EDUCATION

Math at home adds up to achievement in school

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With a randomized field experiment of 587 first-graders, we tested an educational intervention designed to promote interactions between children and parents relating to math. We predicted that increasing math activities at home would increase children's math achievement at school. We tested this prediction by having children engage in math story time with their parents. The intervention, short numerical story problems delivered through an iPad app, significantly increased children's math achievement across the school year compared to a reading (control) group, especially for children whose parents are habitually anxious about math. Brief, high-quality parent-child interactions about math at home help break the intergenerational cycle of low math achievement.

For many families, stories are a regular part of a child's home routine. Parents are motivated to read to their children because they believe this activity promotes children's school achievement. However, they pay much less attention to supporting their children's math learning at home.

A widely held belief among parents is that children's math education is primarily the responsibility of schools and that their role in supporting their children's math learning is not as important as their role in supporting their children's reading (*1*). This belief is reinforced by messages conveyed through the media and schools, which predominantly focus on the need for parents to interact with their children relating to language and reading (*2*). Unfortunately, the notion that math education is the purview only of schools and not also of parents ignores the fact that math input in the home is an important predictor of children's mathematical success (*3*). Here, we demonstrate that a parent-child interactive math app, derived from psychological theories that emphasize the importance of parent involvement in children's learning (*4*), increases first-grade students' math achievement. Moreover, we show that even a small amount of app usage (once a week) especially helps children whose parents are habitually anxious about math. Given the increasing prominence of tablet-style devices and Internet access (*5*), this intervention has the potential to be a low-cost, high-benefit method to ensure that parents' uneasiness with math does not translate into their children's low math achievement (*6*).

Although there is an inherited component to math and spatial thinking (*7*), experiences, including the math talk that young children hear from their parents, are also implicated in children's mathematics achievement. The amount of number talk parents engage in with their preschool children predicts 4- and 5-year-olds' grasp of foundational number concepts (*3*, *8*). The frequency with which parents talk about shape and spatial features of objects—using words like circle, tall, edge, and corner—also predicts children's spatial thinking (an important component of mathematical success) as they enter kindergarten (*9*–*11*).

If parent math talk is important for children's mathematical success, then adding opportunities for parents and their children to discuss numerical and spatial aspects of math throughout the school year should enhance children's math achievement. It might seem unlikely that a few additional opportunities for math-related talk per week would affect children's math achievement. However, many adults are apprehensive about math, reflected as math anxiety (*12*), and tend to avoid math whenever possible. Moreover, highly math-anxious parents provide a low quality of math input in the home (*6*). Therefore, even a modest increase in high-quality parent-child math talk could boost their children's math achievement.

We recruited a demographically diverse sample of primary caregivers (labeled "parents" for simplicity) and their first-grade children (587 families from 22 Chicago area schools). We focused on early elementary school because students who begin school behind peers in math tend to stay behind in later grades (*13*). Families were randomly assigned to a math group (420 families) or reading (control) group (167 families), with our main focus, the math group, oversampled. To control for differences in math learning because children attend schools of varying quality, schools with a reading control classroom had at least one classroom assigned to the math group.

Children and their parents were asked to read topical math (or reading) passages and answer corresponding math (or reading) questions, delivered by an iPad app called Bedtime Learning Together (BLT), several times per week over the course of the school year. The math version of BLT is based on Bedtime Math, an app available for free on iTunes and Android. Participating families were given an iPad Mini to access the story problems.

Each passage had five associated questions ranging in difficulty from preschool to late fifth-grade levels. Families did as many questions as desired during each interaction with the app. The reading and math app passages were similar, except the reading passages contained no numerical or spatial content. Math app questions covered topics such as counting fluency, geometry, arithmetic, fractions, and probability; reading app questions dealt with reading comprehension, vocabulary, inference, phonics, and spelling (see the supplementary materials for examples).

By distributing passages with the iPad app, we were able to track how often parents used the app with their children. In addition to app usage, each child's math achievement (*14*) was assessed at school in a one-on-one session with one of several trained research assistants, both at the beginning (before the iPads were distributed) and at the end of the school year.

