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Exploring effects of an early math intervention: The importance of parent–child interaction

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Abstract

We explore whether training parents' math skills or playing number games improves children's mathematical skills. Participants were 162 parent–child dyads; 88.3% were white and children (79 female) were 4 years (M=46.88 months). Dyads were assigned to a number game, shape game, parent-only approximate number system training, parent-only general trivia, or a no-training control condition and asked to play twice weekly for eight weeks. Children in the number game condition gained over 15% SD on an assessment of mathematical skill than did those in the no-training control. After eight additional weeks without training, effects diminished; however, children of parents in the ANS condition underperformed those in the no-treatment control, which was partially explained by changes in the home numeracy environment.

The mathematical skills of children entering kindergarten vary widely: Some children are unable to recognize Arabic numerals or recite the count list, whereas others can already do simple arithmetic (Jordan et al., 2009; Mazzocco & Thompson, 2005; Zill & West, 2001). This variability has implications for later development and academic achievement, as individual differences in mathematical skills demonstrate remarkable rank-order stability throughout elementary school grades and beyond (Duncan et al., 2007; Jordan et al., 2009). That is, children who enter school with lower levels of mathematical skills typically continue to underperform and tend to take fewer high-level math courses compared to their peers (Davis-Kean et al., 2021). It is therefore important to examine the origins of individual differences in mathematical skills prior to school entry.

In addition to children's domain-general (e.g., general intelligence; Hart et al., 2009; Xenidou-Dervou et al., 2018; language; LeFevre et al., 2010; Slusser et al., 2019, and executive function; Bull & Lee, 2014; Cragg & Gilmore, 2014; Ribner et al., 2018) and domain-specific cognitive skills including approximate and exact number skills (e.g., Halberda et al., 2008; Libertus et al., 2013; Slusser et al., 2019; van Marle et al., 2014), children's learning environments may have substantial impact on their math skill development (Silver & Libertus, 2022). Prior to entering formal schooling (around age

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5 in the United States) much of the environmental influence is a product of the home. Most notably, this home environment is shaped by parents and caregivers and the learning opportunities they create for their children. Extant research has demonstrated several ways in which parents and their daily practices may contribute to their children's mathematical skill development, including through their own mathematical skills (e.g., Brown et al., 2011) and through parenting practices including frequency of engagement with activities that require mathematical thinking (e.g., LeFevre et al., 2009; Susperreguy et al., 2020). In this study, we investigate whether experimentally manipulating aspects of parents' own skills or specific parenting practices with their children affects preschool-aged children's mathematical skill development.

The Role of Parents in Mathematical Skill Development

Math in the Home Environment.

A broad research base has described relations between facets of the home numeracy environment—which is often measured in terms of the frequency with which children play with math-related toys and games and engage with mathematically relevant information by doing activities such as counting, reading Arabic numerals, and doing simple calculations—and math skills (Daucourt et al., 2021; LeFevre et al., 2009; Segers et al., 2015; Susperreguy et al., 2020; but see Elliott & Bachman, 2018 and Hornburg et al., 2021 for discussions of inconsistencies). Researchers often use questionnaires about the frequency with which parents report child engagement with and use of games, toys, and activities that involve mathematically relevant information to ascertain the general home math environment. Individual differences in responses to those questionnaires relate not only to children's math skills concurrently, but also to the development of math skills over time such that children who reportedly engage in more frequent math-related activities such as board games that require counting and arithmetic tend to have greater math skills (e.g., Niklas & Schneider, 2014; Susperreguy et al., 2020). Similarly, children who hear their parents talk more about numbers and other math-related concepts during play and other everyday interactions tend to also have better math skills (Levine et al., 2010; Ramani et al., 2015; Susperreguy & Davis-Kean, 2016).

Importantly, the home numeracy environment appears to be malleable and at least some interventions targeting the home numeracy environment yield positive effects on children's math skills. Simple, low-cost interventions to inform parents about the concept and importance of the home numeracy environment have been shown to affect both the home numeracy environment and children's skills (Niklas et al., 2016), and interventions to make numerical information more salient to adult–child dyads increase the amount of conversation around number concepts (Braham et al., 2018; Hanner et al., 2019). For example, an intervention in a grocery exhibit in a children's museum which prompted parent–child dyads to engage with the concept of selecting a meal given a limited budget yielded greater math talk than a condition in which dyads were asked to create a healthy meal. Children in the budget condition were subsequently more likely to spontaneously attend to number in an imitation task with a researcher (Braham et al., 2018).

Other targeted interventions have found similar results: Parent–child engagement with a tablet-based intervention which provided scripted mathematical problem-solving opportunities improved children's mathematical skills compared to a non-mathematical story condition (Berkowitz et al., 2015). Similarly, parent–child engagement with a picture book that drew attention to quantity (as opposed to other salient characteristics such as color) improved children's understanding of number words and quantity (Gibson et al., 2020). However, not all home-based interventions to increase conversation about and salience of numbers have yielded effects. One intervention with preschool-aged children that successfully increased mathematically relevant conversation during a cooking activity found no effects on children's math skills (Vandermaas-Peeler et al., 2012).

One intervention paradigm that has generally shown positive effects for children's mathematical skill development has involved the use of board games. Several studies have shown engaging with board games which encourage children to count (typically dictated by the use of a spinner to specify the number of spaces a player should move) improve mathematical skill development (e.g., Elofsson et al., 2016; Ramani & Siegler, 2008, 2011; Siegler & Ramani, 2009; Whyte & Bull, 2008). Across various implementations and samples, participants demonstrated increased mathematical skill after only four to six sessions (approximately 60 minutes of play time) over two to three weeks compared to control conditions (e.g., color board games, other number activities). Though there is some evidence to suggest nuances of game design might moderate the effectiveness of number board game play (e.g., circular versus linear, Siegler & Ramani, 2009; Whyte & Bull, 2008; traditional versus digital, de Vries et al., 2021), these positive effects of number board games appear to be robust to differences in country and language (e.g., Cheung & McBride, 2017; Elofsson et al., 2016; Skillen et al., 2018; Whyte & Bull, 2008), as well as individual versus group settings (e.g., Ramani et al., 2012). Numerical card games administered by a trained research assistant have shown similar effects (Scalise et al., 2017). However, effects might not be universal for all children: benefits of number board games were stronger for children who had lower levels of initial knowledge and who were from lower-income families (Ramani & Siegler, 2011).

