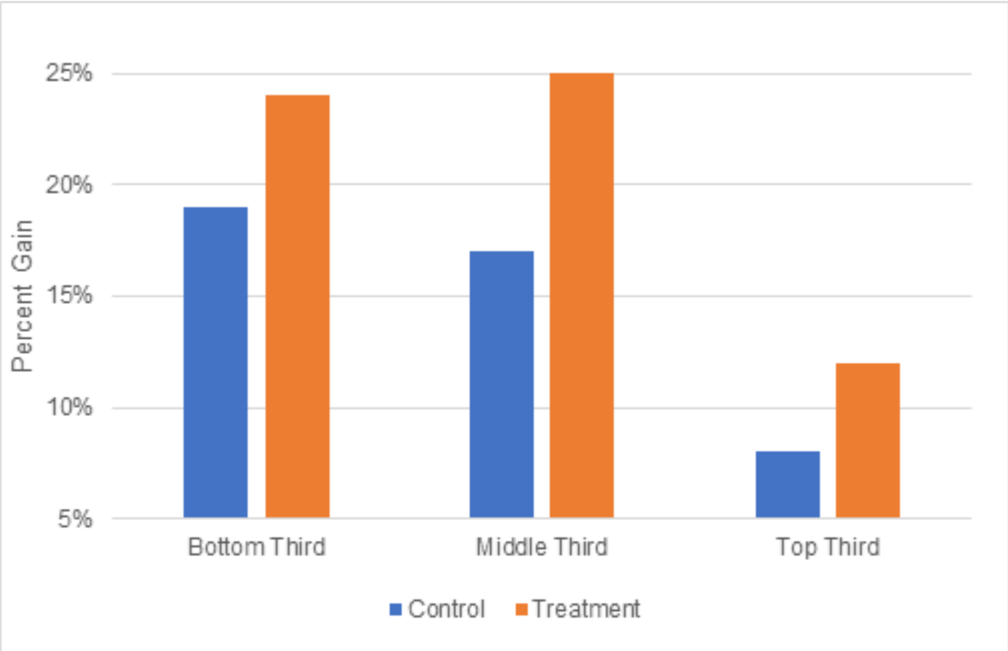

Figure 4: Percent gain in TEMA-3 math scores based on prior knowledge for treatment and control group students based on the approximate top, middle, and bottom thirds at pretest (p < .04, effect size = 0.46). Cutoffs were as follows: top third TEMA-3 score > 50% correct (control n = 67, treatment n = 82); middle third ≤ 50% correct and > 23% correct (control n = 70, treatment n = 80); bottom third ≤ 23% correct (control n = 58, treatment n = 71). (From K study, Thai, Li & Schachner, 2019, with permissions)

The Pre-Kindergarten Study

To confirm that hypothesis and to further evaluate the impact of Mastering Math, this study examined the efficacy of Mastering Math on a younger age group with Pre-K students.

Methods

Treatment and Control Conditions

Similar to the K study, this study used a clustered randomized controlled design. 20 Pre-K classrooms were randomly assigned to either a treatment group or a control group. The study took place over thirteen weeks in the Fall semester of 2017. The treatment group had access to Mastering Math (the same version used in the K study) via individual iPads, and were asked to use it for 15 minutes per day, three days per week, during the eight- to ten-week study period. Treatment teachers were provided with some minimal training into using Mastering Math with students, but they were not provided with strict implementation guidelines around how or when to implement the app in their classroom, other than to aim for 15 minutes of usage for three days per week.

The control group used business-as-usual mathematics instruction and materials.

Instruments

The following measures were collected from both the intervention and comparison groups before the intervention began. They were used to test the baseline equivalence between the intervention and comparison groups and/or served as covariates in the impact analyses.

Test of Early Mathematics Ability (TEMA-3)

The Test of Early Mathematics Ability, third edition, is a primary test of children's informal and formal mathematics knowledge, developed by Western Psychological Services. It is a standardized, nationally normed achievement test (Ginsburg & Baroody, 2003). The test is designed for use with children ages 3 years, 0 months through 8 years, 11 months. It measures four categories of informal mathematics: Numbering, Number Comparisons, Calculation, and Concepts. It also measures four categories of formal mathematics: Numeral Literacy, Number Facts, Calculation, and Basic 10 Concepts. Table 1 provides a description of each category of informal and formal mathematics. The test contains 72 items (each item may have multiple problems) in two forms. The TEMA-3 is not a timed test, and no precise time limits are required for children being tested. Depending on children's mathematics ability, children will be able to complete all 72 items or the relevant portion of the test. On average, it takes 45-60 minutes to administer.

