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Children's Math Anxiety Predicts Their Math Achievement Over and Above a Key Foundational Math Skill

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ABSTRACT

Math anxiety negatively predicts young children's math achievement. While some researchers have suggested that math anxiety may stem from poor math ability, others have argued that math anxiety occurs at all levels of math ability. An important question is whether math anxiety predicts math achievement over and above foundational math skills. We sought to address this issue by examining whether math anxiety predicts future math achievement, controlling for number line estimation, a foundational math skill that predicts future math achievement. We found that 1st graders' math anxiety predicts their math achievement in 1st through 3rd grade, controlling for their number line estimation at the beginning of 1st grade. This finding suggests that math anxiety contributes to future math learning over and above an important foundational math skill. Additionally, we examined whether there are age differences in the relation of first-grade math anxiety to number line estimation at various scales in order to test the hypothesis that the negative effect of early math anxiety on math performance depends on task difficulty. In support of this hypothesis, early math anxiety more closely related to the 0–100 number line task in 1st graders but to the 0–1000 number line task in 3rd graders, suggesting that math anxiety most strongly relates to math skills that are at the cusp of children's understanding at particular grade levels. Together, these findings underscore the importance of fostering young children's positive emotions toward math in addition to providing them with a strong cognitive foundation for math learning.

The cognitive underpinnings of mathematics development have been extensively examined. One well-known line of research has implicated children's understanding of numerical magnitudes, commonly measured through number line estimation tasks, in their math competence (e.g., Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Booth & Siegler, 2008; Case & Okamoto, 1996; Fazio, Bailey, Thompson, & Siegler, 2014; Gunderson, Ramirez, Beilock, & Levine, 2012; Hoffmann, Hornung, Martin, & Schiltz, 2013; Lyons, Price, Vaessen, Blomert, & Ansari, 2014; Siegler & Booth, 2004). Another line of research has shown that children's math competence is associated with factors beyond foundational cognitive skills. Notably, children's math anxiety negatively relates to their math achievement as early as 1st grade (Gunderson, Park, Maloney, Beilock, & Levine, 2018, 2016; Ramirez, Gunderson, Levine, & Beilock, 2013).

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To date, these two lines of research have not been well integrated, and there are many open questions about how foundational math skills, as well as math anxiety relate to future math achievement. Here we begin to address such questions by asking whether children's early math anxiety (in the fall of 1st grade) predicts their future math achievement (through 3rd grade), controlling for the linearity of their early number line representations (in the fall of 1st grade). One possibility is that math anxiety and number line estimation account for the same variance in future math achievement. However, we hypothesized that math anxiety would matter for children's math achievement, over and above their number line estimation, and that these two factors together would account for significantly more variation in future math performance than number line estimation alone.

The relation of math anxiety and math achievement

Math anxiety, a common phenomenon across the globe (Foley et al., 2017), is defined as the fear or apprehension people experience when doing, or even thinking about, math-related activities (Lyons & Beilock, 2012; Richardson & Suinn, 1972). Math anxiety has been shown to interfere with adults' ability to solve math problems both in daily life and in academic situations (Ashcraft, 2002; Beilock, Schaeffer, & Rozek, 2017; Hembree, 1990; Richardson & Suinn, 1972). Moreover, the negative relation between math anxiety and math performance arises early, affecting children as early as 1st grade (Gunderson et al., 2018, 2016; Ramirez et al., 2013; Wu, Barth, Amin, Malcarne, & Melon, 2012).

Some researchers have argued that math anxiety may stem from poor math ability (Carey, Hill, Devine, & Szücs, 2016; Fennema, 1989; Ramirez, Shaw, & Maloney, 2018). For example, Ma and Xu (2004) reported that early math performance consistently predicted later math anxiety in 7th through 12th graders, while the reverse relation – that early math anxiety predicted later math performance – was hardly present. In young elementary school students, Gunderson et al. (2018) found that the relation between fall math performance and spring math anxiety was stronger than the reverse relation, but both of these links were significant, suggesting a bidirectional relation.

Also suggesting that math anxiety may stem from weak math skills, adults' math anxiety is related to basic numerical processing skills, such as counting objects (Maloney, Risko, Ansari, & Fugelsang, 2010) and identifying the larger of two single-digit numbers (Dietrich, Huber, Moeller, & Klein, 2015; Maloney, Ansari, & Fugelsang, 2011). Additionally, math anxiety has been found to mediate the relation between adults' magnitude comparison (a skill further discussed below) and their math performance (Lindskog, Winman, & Poom, 2017), at least in high math-anxious adults (Maldonado Moscoso, Anobile, Primi, & Arrighi, 2020), suggesting that math anxiety may play a central role in the relation between ANS and math performance. However, these findings are not consistent as other studies have found no relation between math anxiety and ANS in children and adolescents (Hart et al., 2016; Wang et al., 2015), as well as in adults (Braham & Libertus, 2018; Dietrich et al., 2015). Thus, there are discrepant results that need to be resolved regarding the relation of math anxiety, ANS, and math performance.