Effective number game interventions have nearly exclusively taken place in classroom settings and been administered by a trained game partner (i.e., a researcher or paraprofessional; Ramani et al., 2012) with some noted exceptions (cf., Scalise et al., 2022; Sonnenschein et al., 2016). More recent evidence has suggested that games played with parents at home might be less efficacious than those played with a trained partner (Ramani & Scalise, 2020). Interventions modeled after successful board or card game interventions and which are implemented with parents have thus far largely reported null results (in comparison to other, non-math board or card games; Scalise et al., 2022; Sonnenschein et al., 2016), though there is some evidence that interventions that center parent–child interaction may have auxiliary effects, as by attenuating the effects of math anxiety (Schaeffer et al., 2018). Notably, other parent—child interventions have relied on highly scripted interactions (e.g., Sonnenschein et al., 2016) and have been limited in both the number of participants and the counterfactual condition. Additional research is needed to test the efficacy of game-based interventions which require little to no training for parent–child dyads. The current study seeks to fill this gap.

Parent Math Skills.

While the mechanism of intergenerational transfer of math skills remains unclear, there is substantial evidence that parents who are good at math tend to have children who are good at math themselves (Borriello et al., 2020; Braham & Libertus, 2017; Brown et al., 2011; Navarro et al., 2018). For example, parents' math fluency, (i.e., their ability to quickly retrieve basic arithmetic facts), is related to a range of their 5- to 8-year-old children's math skills including children's math fluency as well as their ability to solve word problems and written calculations (Braham & Libertus, 2017). One aspect of parents' and children's cognitive functions that may be the basis of these intergenerational associations in math skills is parents' and children's non-symbolic number skills, or approximate number system (ANS) acuity. The ANS is an evolutionarily preserved intuitive sense of number which is associated with and underlies the acquisition of symbolic math skills (for reviews, see Chen & Li, 2014; Schneider et al., 2017), and which produces imprecise estimates of quantity from input across sensory modalities (e.g., sequences of tones, visually or tactilely presented objects, taps of a finger). The imprecision of the numerical representations in the ANS increases with increasing number, meaning that the accuracy of observers' comparison between ANS representations follows Weber's Law (i.e., the discriminability of any two ANS representations is a function of the ratio between them) (Buckley et al., 1974; Dehaene, 1996; Moyer & Landauer, 1967). Parents' ANS acuity is correlated with children's ANS acuity (Braham & Libertus, 2017; Navarro et al., 2018) and also predicts children's overall math skills (Braham & Libertus, 2017). Furthermore, prior research has demonstrated that the ANS is malleable: Adults who repeatedly engage in increasingly difficult approximate number comparisons and operations demonstrate improved ANS acuity (e.g., DeWind & Brannon, 2012), which in turn leads to improvements in symbolic mathematical skills (Au et al., 2018; Bugden et al., 2016; Park & Brannon, 2013). As such, when considering ways that improving parents' math skills might improve children's math ability, we focus on acuity of the ANS as a target of intervention.

While there is suggestive evidence for a causal link between acuity of the ANS and symbolic math skills (albeit with some ongoing debate, cf. Lindskog & Winman, 2016; Merkley et al., 2017), it remains unclear whether improving adults' ANS acuity also affects their behaviors, which may in turn have effects on children's math skills. Notably, a correlational study found that individual differences in parents' ANS acuity were associated with parents' use of number words when playing with their children (i.e., number talk; Elliott et al., 2017). Parents with greater ANS acuity tended to use more numbers greater than ten, and this large number talk was associated with children's performance on a standardized math assessment. Thus, it is possible that parents whose ANS acuity is improved as a result of training may also provide greater opportunity for engagement with math for their children through the provision of more number talk or math-relevant activities, yielding improvements in not only their own math skills, but also the skills of their children. We will test this hypothesis in the current study.

Current Study

Prior research has suggested a range of influences on the development of children's early mathematical skills, including their parents' number skills and the home numeracy environment; however, many studies to date have focused on correlational associations among such skills. Here, we assess causal associations in these two proposed pathways from parent factors to children's math skills by randomly assigning parents to training conditions designed to improve either their own approximate number sense or to increase parents' and children's shared engagement with mathematically-relevant activities (here, a semi-structured board game). For each of these proposed pathways through parent number sense or parent–child interactions, we designed one training condition to target number skills and another as an active control targeting a non-numerical domain. As such, we assigned parents of preschool-aged children to one of four training conditions, two of which were focused on parents alone in the form of a computer task and two of which focused on parent–child interactions in the form of a board game, or a no-training control condition.

We investigate the following questions: (1) Can "training" parents affect children's mathematical skills? That is, does training parents' number skills and/or does encouraging parents and children to play a board game in which numerical features are salient improve children's performance on a test of mathematical skills? (2) If so, do these training effects occur through changes in the home numeracy environment—specifically, in children's engagement with math activities? The goal of this study was to assess whether environmental influences—namely parents' math skills and the home numeracy environment—are causally related to the development of young children's mathematical skills. We hypothesize that the two intervention conditions that targeted parents' and children's math skills will improve children's mathematical skills relative to the two active control conditions and the no-training control. Specifically, we explore whether these improvements would occur via changes in the home numeracy environment.

Methods

Participants

A convenience sample of a total of 162 children (79 female) and their primary caregiver (9 fathers, 153 mothers) from the Pittsburgh, PA area were recruited through flyers, a central research participant database, and mailing lists from 2015–2019. Parents provided informed written consent prior to any data collection as approved by the local Institutional Review Board. Children and their parent attended four in-lab visits: Visit 1 ("Pre-Test") occurred when children were approximately 47 months of age (M_{Age} = 46.88 months, SD = 0.72), and the subsequent three visits occurred every two months following Visit 1 (Visit 2 ("Assignment"): M_{Age} = 48.95 months, SD = 0.90; Visit 3 ("Post-Test"): M_{Age} = 51.05 months, SD = 1.15; Visit 4 ("Follow-Up"): M_{AgeV4} = 53.10 months, SD = 1.38). Of those who participated in data collection at Pre-Test, 87.7% participated at Assignment (n = 143); of those who participated in Assignment, 91.6% (n = 131) participated at Post-Test; 92.3% of those who participated at Post-Test participated at Follow-Up (n = 121). Treatment assignment (described below) was unrelated to failure to return for participation at Post-Test ($\chi^2(4) = 8.34$, p = .080) or Follow-Up ($\chi^2(4) = 7.21$, p = .125). Additionally, parents and children were video-recorded during up to six 10-minute naturalistic free-play sessions in their homes via video-conference between their first and third visit to the lab; however, those data are not included as a part of the present investigation. Primary caregivers enrolled in the sample were primarily white (88.3%), had a Bachelor's Degree or higher (81.9%), and reported a family income of $60,000 or more (69.9%).