The test examiner's manual reports an alpha of 0.94 for Form A and an alpha of 0.96 for Form B (Ginsburg & Baroody, 2003, p.32). The manual also discusses test content-description validity, criterion-prediction validity, and construct-identification validity. The test has been matched for content coverage and difficulty.

For the purposes of this study, 20 TEMA-3 items that best represented the types of numeracy skills found within Mastering Math were selected for use as a modified assessment. All students were administered all 20 selected TEMA-3 items. The experimental score of the selected items was used to analyze children's mathematics ability. The experimental score is simply the number of trials scored correct on the selected TEMA-3 items (one point per correct response). Each TEMA-3 item may have multiple trials. The total number of trials within the selected TEMA-3 assessment is 43. Since participating students were in pre-kindergarten, we especially focused on 10 items (24 trials) that address preschool math skills. The scores represented the percent of trials that were answered correctly, which were calculated by summing the number of trials answered correctly divided by the total number of trials in the assessment. Therefore, the scores range from 0 to 100%. The selected TEMA-3 Form A was used as a pre/post measure for children. The pre-test was administered to students prior to classrooms assignment to the treatment or control condition in August and September of 2017; the post-test was administered in November and early December of 2017 at the conclusion of the study. Of the 10 treatment classrooms, 30% were tested after eight weeks of intervention, 40% were tested after nine weeks of intervention, and 30% were tested after 10 weeks of intervention.

Table 1. Description of Categories of Mathematics in TEMA-3

Categories of Mathematics		Description of the Categories
Informal Mathematics		
	Numbering	Pre-counting numbering abilities: e.g., children learn to recognize collections of one or two items and label them "one" and "two".
	Number Comparisons	Comparing two or more collections: e.g., children learn the term more and use it to label the larger of two collections that obviously differ in number.
	Calculation	Mentally and nonverbally adding two small, previously viewed collections; solving word problems with sums up to 12 by counting or reasoning: e.g., after seeing one item covered and a second item slipped under the cover, children can determine the sum and indicate their answer by producing two items.
	Concepts	Determining key aspects of understanding that underlie number and calculation skills at the counting phase: e.g., children learn that a whole is the sum of its parts and that the whole is larger than any single part.
Formal Mathematics		
	Numeral Literacy	A major transition in children's ability to represent numbers involves the ability to read, write, and understand numerals: e.g., children learn that the numeral 2 is read aloud as "two" and conversely that the spoken word "two" is written as 2.
	Number Facts	Mastery of the basic number combinations and ability to quickly generate the answer to single-digit addition, subtraction, and multiplication facts: e.g., children have learned that 2+0=2 and 3+0=3, they may extract a principle to the effect that adding zero to any number does not change it.
	Calculation	Addition and subtraction accuracy: e.g., children can talk aloud as a problem is being solved and can justify their procedure.
	Basic 10 Concepts	Grouping by 10: e.g., children understand that when one carries, one is really regrouping by units of 10s, 100s, and so on.

In-Game Usage Logs. The Mastering Math app was configured to track user activities and log when participants accessed the app, which games within the app were played, approximately how long participants used the app, and participants' progress on each game.

Sample Characteristics. A total of 20 Pre-K classrooms were recruited through one public school district in Southern California, resulting in 141 children in the treatment condition and 142 in the control condition (total n = 283 students, 55% female). Students in this school district were 85% Hispanic, 9% African American, 6% Caucasian, 2% Asian, and 2% Other. 82% of students in this school district received free lunch, and 27% were English Language Learners. The final analytic sample for student mathematics skills and knowledge achievement included a total of 272 students from 20 classrooms with both non-missing pre and post assessment data. Table 2 presents the individual characteristics of participants by treatment condition. The treatment and control groups did not differ significantly in attrition and age. The control group had more students whose preferred language was Spanish. In addition, the treatment and control groups were equivalent at baseline as measured by the selected TEMA-3 items (see Table 3).