In contrast to the view that math anxiety may stem from poor math skills, research with both adults and children suggests that math anxiety can cause poor math performance. For instance, math anxiety has been found to negatively relate to math performance because it takes up working memory resources (e.g., Ashcraft & Kirk, 2001; Ramirez et al., 2013).

Further, some studies have found that math anxiety is most detrimental to individuals with high working memory capacities (Beilock & DeCaro, 2007; Ramirez et al., 2013). Math anxiety may lead to individuals with high working memory to adopt less efficient strategies when they solve math problems. For example, children with high working memory capacity who were math-anxious adopted less efficient, error-prone finger counting strategies, which are typically used by children with lower working memory (Ramirez et al., 2016)

Regardless of the causal connection between math anxiety and math performance, an important question is whether both math anxiety and foundational math skills uniquely contribute to variance in children's math performance. Here we hypothesized that children's math anxiety would explain variance in their math achievement, over and above a foundational math skill. We tested this hypothesis by examining whether math anxiety predicts children's math achievement over and above a foundational math skill that has been found to be predictive of their math achievement: the linearity of children's number line estimation.

The relation of number line estimation and math achievement

The existence of numerical magnitude representations in humans has been extensively examined. Humans and other species have an approximate number system (ANS) through which they represent number magnitudes in an analog and continuous form (Dehaene, 1997; Gallistel & Gelman, 1992). Supporting this view, it is easier for people to distinguish between quantities that are farther apart than those that are closer together (known as the numerical distance effect; Moyer & Landauer, 1967). Additionally, people – at least those in cultures with left to right writing systems – respond to small numbers more quickly with their left hand and large numbers more quickly with their right hand, reflecting a spatial representation of numerical magnitudes, known as the spatial numerical association of response codes (SNARC effect; Dehaene & Changeux, 1993). A recent meta-analysis reported a positive relation between children's ANS acuity and their math achievement (Chen & Li, 2014; but see Leibovich & Ansari, 2016). Children's ability to represent numerical magnitudes is often measured with a number line estimation task.

In a typical number line task, participants indicate the position of a given number on a line that is anchored at both ends, usually with 0 on the left side and a multiple of 10 on the right. Initially, even for number lines that are relatively small in scale, young children place smaller numbers too far apart and larger numbers too close together, which has been characterized as a logarithmic representation of numbers on a number line (Siegler & Braithwaite, 2017; Siegler & Opfer, 2003; Siegler, Thompson, & Schneider, 2011; but see Barth & Paladino, 2011). Over time and with formal schooling children are able to succeed on number line tasks, placing numbers along the number line in a linear manner. Importantly, they are able to do this successfully for number lines with smaller more familiar right anchors prior to succeeding on placing numbers in a linear manner on number line tasks with larger, less familiar right anchors. The shift to a linear representation of numbers has been found to occur before kindergarten on a 0–10 scale, from kindergarten to 2nd grade on a 0–100 scale, and from 2nd grade to 4th grade on a 0–1000 scale (Berteletti et al., 2010; Booth & Siegler, 2006; Siegler & Booth, 2004; Siegler & Opfer, 2003).

Number line estimation predicts later performance on math problem solving, arithmetic, calculation, and math achievement more broadly (Booth & Siegler, 2008; Gunderson et al., 2012; Lyons et al., 2014; Siegler & Booth, 2004). Additionally, number line estimation correlates with other measures of estimation such as measurement, knowledge of symbolic numbers and numerical order, counting ability, and number comparison (Berteletti et al., 2010; Booth & Siegler, 2006; Fazio et al., 2014; Hoffmann et al., 2013); and engaging in number line estimation activates brain regions associated with numerical magnitude and spatial processes (Berteletti, Man, & Booth, 2015). Further, number line performance mediates the relation between ANS acuity in kindergarten and arithmetic skill in 1st grade (Wong, Ho, & Tang, 2016), and is more strongly related to broad mathematical competence than numerical magnitude comparison or working memory (Schneider et al., 2018). The relation between number line estimation and math competence is robust, as it is found using various accuracy measures of number line estimation and various measures of math performance, suggesting that number line estimation taps into a foundational understanding of number that is broadly important for mathematical thinking (Gross et al., 2018; Schneider et al., 2018). In a meta-analysis, Schneider et al. (2018) reported a strong association between number line estimation and math competence (r = 0.441), with 19.6% of the variance in math competence being explained by number line estimation.