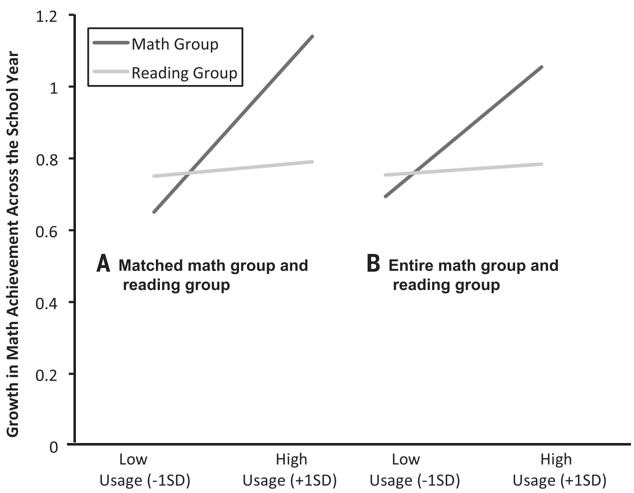

Fig. 1. Estimated number of months of math knowledge children gained across the school year (1 equals 9 months or one school year) as a function of average weekly app use.

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Students were randomly assigned to the math or reading group at the classroom level to minimize spillover across treatment conditions. All analyses were conducted using Hierarchical Linear Modeling (HLM) (*15*) (see the supplementary materials for models) to account for the nesting of students within classrooms.

We began by directly comparing the math achievement of children in the math and reading groups for schools where we had matched math and reading classrooms (math group: n = 226 families; reading group: n = 167 families). Matching students in this way allowed us to compare math and reading families sampled from the same schools. The more times parents and their children used the app (ranging from 0 to 6.28 times per week), the higher children's math achievement at school year's end (controlling for beginning-of-year math achievement), but only for children in the math group, as shown by a group by use interaction on end-of-year math achievement [$\hat{\beta}_{21} = 4.03, t = 2.83, P = 0.005$] (Fig. 1A and Model S1). This interaction demonstrates that it is not any engagement with parents about academic content that increases children's math achievement but engagement with math specifically.

Looking separately at the math and reading groups, among all families in the math group (n = 420 families), the more times children and their parents used the math app, the higher children's end-of-year math achievement (controlling for beginning-of-year math achievement) [$\hat{\beta}_{20} = 2.88, t = 4.01, P < 0.001$] (Model S2). Unlike the math group, a similar model for the reading group showed no significant relation between frequency of app usage and end-of-year math achievement [$\hat{\beta}_{20} = 0.22, t = 0.25, P = 0.81$] (Model S2). More use of the math app (defined as +1 SD above the mean in app use) corresponded to approximately a 3-month math achievement advantage over using the reading app often (Fig. 1, A and B).

If using the math app bolsters children's math achievement because it facilitates parent/child interactions about math, then children whose parents have the most math anxiety and provide lower-quality math input at home (*6*) should especially benefit from using the math app. Moreover, if parents' math anxiety is linked to variations in how much children grow in math achievement across the school year, then using the math app should decrease or eliminate differences in math achievement growth between children with low-math-anxious parents and children with high-math-anxious parents. Obtaining this latter result would highlight the importance of introducing parent-child math activities at home to ensure that all children (regardless of their parents' level of anxiety and comfort with math) have the opportunity to maximally achieve in math across the school year.

Many adults, in the United States and worldwide, feel at least some apprehension toward math (*16*, *17*). The math app may provide parents with math anxiety an opportunity to talk to their child about math in engaging and effective ways—supporting the kind of math conversations they most likely would not otherwise have. To explore this idea, we assessed parents' math anxiety—their tendency to feel tension, apprehension, or fear in mathematical situations (*18*). This was done through a math-anxiety questionnaire given to them when they picked up their iPad at the beginning of the school year.

We expected the math achievement of children with high-math-anxious parents to be more affected by use of the math (versus reading) app because these children would not generally be provided with high-quality math input at home (*6*). Therefore, we first separated parents on the basis of whether they were lower or higher in math anxiety (median split). We then performed an "intent-to-treat" analysis in which we looked at the effect of group (math versus reading app) on children's end-of-year math achievement (controlling for beginning-of-year math achievement) independent of actual app usage. For children of high-math-anxious parents, we found a significant effect of group, with children in the math group outperforming those in the reading group by almost 3 months in math achievement by school year's end[$\hat{\beta}_{21} = 5.25, t = 1.99, P = 0.048$]. We did not find this same pattern for children of low-math-anxious parents [$\hat{\beta}_{31} = -0.61, t = -0.27, P = 0.79$] (Model S3). An intent-to-treat analysis allows us to rule out factors possibly related to app usage—such as motivation or interest—as explaining our findings.