Table 2. Participant Demographic Information, by Experimental Condition

	Treatment		Control		p-value
	Number	Percent	Number	Percent	
Attrition					0.14
In analytic sample	133	94.33%	139	97.89%	--
Attrition	8	5.67%	3	2.11%	--
Preferred Language					0.05*
English	118	88.72%	107	76.98%	--
Spanish	11	8.27%	25	17.99%	--
English/Spanish	4	3.01%	7	5.04%	
	Treatment	Control	Difference	Effect Size	p-value
Age					0.74
Mean	4.47	4.46	0.01	0.04	
Standard deviation	0.25	0.25	--		--
N	131	139	--		--

* Significantly different from zero at the .05 level, two-tailed test.

Table 3. Key Measures at Baseline, by Experimental Condition

Measure	Treatment	Control	Difference	p-value
Overall Experimental Score of Selected TEMA Items				
Mean	0.32	0.31	0.01	0.95
Standard deviation	0.16	0.16	--	--
N	133	139	--	--
Experimental Score on Preschool Math Skills				
Mean	0.40	0.40	0.001	0.99
Standard deviation	0.24	0.23	--	--
N	133	139	--	--

Data Analysis Methods

Assignment to the treatment or control groups occurred at the classroom level, creating a "cluster" intervention design. Given this design, a hierarchical linear model was used to investigate the impact of the Mastering Math app on student mathematics knowledge and skills (postMATH), structuring students nested within classrooms. This model is preferred to more precisely estimate the impact of the intervention when within-group and between-group effects need to be accounted for (Raudenbush, 1997). To control for student performance at baseline, we included students' pretest scores on mathematics knowledge and skills (preMATH) and preferred language as covariates in the Level 1 model. The Level 2 model included the intervention variable (TREAT). The main effect model was specified using the covariates listed above, and run using Stata 14 statistical analysis software. The models were specified as follows.

$$\text{Level 1: } postMATH_{ij} = \pi 0_j + \pi_{1j}(preMATH)_{ij} + \pi_{2j}(\text{Preferred Language})_{ij} + e_{ij}$$

$$\text{Level 2: } \pi_0 = \beta_{00} + \beta_{01}(TREAT)_j + r_{0j}$$

This model allowed researchers to compare the treatment group's post-intervention outcomes with those of the control group, after adjusting for difference in baseline scores.

Several approaches were utilized to address missing data. Students who did not take both the pre- and post-assessments were excluded from the analytic sample for the outcome measure. For the outcome measure, missing item responses were treated as incorrect responses. Participants who missed all the items in the outcome measures were removed from the corresponding analyses.

Results & Discussion

Throughout the intervention, students on average actively engaged in Mastering Math games for 343 minutes. They demonstrated mastery on 7 skills, and 5% of students were able to master all of the skills available in Mastering Math at the time. Most of the students were able to play games focusing on skills such as count all, count forward, count out, and number recognition. However, the majority of the students did not have exposure to games that teach count backward, count on, and mental number line.

Overall Impact on Children's Knowledge and Skills in Mathematics

The results indicate that the Mastering Math app intervention was positively associated with gains in children's knowledge and skills in mathematics, as measured by the selected TEMA-3 items (see Table 4). Adjusted mean differences on the post-test measure of the selected TEMA-3 items show that the treatment group exceeded the control group (point estimate of 2%; effect size = 0.13); however this difference was not significant at the .05 level after accounting for differences in baseline children's mathematics development and participant preferred language. A similar positive trend was found on the post-test measures of the selected TEMA-3 items on preschool math skills.

Table 4. Impact Analysis of Student Outcome Measures

	Adjusted Mean					
Impact Measure	**Treatment (Standard Deviation)**	**Control (Standard Deviation)**	**Difference (Standard Error)**	**p-value**	**95% Confidence Interval**	**Effect Size**
Overall Experimental Score of Selected TEMA-3 Items	0.43 (0.19)	0.41 (0.17)	0.02 (0.02)	0.20	-0.01 – 0.05	0.13
Experimental Score on Preschool Math Skill	0.55 (0.26)	0.53 (0.24)	0.02 (0.02)	0.22	-0.02 – 0.07	0.08