Children received a small gift (e.g., a book or stuffed animal) as a reward for participating in each in-lab data collection visit and received stickers to maintain attention and motivation throughout data collection. Parents received $8 per hour for participating in each data collection session.

Procedures

Data are drawn from a longitudinal study that examined relations between parent and child mathematical skills, as well as the role of parent–child dyadic interactions in the transmission and development of those skills. Visit protocol followed a fixed order: During each visit to the lab, children and their parents were first asked to play in a room filled with a standard set of toys for ten minutes, after which the parent completed a set of questionnaires. Finally, both parents and children completed a battery of cognitive tasks described in more detail below. Visits took approximately 90 minutes, on average, and were conducted by two trained research assistants. More details regarding the full study can be found in Elliott et al., 2022; Silver et al., 2020, 2021, 2022; and Thippana et al., 2020.

Training Conditions

At the end of the Assignment visit (i.e., the second visit to the lab), parents and children were randomly assigned to one of five training conditions: A parent–child number board game (n = 35), a parent–child shape board game (n = 32), a computerized parent ANS training game (n = 32), a computerized parent general knowledge (trivia) training game (n = 33), or a no-training control condition (n = 31). All parents except for those in the no-training control condition were given materials and instructions for their assigned condition as well as a brief demonstration of how to use their assigned materials. Parents were asked to complete their assigned training for 10 minutes at least 2 times per week for the intervening eight weeks between the second and third lab visit for a total of 16 training sessions; participants returned their training materials at their subsequent lab visit (Post-Test). Trained research assistants were on call for technical support as needed, and families were emailed a reminder to complete training sessions each week. Parents were asked to complete a brief log with the date, time, and any issues that arose during each training session. Each of the training conditions is described in detail below. A visual depiction of treatment conditions is presented in Figure 1.

Parent–Child Number Board Game—In the number board game training, parents and children played a number board game similar to the one used by Ramani and Siegler (2008). This game was designed using the commercially available game "All Around the Playground" with modifications to include number content. Specifically, families received a spinner with the numbers "1" through "6" written on it and a board with a square labeled "Start", followed by 64 colored shapes arranged with the corresponding Arabic numerals written in each shape, followed by a square labeled “Finish”. Arabic numerals were written on the board in permanent marker by research staff. Parents and children were instructed to move their token from start to finish and advance it the number of spaces indicated on the spinner. While they moved their token, they were instructed to say the number words on the corresponding squares (e.g., if a child’s token was on “3” and they spun a “2”, they said “4, 5”). If the child erred or could not name the numbers, the parent was instructed to correctly name them and then ask the child to repeat the names while moving the token.

Parent–Child Shape Board Game—In the shape board game training condition, parents were instructed to play “All Around the Playground” without the number-related modifications described above. Specifically, parents and children were given the original game’s spinner, which contained six different shapes, and the original board with 64 tiles that each contained a shape. Parents and children were instructed to move their tokens to the next appropriate shape while saying the shape names of each shape along the way. If the child erred, the parent was instructed to correctly name the shape and then ask the child to repeat the names while moving the token. Labeling the shapes was not included in the original instructions for this game but was included to parallel the number labeling aspect of the Number Board Game condition.

Parent ANS Training Game—To improve parents’ ANS acuity, parents received a laptop computer pre-loaded with a non-symbolic arithmetic task similar to the one used by Park and Brannon (2013). On each trial of this training task, parents viewed an animation of two dot arrays containing from 9 to 36 dots sequentially moving behind an occluder too quickly to be counted. Trials included non-symbolic addition (i.e., two sets of dots moving behind an occluder) and subtraction (i.e., one set moving behind an occluder, and a smaller subset moving out from behind the occluder). On half of the trials, parents were asked to indicate whether the sum of or difference between the dots in the two arrays was more or less than the number of dots in a third array. In the other half of the trials, they indicated which of two arrays contained a number of dots equivalent to the sum of or difference between the number of dots in the two initially presented arrays. Task difficulty was manipulated each session based on past performance by adjusting incorrect answers to be closer or further from the correct response (i.e., making trials more or less difficult) to maintain performance around 70–85% accuracy.

Parent Trivia Training Game—Similar to the control condition used by Park and Brannon (2013), parents were trained to solve general knowledge questions. Sample questions included “What does “pp” on a music score mean? 1) Very Quiet, 2) Quiet, 3) Loud, 4) Very Loud 5) Repeat.” Or “What is a group of toads called? 1) Club, 2) Knot, 3) Group, 4) Hub, 5) Pack.” After each question, parents were told whether their selection was correct or not. When a question was answered incorrectly, the correct answer was not given; instead, the question appeared again on later trials.

Measures

Parents and children each completed a series of standardized tasks in a quiet, one-on-one setting at each lab visit.

Child Skills

Mathematical Skill.: To measure children's mathematical skill, the Test of Early Math Ability-Version 3 (TEMA-3; Ginsburg & Baroody, 2003) was used. The TEMA-3 is a standardized measure of children's number skills, calculation skills, number comparison ability, Arabic numeral literacy, and understanding of numerical concepts, and is normed for children age 3 years 0 months to 8 years 11 months. Psychometric reports by the developers of the TEMA-3 demonstrate excellent internal consistency (with coefficients greater than 0.92) and good test-retest and alternative form reliability (with coefficients greater than 0.80; Ginsburg & Baroody, 2003; Kline, 2000); internal consistency was also acceptable in the present sample (α = .89-.93). Raw scores were used to adequately capture growth over time.

Parent Skills

Mathematical Skill.—To measure parents' mathematical skill, two subtests of the Woodcock-Johnson Tests of Achievement III (Woodcock et al., 2001) were used. Parents first completed the Math Calculation subtest, an untimed test in which they were asked to solve math problems including arithmetic, algebra and calculus. Parents then completed the Math Fluency subtest, a timed test in which they were asked to solve simple arithmetic problems as quickly and as accurately as possible in three minutes. Scores on both subtests were then used to compute a normed Math Calculation Skills Composite Score. The Math Calculation Skills Composite Score has previously been shown to demonstrate excellent reliability with Cronbach's alpha of 0.94 (Woodcock et al., 2001).