We next looked at the effect of math app usage, separately, on children whose parents were lower or higher in math anxiety. For children with high-math-anxious parents, we found a significant effect of amount of usage [$\hat{\beta}_{20} = 2.83, t = 3.23, P = 0.002$] (Model S4). For children of low-math-anxious parents, the parallel model also yielded a significant overall effect of app usage [$\hat{\beta}_{20} = 2.76, t = 2.52, P = 0.01$] (Model S4).

To explore these usage effects further, we separated families into three usage groups: Families who had the app but did not use it much (Bin 0: averaging ≤ 0.50 uses per week; M = 0.22, n = 122 families); families who used the app on average one time per week (Bin 1: averaging 0.51 to 1.50 uses per week; M = 1.00, n = 153 families); and families who used the app on average 2 or more times per week (Bin 2+: averaging 1.51 to 4.30 uses per week; M = 2.42 uses per week, n = 119 families).

Children of high-math-anxious parents who used the math app about once a week (Bin 1) grew significantly more in math achievement than children of high-math-anxious parents who used the app the least (Bin 0) [$\hat{\beta}_{20} = 8.08, t = 3.14, P = 0.002$] (Fig. 2). However, children of high-math-anxious parents who used the app two or more times a week (Bin 2+) did not show significant growth over children who used the app once a week (Bin 1) [$\hat{\beta}_{20} = 0.52, t = 0.27, P = 0.79$]. If high-math-anxious parents typically provide little and/or low-quality math input in the home, then even a modest amount of high-quality interaction about math should increase the quantity and quality of math input their children receive and therefore boost children's math achievement, as we found.

For children of low-math-anxious parents, the only significant effect was that, at higher doses of math-app use (Bin 2+), these children grew significantly more in math achievement than those who interacted with their parents relating to the app less often (Bin 1) [$\hat{\beta}_{20} = 7.31, t = 2.81, p = 0.006$]. There was a slight dip in performance between those who used the app the least (Bin 0) and those who used it once a week (Bin 1), although this difference was not significant [$\hat{\beta}_{20} = -4.35, t = -1.61, P = 0.11$]. Additionally, there was no significant difference between those who used the app the least (Bin 0) and those who used it the most (Bin 2+) [$\hat{\beta}_{20} = 1.60, t = 1.02, P = 0.31$]. There is likely less of a meaningful usage effect for children of low-math-anxious parents because these parents are already providing rich math input at home (see the supplementary materials for comparable reading group analyses).

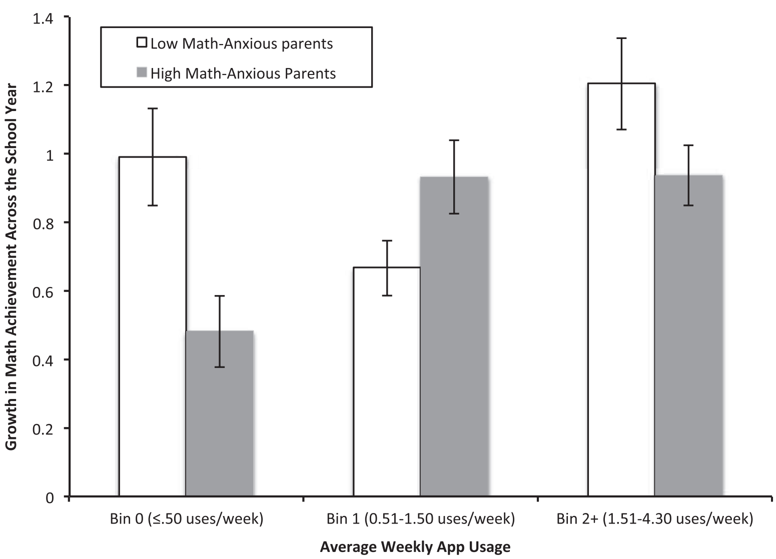

Fig. 2. Number of months of math knowledge children gained across the school year (1 equals 9 months or one school year) as a function of average weekly app use and parents' math anxiety.