Effect size was calculated by dividing impact estimate by the control group unadjusted standard deviation of the outcome variable

Impact by Prior Knowledge

Students with the highest quartile of TEMA-3 pretest score (High prior knowledge) had the greatest and statistically significant gains from Mastering Math ($t(77) = 2.40$, $p = .02$, effect size = .54) compared to the control group (see Figure 5). Students with the lowest quartile of TEMA-3 pretest score (Low prior knowledge) did not show any difference in gains ($p > .10$). Those in the middle 50% at pretest showed an advantage toward Mastering Math, but the effects were not statistically significant (p's > .07). This suggests that students needed to have a certain prior knowledge requirement in order to benefit from Mastering Math.

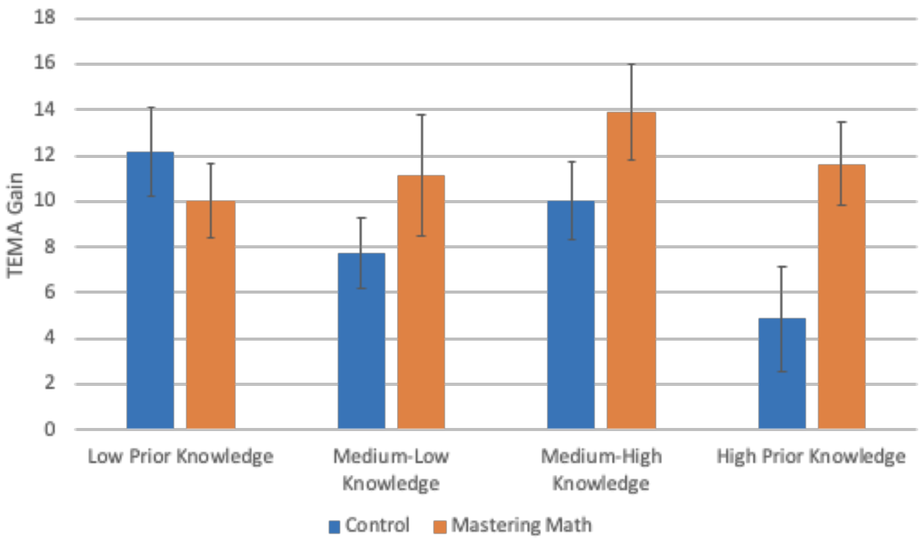

Figure 5: PreK learning gain by prior knowledge quartiles

Interestingly, when relating to performance within Mastering Math, Treatment children with Low prior knowledge were indeed those who were most often "stuck" in the games (see Figure 6). "Stuck" is defined as not having progressed after 5 activities in the same level within any game (Owen et al., 2019). While over 25% of students were identified as Productive in the Low prior knowledge group, an overwhelming 62% were stuck in the games. And this percentage of Low prior knowledge students identified as "stuck" in the games were drastically greater than those with higher prior knowledge, which averaged around 10% of students. Prior research has shown that in-game performance is directly correlated with actual learning outcomes, as measured by external assessments (Thai, Li, & Schachner, 2019; Jacobs et al., 2019; Owen et al., 2019). This confirms that finding of the alignment between game play and learning outcomes, but more importantly, suggests that game play experience can be improved to address the needs of children with low or no relevant prior knowledge. In the following section, we consider several hypotheses and evaluated the available data to derive insights into what improvements need to be made.