Approximate Number System Acuity.—Parents completed a non-symbolic number comparison task similar to that used by Halberda, Mazzocco, and Feigenson (2008). Parents were shown sets of yellow and blue dots varying in size and asked to indicate as quickly and as accurately as possible which color was more numerous by pressing one of two keys on a keyboard labeled with yellow and blue stickers. Parents completed 4 practice trials with preselected stimuli presented in a random order, followed by 150 test trials, including equal number of trials for each of five ratios (1.33, 1.25, 1.2, 1.14, 1.11). Stimuli were displayed for 1500 ms on a 23-inch computer monitor, followed by a blank screen until parents responded. The number of dots in each set ranged from 12 to 36. To avoid the use of perceptual cues instead of number to solve the task, one-third of trials were Correlated (i.e., the side with the larger number also had the larger cumulative area), one-third of trials were Anti-Correlated (i.e., the side with the smaller number had the larger cumulative area but cumulative perimeter was equal) and one-third of trials were Neutral (i.e., the arrays had equal cumulative areas). Performance was quantified as the percentage of correct responses across all trials.

Home Activities

At each lab visit, parents completed a home activities questionnaire which was designed to measure individual differences in the home numeracy environment (LeFevre et al., 2009); however, only questionnaires from Pretest and Post-Test were used. Parents were asked to indicate how frequently they participated in each of 40 activities (e.g., "Identifying names of written numbers," "Identifying sounds of alphabet letters") with their children on a scale from 0 (*did not occur*) to 4 (*almost daily*) in the last month. Of the 40 total activities, 23 were related to mathematics broadly (most of which were related to numeracy, though some were related to measurement and spatial skills such as playing with blocks, building Lego or construction sets, and measuring ingredients while cooking) and 3 were related to literacy. The remaining 14 items pertained to general activities (e.g., "Making collections") or fine-motor skills (e.g., "Buttoning buttons") and were not used in this investigation. Responses to items pertaining to math were averaged to create a "frequency of home math activities" variable; responses pertaining to literacy were averaged to create a "frequency of home literacy activities" variable. Internal consistency was acceptable for the home math activities at Pre-Test (α_{Math} = .80) and Post-Test (α_{Math} = .84). Internal consistency was below accepted norms for the home literacy activities (Pre-Test: $\alpha_{Literacy}$ = .41; Post-Test: $\alpha_{Literacy}$ = .59); however, as literacy activities were included as a contrast for math activities and were ancillary to the purposes of the investigation, the items were retained as written.

Covariates

A series of covariates was included in all tested models. These included indicator variables for whether or not the child was male and whether the primary caregiver had received a Bachelor's degree or higher. Additional covariates included child age and child vocabulary at Pre-Test. Child vocabulary was assessed using the Developmental Vocabulary Assessment for Parents (DVAP; Libertus et al., 2015), a parent-report measure of child vocabulary size for children aged 2 to 7 based on the Peabody Picture Vocabulary Test (PPVT-4; Dunn & Dunn, 2007). The parent was given a list of 212 vocabulary words and was asked to indicate which of those words they had heard their child say. Total number of words was used as a measure of children's vocabulary in analyses. Validity of this measure is reported in Libertus et al. (2015).

Child inhibitory control was assessed using a Day-Night Stroop task (Gerstadt et al., 1994). In this assessment, children were told to say "night" when shown an image of a cartoon sun and "day" when shown a cartoon image of a moon. This required children to inhibit their prepotent association response. Children received 16 trials (8 "day" trials, 8 "night" trials). Children were not given any feedback after responding to a trial. For each trial, children could receive 0, 1 or 2 points for their response. Children received 2 points for a correct response, and 1 point for an incorrect response that they then self-corrected. Children received 0 points for incorrect responses. Scores were averaged to create an aggregate measure ranging from 0 to 2. Past work demonstrates that the Day-Night Stroop task is a reliable measure of young children's interference control that is highly correlated with other measures of inhibition, with correlation coefficients as high as 0.79 (Montgomery & Koeltzow, 2010).

Results

Descriptive Statistics

Descriptive statistics and correlations among study variables are reported in Table 1.

Treatment Randomization

We first sought to test whether there were any baseline differences that existed despite randomization to condition. One-way Analyses of Variance (ANOVAs) revealed that during children's first visit to the lab—two months prior to randomization to condition—there were no systematic differences on the basis of the primary caregiver's ANS acuity ($F(4,152) = 0.66$, $p = .619$) or math skills ($F(4,155) = 0.83$, $p = .508$), nor were there differences on the basis of child math skills ($F(4,147) = 0.87$, $p = .483$) by treatment condition. Finally, we found no significant differences in assignment to treatment condition for planned covariates: Chi-squared tests revealed there was no difference on the basis of whether or not the primary caregiver had received a Bachelor's degree ($\chi^2(4) = 2.22$, $p = .695$) or whether the child was male ($\chi^2(4) = 3.59$, $p = .424$); one-way ANOVAs revealed no difference on the basis of child age ($F(4,158) = 0.88$, $p = .480$), vocabulary ($F(4,156) = 2.20$, $p = .071$), or performance on the Day-Night Stroop task ($F(4,128) = 0.24$, $p = .915$).

We were next interested in whether adherence to training—or fidelity—differed by treatment condition. Each participating parent assigned to a treatment condition (that is, not assigned to the no-treatment control condition) completed a log reporting frequency of engagement in training. Number of trainings ranged from 0 to 18 (M = 8.04; SD = 6.19). There was no difference by treatment condition ($F(3,95) = 1.71$, $p = .170$). As such, number of training sessions parents reported to have completed was not considered as a covariate.

Treatment Effects

To test efficacy of assignment to training condition, we computed two linear regressions, one each predicting TEMA scores at Post-Test (i.e., two months after Assignment) and TEMA scores at Follow-Up (i.e., two months after Post-Test). TEMA scores at Post-Test and Follow-Up were regressed on treatment condition (with "no training" as reference group) to test treatment effects; TEMA scores at Pre-Test were included as a covariate to estimate change in mathematical skills due to training over and above stability. Additionally, outcomes were regressed on a set of control covariates (i.e., indicator variables for whether or not the child was male and whether the primary caregiver had received a Bachelor's degree or higher; continuous variables for child age, vocabulary, and inhibitory control). Data were determined to be missing completely at random conditional upon included covariates, $\chi^2(14) = 12.86$, $p = 0.538$ (Li, 2013; Little, 1988). Models were estimated in MPlus 8.0 (Muthén & Muthén, 2017) and missing data were accounted for using Full Information Maximum Likelihood estimation (Enders, 2001). The analytic sample included all dyads who participated in at least one wave of data collection (i.e., N = 162).