While number line estimation explains some of the variance in children's math performance (19.6%; Schneider et al., 2018), there is considerable variation that is not explained by this foundational skill. To gain a better understanding of how children's math achievement develops, we need to consider cognitive factors that have consistently been found to be important (e.g., number line estimation), while also examining the role of non-cognitive factors, particularly children's math anxiety, which have also been associated with math performance. In this study, we strive to provide a more complete picture of children's math development by examining whether math anxiety predicts children's math achievement, controlling for their number line estimation. If math anxiety does not explain additional variance in children's math achievement over and above their number line estimation, that would suggest that math anxiety may reflect the strength of children's foundational math skills. However, if math anxiety accounts for additional variance in math achievement over and above their number line estimation, this would suggest that both foundational math skills and positive emotions about math contribute to math achievement.

The relation of math anxiety to math tasks of varying complexity

In addition to examining whether math anxiety plays an important role in children's math achievement, it is also important to examine whether children's math anxiety matters for performance on all math tasks, or whether it matters more for particular math tasks. Existing findings suggest that math anxiety is more detrimental to performance on complex math tasks, compared to simple math tasks, and that this is the case for adults and children. For example, adults' math anxiety has been found to matter more for complex arithmetic problems involving calculations, and less for simple arithmetic problems involving memory retrieval (Ashcraft & Faust, 1994; Faust, Ashcraft, & Fleck, 1996). Similarly, 2nd and 3rd grade children's math anxiety has been found to negatively predict performance on calculations, but not geometric reasoning (as assessed by a simple task in which children described, compared and classified shapes; Vukovic, Kieffer, Bailey, & Harari, 2013). Additionally, in a meta-analysis Namkung, Peng, and Lin (2019) found that math anxiety is more strongly related to children's performance on advanced math tasks that require multiple steps to complete than simpler math tasks. However, in these studies the math tasks children completed differed not only in their complexity, but also in their format, making it difficult to rule out the possibility that the format of the math tasks, rather than task complexity plays a role in how math anxiety relates to math performance. To address this issue, it is important to use a particular math task and systematically manipulate its complexity.

One study has examined the relation between math anxiety and math performance on a task that can be adjusted to be simpler or more complex, while remaining the same in structure. In a study of adults, Núñez-Peña, Colomé, and Aguilar-Lleyda (2018) found that math anxiety negatively predicted performance on a number line task with less familiar anchors, but not performance on a number line task with more familiar anchors. Similarly, adults' math anxiety has been found to predict fraction number line estimation (Sidney, Thalluri, Buerke, & Thompson, 2019), which could be considered a complex number line estimation task. However, this approach of manipulating math task complexity while keeping the structure of the task the same – as opposed to changing the format of the math task entirely – to examine how the relation between math anxiety and math performance depends on task complexity has not been used in studies of children.

In the current study, we address this question by examining the relation of children's math anxiety to performance on number line tasks that vary the magnitude of the rightmost anchor, which changes the range over which children must estimate their number placements. Additionally, we assessed children longitudinally from 1st grade through 3rd grade, an age range that has been shown to perform differently on number line tasks involving different scales (Booth & Siegler, 2006; Siegler & Booth, 2004; Siegler & Opfer, 2003). Importantly, because the structure of number line tasks remains constant as the task difficulty changes, number line estimation is an ideal task to use to examine how math anxiety relates to math performance over a developmental period when the difficulty of particular number line tasks changes.

We predicted that children's math anxiety would be particularly harmful for performance on challenging math tasks because math anxiety takes up working memory resources that are necessary for solving complex math problems (e.g., Ashcraft & Kirk, 2001; Ramirez et al., 2013). For very easy tasks, it is possible that the ruminations that math-anxious children have about their math performance may not interfere with performance because children still have adequate working memory resources to succeed at these tasks. For very difficult tasks on which even low math-anxious children do not place numbers in a linear manner, (e.g., a 0–1000 number line task for a 1st grader), math anxiety is also unlikely to contribute to performance because working memory resources are not a determinative factor in predicting their performance. Thus, it is possible that the relation between math anxiety and number line performance will be most marked for the scale that is at the cusp of children's skill at each grade level (i.e., is neither too easy nor too difficult).

We hypothesized that math anxiety would relate to performance on number line tasks with smaller scales in earlier grades and number line tasks with larger scales in later grades, in line with the idea that math anxiety is most detrimental to performance on math tasks at particular levels of difficulty. Such a finding would indicate that the relation between math anxiety and math performance may have reverberating negative effects on math learning, interfering with the learning of new skills and concepts at successive grade levels.