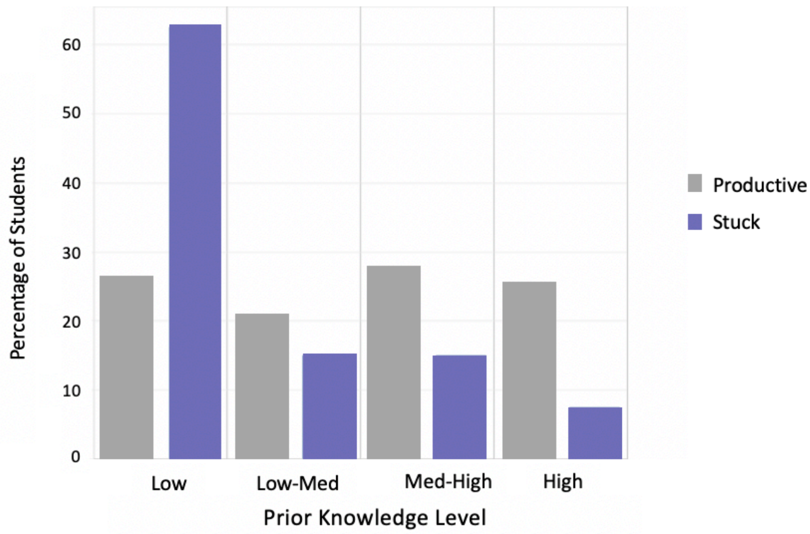

Figure 6: Percentage of PreK student experiencing stuck and productive states in Mastering Math by prior knowledge level.

Why might Low prior knowledge students get stuck in Mastering Math?

There are a number of possible reasons as to why students may be stuck in the first place. One likely reason is the lack of prerequisite knowledge for the games, but what kind of prerequisite knowledge? When we look at the TEMA-3 pretest performance of Low prior knowledge students, 70% of low prior knowledge students could not count to five on fingers, 93% couldn't identify numbers 1 –5, and 98% couldn't produce finger displays to 5. These basic counting forward and number identification skills are the basic building blocks to higher number sense skills, as they are also reflected on our knowledge map. Children who have difficulty with these tasks likely do not know the number words from one to five, can recognize that the symbols for numbers (i.e., 1) go with the sounds (i.e., "one"), and/or know to point to each of the objects (or fingers) once and only once as each number word is said. Accuracy in finger displays is useful for finger counting, a technique that many young children employ (Andres, Di Luca, & Pesenti, 2008).

Correspondingly, a large percentage of Low prior knowledge students could not complete the games that address the most foundational skills on the knowledge map. 55% of Low prior knowledge students were stuck on a game involving counting forward on a tightrope, compared to 0% of High prior knowledge students. In this game, students were asked to place the appropriate Shapeys marked with numbers 1 to 5 onto the tightrope in the correct order (see Figure 7). Low prior knowledge students who could not demonstrate mastery on either game (by placing numbers 1 to 5 in the correct order) were not able to progress deeper in the knowledge map.

Similarly, 37% of Low prior knowledge students did not demonstrate mastery on another foundational game that reinforces the identification of numbers 1 to 5 (i.e. Tagging Game 1-5, see Figure 8), compared to only 8% of higher prior knowledge students. In this game, students were presented with a moving array of numbers from 1 to 5, and were asked to identify all instances of a given number. While not all students who performed poorly on number identification on the pretest were stuck in the Tightrope or Tagging game, the relatively large percentages of Low students were, suggesting that these games may not be enough to introduce students to number naming. This suggests that prerequisite content aimed to introduce number naming of numbers may be necessary in Mastering Math for those children very little to no prior knowledge.

Figure 7: Screenshot of Tightrope game.

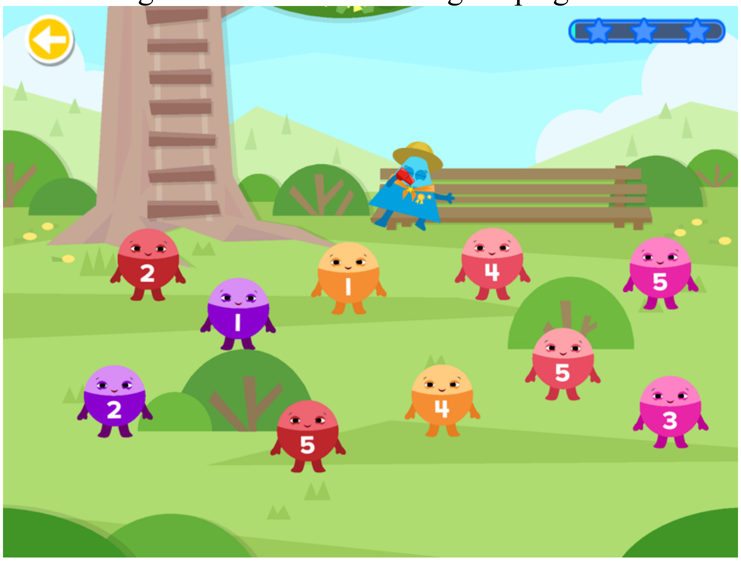

Figure 8: Screenshot of Tagging game.