When families in the math group used the app the least (Bin 0), children with high-math-anxious parents grew significantly less in math achievement by the end of the school year relative to children with low-math-anxious parents [$\hat{\beta}_{20} = -7.94, t = -2.42, P = 0.02$] (Fig. 2 and Model S5). Strikingly, using the math app mitigated this negative relation between parents' math anxiety and children's math achievement. When families used the app on average once a week or more, children with high-math-anxious parents made gains in math achievement by the end of the school year that did not significantly differ from those made by children with low-math-anxious parents {Bin 1: [$\hat{\beta}_{20} = 3.44, t = 1.53, P = 0.13$]; Bin 2+: [$\hat{\beta}_{20} = -3.60, t = -1.21, P = 0.23$]} (Model S5).

Thus, when parents and children interact about math story problems—even as little as once a week—children show increased math achievement by the end of the school year. The benefits of occasional math-related interactions are especially apparent for children whose parents are anxious about math. By providing an engaging way for math-anxious parents to share math with their children, the math app may help cut the link between parents' high math anxiety and children's low math achievement (*6*).

The current findings are of particular relevance in view of the multibillion-dollar educational app market (*19*). Scant research exists on the effectiveness of apps marketed as educational (*20*), and the research that has been done does not always find benefits for children's learning. Use of enhanced e-books that target literacy can actually be detrimental to children's basic reading comprehension when they contain distracting sounds and animations (*21*). The math app used here has several specific features that may have contributed to its effectiveness. First, it was basic in nature (very few sounds, animations, or videos) to avoid distracting elements. Second, it was designed to align with the goals of the Common Core Standards at varying grade levels. Third, it was designed to be used by parents and children together, based on the known importance of early parental input, and specifically parent math talk, for children's achievement. The app may give parents—especially high-math-anxious parents or even parents with less skill or interest in engaging in math—more and better ways to talk to their children about math not only during app usage but also in other everyday interactions. We have shown that using this math app enhances the likelihood that children will succeed in math, which is essential for academic success and for the robustness of the science, technology, engineering, and math pipeline.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/350/6257/196/suppl/DC1
Materials and Methods
Supplementary Text
Fig. S1
Table S1
Models S1 to S8
Accessory Data File S1

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PLANT SCIENCE

Visualization of cellulose synthases in *Arabidopsis* secondary cell walls

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Cellulose biosynthesis in plant secondary cell walls forms the basis of vascular development in land plants, with xylem tissues constituting the vast majority of terrestrial biomass. We used plant lines that contained an inducible master transcription factor controlling xylem cell fate to quantitatively image fluorescently tagged cellulose synthase enzymes during cellulose deposition in living protoxylem cells. The formation of secondary cell wall thickenings was associated with a redistribution and enrichment of CESA7-containing cellulose synthase complexes (CSCs) into narrow membrane domains. The velocities of secondary cell wall–specific CSCs were faster than those of primary cell wall CSCs during abundant cellulose production. Dynamic intracellular trafficking of endomembranes in combination with increased velocity and high density of CSCs, enables cellulose to be synthesized rapidly in secondary cell walls.

Cellulose, the most abundant biopolymer on Earth, is a key biomechanical component of land plants and a valuable natural resource. Cellulose in the primary cell wall, which is laid down during plant growth, determines plant shape (*1*). However, the bulk of terrestrial biomass is composed of the cellulose in secondary cell walls, which are laid down after the cell has stopped growing to strengthen plant vasculature and structure (*2*). The strength of these walls is derived from the organization of cellulose microfibrils, which, relative to primary cell walls, possess cellulose with a higher degree of polymerization, increased microfibril crystallinity, and a higher degree of microfibril organization (*2*, *3*).

Cellulose is synthesized at the plasma membrane by cellulose synthase (CESA) enzymes that are organized in multiprotein cellulose synthase complexes (CSCs) (*4*). In *Arabidopsis thaliana*, 10 CESA isoforms exist, with CESA1, CESA3, and CESA6 involved in primary cell wall synthesis

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