Treatment Effects on Child Math Skills at Post-Test—Results of the linear regression testing treatment effects at Post-Test are shown in Column 1 of Table 2 and are shown visually in Figure 2. Children of parents randomized to the parent–child number board game improved math skills relative to children in the no-training control condition, $b = 2.98$, $p = .021$. That is, children who played the parent–child number board game answered, on average, three more questions correct on the TEMA (over 15% of a standard deviation) than did children who were in the no-training control condition, controlling for scores at pre-test. In contrast, children of parents in the other training conditions (parent

ANS training, parent trivia training, parent–child shape board game) did not differ from those in the no-training control condition in their TEMA scores ($-1.21 < bs < 1.27$, $ps > .339$).

Treatment Effects on Child Math Skills at Follow-Up—Results are shown in Column 2 of Table 2 and are shown visually in Figure 2. In contrast to results at Post-Test, gains in TEMA scores for children in the parent–child number board game did not persist to Follow-Up. Compared to the no-training control condition, only children of parents in the parent ANS training condition differed; those children whose parents participated in the parent ANS training condition demonstrated lower math skills than did those in other conditions, $b = -2.91$, $p = .024$, such that they answered, on average, three fewer questions correct on the TEMA than did participants in other groups.

To better understand this iatrogenic effect (wherein we found negative effects contrary to our hypothesized direction), we further examined effects of condition on parents' math abilities and ANS acuity (rather than children's) at Follow-Up. We used the same analytic approach as described above wherein the outcome measure from Follow-Up was regressed on treatment condition (with "no training" as the reference group) and performance on the same measure during Pre-Test to estimate change due to training over and above stability. Only the covariate relevant to parents (i.e., completion of Bachelor's degree or higher) was included; those pertaining to child (i.e., age, sex, vocabulary, inhibitory control) were not. Specifically, we were interested in whether being assigned to a parent training condition led to change in parents' cognitive skills, namely ANS acuity and mathematical skills. Results are presented in Table 3. Indeed, we found a marginally significant effect of training condition on parents' ANS acuity such that being assigned to the parent ANS training condition resulted in approximately a fifth of a standard deviation increase in performance on the ANS acuity task as compared to the no-training control, $b = 0.05$, $p = .051$. There was no effect of condition on parent symbolic math skills. To determine whether gains in ANS had any effect on child math skills, we computed a latent change score to estimate the change in parent ANS acuity from Pre-Test to Post-Test. There was no direct effect of change in parent ANS acuity on child math skills ($b = -0.93$, $p = .890$). Tests of indirect effects with 1000 bootstraps revealed no indirect effect of assignment to the parent ANS training condition to change in child TEMA scores via change in parent ANS acuity ($b = -0.002$, 95% CI [−.59,.45]).

As negative effects of parent training condition on child math were not attributable to changes in parent skills, we then sought to investigate ways in which assignment to training condition might have had unanticipated consequences for children's home learning environments. To test this, we used data from parent-reported home activities completed at each visit. We computed two latent change scores to estimate change in home numeracy and home literacy activities from Pre-Test to Post-Test and tested direct (change in activities on math skills) and indirect effects (training effects on math skills through change in activities) with 1000 bootstraps. The amount of change in reports of both math and literacy activities did not appear to differ by condition for either numeracy or literacy ($ps > .240$), although interestingly both increased over time ($ps < .001$). In turn, change in parent-reported math activities was related to child TEMA scores ($b = 3.36$, $p = .002$) such that a 1 SD increase in math activities corresponded to over a 3-point gain in TEMA scores; change in parent-reported literacy activities was not related to TEMA scores ($b = 0.90$, $p = .127$). Despite non-significant pathways from training to change in math activities, a significant indirect effect of assignment to the parent ANS training condition on child TEMA scores via changes in math activities emerged ($b = -0.61$, 95% CI [−1.56,−0.10]). Furthermore, when controlling for changes in home math activities, the negative effect of assignment to parent training condition was reduced such that it was no longer different from zero ($b = -1.69$, $p = .098$), suggesting changes in home math activities fully mediated the negative effects of parent ANS training condition. In contrast, there was no indirect effect through changes in literacy activities ($b = -0.29$, 95% CI [−1.12,0.02]). Results are depicted visually in Figure 3.

Discussion

The goal of this study was to assess whether environmental influences—namely parents' math skills and the home numeracy environment—are causally related to the development of young children's mathematical skills. To test this, parent–child dyads were randomly assigned to one of four training conditions (contrasted with a no-training control condition), two of which targeted parent skills and two of which targeted parent–child interactions. Within each of the parent skill and the parent–child interaction conditions, one condition was specifically designed to improve age-appropriate mathematical skills (i.e., parents' approximate number system acuity and children's counting abilities, respectively) and the other served as an active control. We hypothesized that the two intervention conditions that targeted parents' and children's math skills would improve children's mathematical skills relative to the two active control conditions and the no-training control. Specifically, we explored whether these improvements would occur via changes in the home numeracy environment.

Our hypotheses were partially supported, though only for the parent–child interaction condition. Immediately after training completion, children in the parent–child number board game condition outperformed those in the no-training control condition; however, positive effects of condition faded out by Follow-Up two months later. In contrast and contrary to our hypotheses, children of parents randomly assigned to the parent ANS training condition significantly *underperformed* their peers in the no-training control condition by Follow-Up. This negative association appears to be fully mediated by a change in parent-reported home numeracy environment. Unsurprisingly, randomization to either of the non-numerical training conditions (i.e., the parent trivia condition and parent–child shape board game condition) did not result in discernable differences in child mathematical skill from the no-treatment control.

Dyadic Interaction around Math Supports Math Learning

Prior studies (e.g., Elofsson et al., 2016; Ramani & Siegler, 2008, 2011; Siegler & Ramani, 2009; Whyte & Bull, 2008) have demonstrated the efficacy of board games as a tool to improve children's mathematical skills; however, extant studies have implemented game play in classrooms and laboratory settings with researchers, paraprofessionals, and teachers as play partners. This study marks an important transition to exploring the causal effects of board game play in the home with parents as play partners. Consistent with prior studies we found that playing a simple math game that prompted skills broadly associated with number sense (e.g., counting, understanding of cardinal values, symbol identification, one-to-one correspondence) improved children's mathematical skills to a greater extent than did other training conditions or no training. That randomization to the parent–child number game condition corresponded to an average three-point increase on a standardized test of mathematical skill suggests that sometimes an easy, fun intervention can have meaningful effects.