This result also calls for a re-examination of the design of educational technology to appropriately measure and teach foundational skills with very young children. Consider the skill of reading or naming numerals, for example. The first 10 written numerals in the English language (from 0 to 9) are completely arbitrary and must be learned through rote memory. To assess a child's ability of reading numerals, a typical assessment involves presenting her a number "4" and ask her to respond verbally "What number is this?". Typical instructional activities should similarly include many opportunities for her to hear the sound "four" with the written numeral 4, and to practice saying the sound upon seeing the number. When it comes to translating these tasks to educational technology, particularly a game-based one, there are major technological and design constraints (e.g., such as the lack of effective speech recognition for children).

Despite major advances in technology in the past few decades, at the time of this research, reliable speech recognition technology for young children to use independently is not available. This meant that we could not ask the child to speak "four" to assess whether they know what number is 4. We also needed to rely more on visual representations to drive children's interactions. For example, in the Tagging game, rather than asking students to say aloud the name of the number, we asked them to tap on all instances of the number given its sound. We found this design compromise acceptable, as number recognition (vs. number naming) is an important prerequisite to later games and could provide reinforcement opportunities for children throughout all games in the system.

Our results suggest however, that children require more opportunities and experience with numbers than our games could provide. For example, recall that it may take a year for students to go from producing a set of 1 to producing a set of 4 items (Wynn, 1992). If a child has not had exposure or practice counting out sets of 1-5 items prior to entering PreK or K, they may not be able to master this concept and skill with just 5 rounds of exposure with game-based instruction. These children need more, and a different kind of handholding, to succeed. It can be done via additional content addressing mathematics readiness, targeting skills as early as distinguishing symbols as numbers vs. letter, and via providing many more opportunities for number naming and counting practice. These can be done within the app and beyond the app, by providing parents and caretakers with activities and instructional resources to help them engage with their children in mathematics prior to formal schooling.

Other Hypotheses

Another possible reason for the lack of progress of Low prior knowledge students may be that the language selection was not accurate for them. 37% of Low prior knowledge students and 33% of medium-low prior knowledge students played in their non-native language (i.e., an ELL learner fluent in Spanish uses the English version rather than the Spanish version of the app), compared to 17% of students in the medium-high and 14% in the high prior knowledge groups. This was primarily due to the teachers' decision to keep the app language in English. Future studies may explore this possibility by encouraging native language selection.

One last important consideration for the design of game-based instruction for young children is their executive functioning, specifically related to motor skills. Our frequent user testing ensured that most children can engage effectively with Mastering Math, but it remains a possibility that Low prior knowledge students may require additional scaffolding when it comes to interacting with a tablet. Future research can combine observations with click-level data to better understand, measure and monitor how executive functioning may affect learning within the games.

Conclusion

This study evaluated data from efficacy studies of an adaptive game-based mathematics digital curriculum for preschool students. Analyses revealed that preschool children with low prerequisite knowledge at the start of the school year were unable to progress effectively in the program. Results of this study confirm the need for the development of interventions that address early mathematics readiness skills for students and highlight important considerations for the development of educational technology for young children. Educational technologies provide important opportunities to provide reliable and equitable access to high-quality education and personalization at scale, especially in preparing children for success in school. There are currently too few educational programs available that can address early mathematics readiness skills for students. This study calls for programs that can identify children who may not be able to take advantage of school instruction and provide appropriate interventions to address their needs prior to the onset of formal schooling.

References

Andres, M., Di Luca, S., & Pesenti, M. (2008). Finger counting: The missing tool? Behavioral and Brain Sciences, 31(6). 642-643.

Betts, A. (2019). Mastery learning in early childhood mathematics through adaptive technologies. In IAFOR (Ed.). The IAFOR International Conference on Education – Hawaii 2019 Official Conference Proceedings. Paper presented at the IAFOR International Conference on Education: Independence and Interdependence, Hawaii (pp. 51-63). Japan: The International Academic Forum.

Blevins-Knabe, B. (2016). Early mathematical development: How the home environment matters. In Blevins-Knabe & Berghout Austin, A.M. (Eds.) Early Childhood Mathematics Skill Development in the Home Environment, (pp. 7-28). Switzerland: Springer International Publishing.