Despite improved performance on a standardized test of mathematical skills as compared to a no-training control condition, effects were non-significant eight weeks after training had stopped. There are several reasons this might be the case. First, it is possible that some effects were sustained but that the current study is underpowered to detect an effect of that size. A post-hoc power analysis revealed that a simple analysis of group differences with repeated measures given a sample of this size was approximately 0.60, far below commonly accepted thresholds. Results of an analysis with a larger sample might have reached conventional levels of statistical significance with regard to effects of parent–child number game being sustained through Follow-Up (albeit attenuated). Either way, it is important to note that participants returned their assigned training games at Post-Test and therefore did not play them between Post-Test and Follow-Up; it is likely critical to sustain the intervention in order to see sustained gains in mathematical skills.

The findings of short-term effects echo those of some successful home training studies that have relied upon parent–child interaction, though they are contrary to others. Using a parent–child card game, Scalise and colleagues (2022) found no effects of randomization to a number game condition as compared to a shape game condition. However, there may be something critical to the inherent embeddedness of a number line in board games or to connecting number words with physical actions (de Vries et al., 2021; Siegler & Ramani, 2009; Whyte & Bull, 2008). Concerning a more closely matched paradigm, we find positive effects of the parent–child board game condition whereas Sonnenschein and colleagues (2016) failed to find effects of a similar intervention. While we use a different counterfactual condition (a no-training control rather than a different board game), it is unlikely that is the reason for the difference in findings: Children assigned to the parent–child number game outperformed those in the parent–child shape board game by approximately 2.5 points at Post-Test ($b = -2.59$, $p = .028$). It is possible that the present study was better powered to detect a smaller effect or, alternatively, that the scripted nature of game play in the study by Sonnenschein et al. (2016) limited the extent to which parents could adapt game play to meet the child's needs.

On the other hand, our findings support those of other parent–child interaction studies. For example, Gibson and colleagues (2020) randomly assigned children and parents to a picture book whose text specifically referenced number and depicted a numerical match between text, objects, and Arabic numerals. Children in this number book condition had improved understanding of number words as compared to children in the control condition. It is likely that by receiving repeated practice engaging with number words and set sizes (e.g., by seeing, counting, and discussing number words in the context of a picture book or in the current study, by moving a token the number of spaces that appear on a spinner), children might gain greater understanding of number symbols, counting, and cardinality than by engaging with adjectives or colors. Similarly, Berkowitz and colleagues (2015) found that randomization to a tablet-based instructional application to be used by parent–child dyads which focused on mathematics (as opposed to reading) resulted in improvements in children's mathematical skills. While the tablet intervention was designed for older children (first grade, or approximate age 6.5 years), effects might have been due to a similar mechanism wherein there was simply increased attention to and practice with numerical information in the home. Importantly, both studies by Gibson et al. (2020) and Berkowitz et al. (2015) found moderations of treatment effects (Gibson et al. by children's number understanding at the start of the study; Berkowitz et al. by parents' math anxiety), suggesting the main effects reported here might be masking heterogeneity of treatment by other factors. Further investigation is needed to better understand the role of children's baseline knowledge in mathematical skill and parent characteristics that might result in differential development from the same instructional material.

As a potential corollary to the positive effects of parent–child number games, we found a negative effect of a parent ANS training condition (relative to a no-training control condition), which was fully mediated by a change in the home numeracy environment. One possible explanation for these unexpected findings lies in the indirect effects seen through parents' engagement in math activities whereby parents in the ANS training condition engaged in less mathematically relevant play with their child. However, this fails to address why parent ANS training might have affected the home numeracy environment. On the one hand, parents may have found the training games to be burdensome, particularly for the ANS condition, and this additional demand may have decreased parents' time to engage in math activities with their children. Alternatively, the game was designed to be challenging and included feedback on performance, which may have inadvertently shifted parents' attitudes about math, math confidence or motivation to engage in math activities and in turn affected their interactions with their children. Given that these negative impacts were unique to the parent ANS training and not the parent trivia training condition, which required the same time of parents, we suspect the latter explanation may be more likely. Surprisingly, although the parent–child number game condition effects were observed at Post-Test but faded out by the Follow-Up assessment, the opposite was true of these negative effects of parent ANS training, suggesting that the mechanism underlying these effects may be more gradual. Alternatively, it is possible that—as with the lack of sustained positive effects of the parent–child number board game training—the present study is simply underpowered to detect a small negative effect of training at Post-Test. Although we are unable to determine the cause of these unexpected negative findings, we find them concerning. Further study is needed to investigate potential sources of these negative effects, including effects of training on attitudinal characteristics and on parents' time.

Short-Term Parent ANS Training Does Not Relate to Child Math Learning

There has been some correlational evidence to suggest that parent math skills are transmitted to their children. Several studies have found that—above and beyond factors including sociodemographic characteristics—parents who are better at math tend to have children who are better at math (e.g., Borriello et al., 2020; Braham & Libertus, 2016; Brown et al., 2011; Navarro et al., 2018), though little is known about the mechanisms of transmission and the extent to which it might be purely about shared environment. One recent investigation using a behavioral genetics approach found that both parent skills and the home environment played a role in the development of mathematical skills. Using a sample of children living with non-relative adopted families since before the age of three months, Borriello and colleagues (2020) found that both birth parents' mathematical skills and adoptive fathers' mathematical skills were correlated with children's skills, suggesting some support for both a genetic and environmental component to individual differences in children's skills.