Bloom, B. (1968). Learning for mastery. In J.H. Block (Ed.), Mastery learning: Theory and practice (pp.47-63. New York, NY: Holt, Rinehart, & Winston.

Claessens, A., & Engel, M. (2013). How important is where you start? Early mathematics knowledge and later school success. Teachers College Record, 115(6), 1–29.

de Brey, C., Musu, L., McFarland, J., Wilkinson-Flicker, S., Diliberti, M., Zhang, A., Branstetter, C., and Wang, X. (2019). Status and trends in the education of racial and ethnic groups 2018 (NCES 2019-038). U.S. Department of Education. Washington, DC: National Center for Education Statistics. Retrieved from https://nces.ed.gov/pubsearch/

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., & Japel, C. (2007). School readiness and later achievement. Developmental Psychology, 43(6), 1428–1446.

Duncan, G., & Magnusen, K. (2011). The nature and impact of early achievement skills, attention skills, and behavior problems. In Greg J. Duncan and Richard J. Murnane (eds.), Whither Opportunity: Rising Inequality, Schools, and Children's Life Chances (pp. 47-69). New York: Russell Sage.

Elliot, L., & Bachman, H.J. (2018). SES disparities in early math abilities: The contributions of parents' math cognitions, practices to support math, and math talk. Developmental Review, 49, 1-15.

Ginsburg, H. & Baroody, A. (2003). TEMA-3 Examiners Manual (3rd ed.). Austin, TX: PRO-ED.

Goodell, J., & Thai, K.P. (in press). A Learning Engineering Model for Learner-Centered Adaptive Systems. To appear in Proceedings of the Human-Computer Interaction International Conference, Workshop on Conceptual Modeling of Adaptive Instructional Systems (AISs).

International Society of the Learning Sciences (ISLS), https://www.isls.org/Apr-2019, last accessed December 2019.

Jordan, N., & Levine, S. (2009). Socioeconomic variation, number competence, and mathematics learning difficulties in young children. Developmental Disabilities Research Reviews, 15, 60-68.

Lee, J.S., & Ginsberg, H. (2009). Early childhood teachers' misconceptions about mathematics education for young children in the United States. Australian Journal of Early Childhood, 34(4), 37-45.

National Assessment of Educational Progress (NAEP). (2015). The Nation's Report Card: Mathematics & reading assessments State comparisons. Retrieved from: https://www.nationsreportcard.gov/reading_math_2015/#reading/state/comparisons/NP?grade=4

Nguyen, T., Watts, T.W., Duncan, G.J., Clements, D.H., Sarama, J.S., Wolfe, C., & Spitler, M.E. (2016). Which preschool mathematics competencies are most predictive of fifth grade achievement? Early Childhood Research Quarterly, 36, 550-560.

Owen, V. E. (in press). Learning science in data-driven adaptive design for young children. To appear in the Proceedings of the International Conference on Artificial Intelligence in Adaptive Education, 2019.

Owen, V. E., & Hughes, D. (2019). Bridging Two Worlds: Principled Game-Based Assessment in Industry for Playful Learning at Scale. In Game-Based Assessment Revisited (pp. 229-256). Springer, Cham.

Owen, V. E., Roy, M.-H., Thai, K.P., Burnett, V., Jacobs, D., Keylor, R., & Baker, R. (2019). Detecting wheel-spinning and productive persistence in educational games. Proceedings of The 12th International Conference on Educational Data Mining (EDM 2019).

Siegler, R. (2009). Improving the numerical understanding of children from low-income families. Child Development Perspectives, 3, 118-124.

Simon, M. (1995). Reconstructing mathematics pedagogy from a constructivist perspective. Journal for Research in Mathematics Education, 26(2), 114-145.

Thai, K.P., Li, L., & Schachner, A. (2019). Accelerating Early Math Learning with a Digital Math Resource: A Cluster Randomized Controlled Trial. AERA Annual Meeting, Toronto, Canada, Apr-2019.

Vygotsky, L. (1986). Thought and language: Newly revised and edited. A. Kozulin (Ed). Cambridge, MA: The Massachusetts Institute of Technology.

Wynn, K., (1992). Childrens' acquisition of the number words and the counting system. Cognitive Psychology, 24, 220-251.

Contact email: albetts@buffalo.edu