Results from the present study complement these findings insofar as they suggest intergenerational transmission of parent to child math skills does not operate at a rapid pace. In other words, immediate increases in parents' ANS acuity may not be sufficient to lead to hypothesized changes in parents' behavior whereby they would be more likely to engage with mathematical information, games, and toys. Rather, frequency of engagement is likely rooted in habit, dyadic routines, and available time. It is possible that encouraging parents to engage more in individual training resulted in less available time to play with their child. Although we find that randomization to the parent ANS training condition was actually negatively related to children's math skills, we do not assume that these results indicate true negative intergenerational associations. Despite the fact that we did see improvement in parent ANS acuity as a result of randomization to the parent ANS training condition, changes in ANS did not mediate associations between condition and children's math skills, suggesting that the increases in ANS acuity parents gained from training were not associated with children's math skills. As noted above, this effect was instead fully explained through differences in the home numeracy environment. It remains possible the experimental manipulations of other aspects of parent math, such as symbolic math skills or math attitudes, could positively relate to children's math outcomes, or that these causal pathways may be stronger at different developmental stages. Alternatively, to the extent that these intergenerational links found in prior work reflect genetic transmission, experimental manipulations in parents' math skills would have no consequences for children's learning, as the process through which these skills are transmitted has already occurred. In sum, although we did not find evidence that parents' ANS acuity was causally linked to children's math skills, we cannot conclude that no causal pathways might exist between parents' and children's math skills.

Limitations

Despite several strengths of this study, there are a number of limitations that warrant discussion. First, the study was underpowered to detect small effects that might result from simple, low-cost interventions such as these. As such, results should be interpreted as exploratory; it is possible that given a larger sample, other training conditions might have yielded effects (positive or negative) on children's math skills or that effects of the parent–child number game might have been sustained through Follow-Up; indeed, a visual analysis of Figure 2 suggests the parent trivia training might also have had an iatrogenic effect and that effects of the parent–child number board game continue but are slightly attenuated. However, given that the direction and magnitude of effects that resulted from randomization to the parent–child number board game condition are consistent with those from prior studies (e.g., Elofsson et al., 2016; Ramani & Siegler, 2008, 2011; Siegler & Ramani, 2009; Whyte & Bull, 2008), we are cautiously optimistic about this approach as an effective intervention for improving young children's math skills.

Second, it is important to note the homogeneous group of parents and children enrolled in the study. Nearly 90% of participating primary caregivers were white, and over 80% had a Bachelor's degree or higher. This is clearly not representative of a broader worldwide or US population, nor even is it representative of the county in which most participants resided. While we suggest there may be evidence for the efficacy of math games for young children as a way to support mathematical skill development, further investigation is needed to better understand how these effects might be accentuated or attenuated in other groups of participants.

Third and finally, we recognize that there are likely omitted variables that might have contributed to results from this study. While treatment randomization minimized baseline differences among groups on assessed characteristics, it is still possible that there were unintended systematic differences among other unmeasured baseline characteristics. Additionally—and inherent to low-touch interventions such as this—it is possible that treatment fidelity differed across groups in ways beyond those we tested here. While the number of parent-reported training sessions did not differ between groups, there may still have been differences in the ways in which games were played (as compared to how they were designed or intended to be played) or the amount of time dedicated to games within training sessions. Likewise, it is possible that there were attitudinal differences that emerged over the course of training (e.g., if participants in one condition found that game play was more fun or engaging than did those in another). However, the limited control over fidelity to treatment is also one of the strengths of this study. That we found children's math skills improved as a result of randomization to the parent–child number game condition suggests that even with limited oversight, this might be an efficacious way to provide supports for young children's math skill development.

Conclusions

In spite of these limitations, results from this study show the promise of low-touch, low-cost interventions to improve young children's mathematical skills. While further research is needed to better understand generalizability and/or specificity of these findings, our results —building upon the work of others who have found similar effects (e.g., Elofsson et al., 2016; Ramani & Siegler, 2008, 2011; Siegler & Ramani, 2009; Whyte & Bull, 2008)— suggest that introducing families to simple games that promote parent–child engagement around mathematically meaningful play can promote math learning in fun, natural contexts. There is now repeated evidence of positive findings of similar interventions, and the time may be ripe to further sow the seeds of mathematical play. Programs such as "Reach Out and Read" have been operating to improve access to literacy materials for over 30 years (Zuckerman, 2009); the time has come to similarly improve access to research-based games that promote mathematical play.

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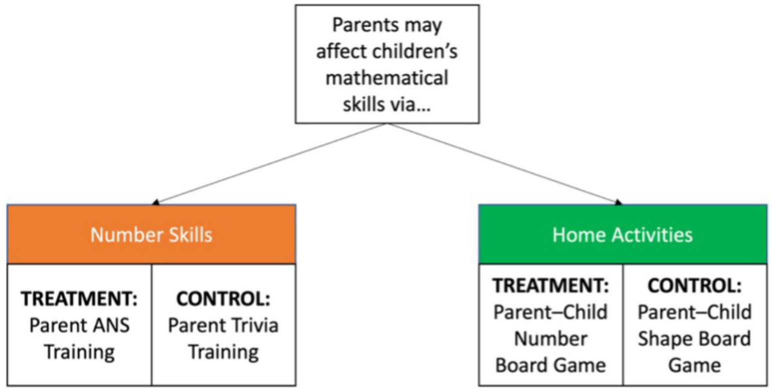

Figure 1:
Visual depiction of assigned training conditions.

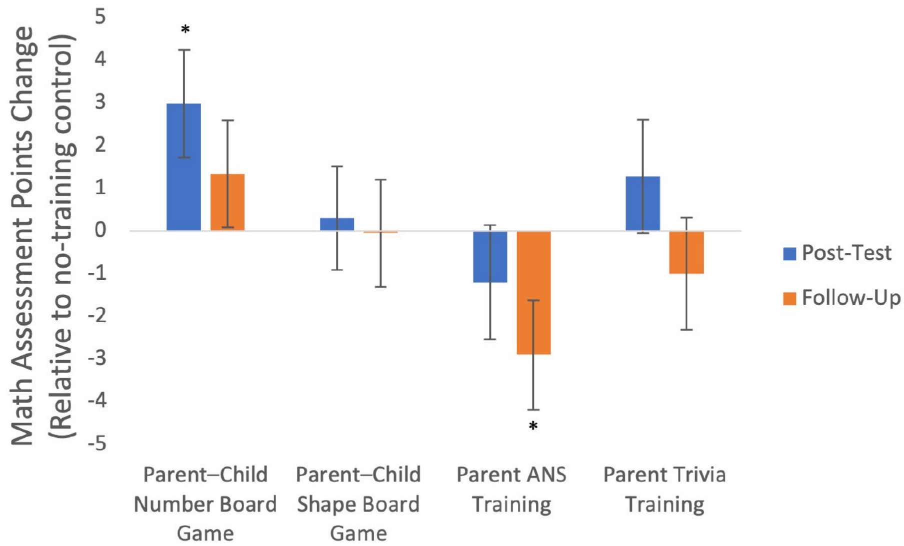

Figure 2:

Child TEMA Scores in the four active training conditions at Post-Test and Follow-Up relative to the no-training control condition

NOTE: * denotes significant difference from no-training control, $p < .05$

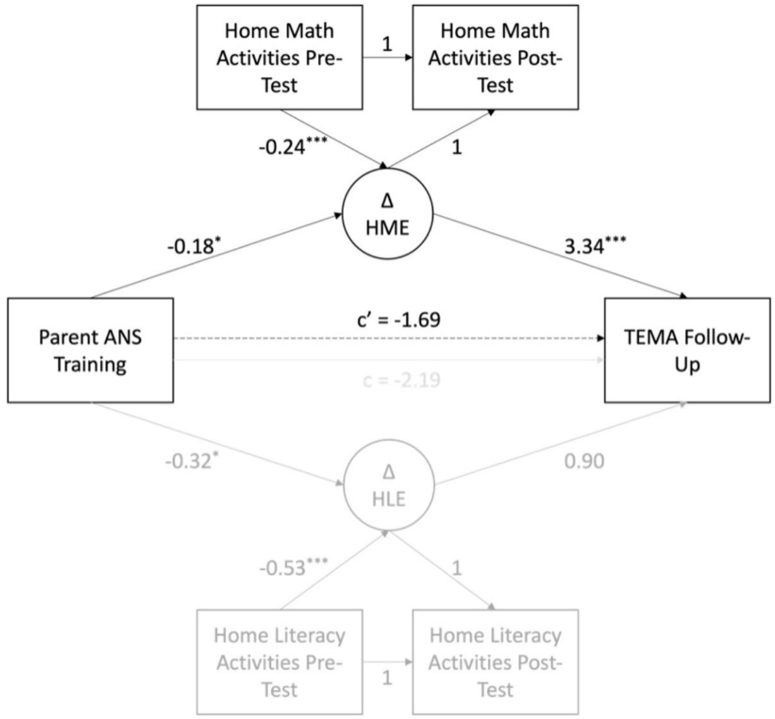

Figure 3:

Mediation model depicting change in home math environment as mediating the negative relation between parent ANS training and child TEMA scores

NOTE: *** $p < .001$, ** $p < .01$, * $p < .05$; HME—Home Math Environment; HLE—Home Literacy Environment; ANS—Approximate Number System; TEMA—Test of Early Mathematical Ability; Covariates included: TEMA pre-test score, alternate treatment conditions, child vocabulary, child age, parent ≥ bachelor's degree

Table 1.

Descriptive statistics and bivariate correlations among measures

		1	2	3	4	5	6	7	8
1	TEMA Score Pre-Test	—							
2	TEMA Score Post-Test	0.79***	—						
3	TEMA Score Follow-Up	0.78***	0.88***	—					
4	Child Vocabulary	0.03	−0.03	−0.05	—				
5	Child Inhibitory Control	0.29**	0.22*	0.21*	0.03	—			
6	Math Activities Pre-Test	0.14	0.24**	0.09	0.16	−0.05	—		
7	Literacy Activities Pre-Test	0.25**	0.20*	0.18*	0.03	0.00	0.48***	—	
8	Child Age	0.02	0.07	0.04	−0.06	0.01	−0.10	−0.19*	—
	N	152	123	129	140	133	161	161	162
	Mean	10.23	16.23	16.99	104.42	1.31	1.64	2.91	3.91
	SD	5.55	7.34	7.60	27.70	0.55	0.50	0.84	0.06
	Range	0 – 27	1 – 43	2 – 43	44 – 182	0 – 2	0.73 – 2.96	0.67 – 4.00	3.75 – 4.04

NOTE:

*** $p < .001$

** $p < .01$

* $p < .05$

Table 2.

Regression Results Testing Effects of Treatment Condition on Child Math Skills at either Post-Test or Follow-Up

	Post-Test			***Follow-Up***		
	b	***SE***	***p-value***	***b***	***SE***	***p-value***
TEMA Score Pre-Test	**1.04**	**0.08**	**< .001**	**1.02**	**0.08**	**< .001**
Parent–Child Number Board Game	**2.98**	**1.27**	**.019**	1.33	1.26	.290
Parent–Child Shape Board Game	0.30	1.22	.807	−0.06	1.25	.963
Parent ANS Training	−1.21	1.34	.366	**−2.91**	**1.29**	**.024**
Parent Trivia Training	1.27	1.33	.339	−1.01	1.31	.443
Child Vocabulary	0.02	0.02	.324	0.02	0.02	.106
Child Inhibitory Control	0.64	0.77	.406	0.45	0.75	.549
Child Male	1.18	0.82	.150	1.02	0.81	.206
Child Age	−3.20	4.61	.487	0.96	4.68	.838
Parent ≥ Bachelor's Degree	−0.02	0.89	.980	−1.11	0.89	.214

NOTE: Bold—p < .05; ANS—Approximate Number System

Table 3.

Regression Results Testing Effects of Treatment Condition on Parent Math Skills

		Post-Test			Follow-Up		
		b	***SE***	***p-value***	***b***	***SE***	***p-value***
Parent ANS	Pre-Test Parent ANS	*0.21*	*0.12*	*.067*	**0.29**	**0.08**	**< .001**
	Parent–Child Number Board Game	−0.01	0.02	.579	0.07	0.11	.533
	Parent–Child Shape Board Game	−0.01	0.02	.556	−0.05	0.11	.667
	Parent ANS Training	0.02	0.02	.321	*0.20*	*0.10*	*.051*
	Parent Trivia Training	0.02	0.03	.448	0.19	0.11	.077
	Parent ≥ Bachelor's Degree	−0.02	0.02	.338	0.03	0.08	.752
Parent Math	Pre-Test Parent Math Skills	**0.95**	**0.04**	**< .001**	**1.03**	**0.05**	**< .001**
	Parent–Child Number Board Game	−1.76	1.33	.186	0.45	1.72	.795
	Parent–Child Shape Board Game	−0.23	1.34	.867	1.32	1.72	.442
	Parent ANS Training	0.04	1.34	.974	0.59	1.76	.736
	Parent Trivia Training	−1.10	1.40	.434	0.12	1.82	.947
	Parent ≥ Bachelor's Degree	−0.39	0.92	.671	−1.49	1.18	.209

NOTE: Bold—$p < .05$; Italicized—$p < .07$; ANS—Approximate Number System