The current study

We assessed children's math anxiety, number line estimation on a 0–100 and a 0–1000 scale, and math achievement across five timepoints (1st grade fall and spring; 2nd grade fall and spring; 3rd grade fall) to better understand how these variables relate to each other and change over time. We address the following two questions. First, does math anxiety predict future math achievement, controlling for number line estimation? Second, does the relation between early math anxiety and number line estimation on different number line scales change over time?

Regarding our first question, we hypothesized that 1st grade math anxiety would remain a significant predictor of future math achievement, controlling for number line estimation, which would support the theory that math anxiety does not simply stem from poor math ability, but rather negatively contributes to math achievement over and above a foundational math skill. Regarding our second question, we hypothesized that 1st grade math anxiety would negatively predict number line estimation on a 0–100 scale when children are younger (in 1st grade), and on a 0–1000 scale later, when children are older (in 3rd and perhaps 2nd grade) reflecting the fact that these number line tasks are appropriately complex at these grade levels (i.e. not too simple and not too difficult).

Method

Participants

The data analyzed in the current study were collected as part of a larger longitudinal randomized control trial, examining the effectiveness of a math app that parents and children engaged with to support children's math learning (Berkowitz et al., 2015; Schaeffer, Rozek, Berkowitz, Levine, & Beilock, 2018). A demographically diverse sample of 1st graders and their primary caregivers were recruited and followed longitudinally. Families were randomly assigned to an intervention (math) or control (reading) condition. In the current study, our analyses examined participants in the control condition, from the fall of 1st grade through the fall of 3rd grade, as the intervention condition could possibly alter the relations we focus on. The control condition included 176 children from Chicago area schools. Fourteen children were excluded due to missing data, leaving us with 162 participants (81 girls) at our first time point. At subsequent time points, we had data for 104 to 150 participants, due to sample attrition over time (see Table 1). Caregiver reports of race/ethnicity (N = 155) indicated that students were 51% White, 32% Hispanic, 9% African American, 6% Asian or Asian American, and 1% American Indian or Alaskan Native. Annual household income was reported by 138 caregivers with 7% earning less than 15,000, USD 15% earning 15,000 USD-$34,999, 9% earning 35,000 USD-$49,999, 8% earning 50,000 USD-$74,999, 9% earning 75,000 USD-$99,999, and 53% earning more than 100,000. USD

Measures and procedure

In the current study, we focus on a subset of the measures given at each time point. Children completed tasks in their school in a one-on-one session with an experimenter during fall

Table 1. Descriptive statistics for variables at all time points.

	1st fall		1st spring		2nd fall		2nd spring		3rd fall	
Measures	M (SD)	Range (N)	M (SD)	Range (N)	M (SD)	Range (N)	M (SD)	Range (N)	M (SD)	Range (N)
Math Anxiety	2.55 (0.72)	1.00–4.75 (162)	2.29 (0.78)	1.00–4.44 (150)	2.16 (0.78)	1.00–4.31(132)	1.92 (0.75)	1.00–5.00 (126)	2.07 (0.77)	1.13–5.00 (104)
Lin R^2 (0–100)	0.74 (0.21)	0.08–1.00 (162)	0.87 (0.16)	0.08–1.00 (150)	0.88 (0.16)	0.20–1.00 (132)	0.94 (0.10)	0.19–1.00 (127)	0.94 (0.07)	0.69–1.00 (105)
Lin R^2 (0–1000)	0.58 (0.19)	0.02–0.98 (162)	0.66 (0.16)	0.17–1.00 (150)	0.70 (0.18)	0.02–1.00 (132)	0.75 (0.19)	0.05–1.00 (127)	0.80 (0.17)	0.29–1.00 (105)
AP (W Score)	457.87 (17.47)	393–507 (162)	473.27 (20.80)	428–526 (149)	477.46 (18.08)	427–526 (128)	492.66 (18.86)	435–534 (125)	494.37 (20.93)	436–539 (104)

and spring of 1st and 2nd grade and fall of 3rd grade. At each time point, achievement measures were administered during one session, and emotion measures were administered during a session the following school day.[1]

Math anxiety

Children completed a modified version of the revised Child Math Anxiety Questionnaire (CMAQ-R: Ramirez et al., 2016), which was designed to be appropriate for 1st graders. The 16-item measure asked children how nervous they would feel during various math-related situations. Eight math problems were modified for children in 3rd grade to reflect the type of math knowledge expected of older students. For example, 1st and 2nd graders were asked "How do you feel when you have to solve 34–7?", while 3rd graders were asked "How do you feel when you have to solve 35 divided by 7?" To respond, children pointed to one of five smiley faces displaying an emotional gradient from "not nervous at all" to "very very nervous." Math anxiety was scored on a scale of one (low math anxiety) to five (high math anxiety). Because the math anxiety questionnaire involved specific math problems that changed for older children, we did not compare changes in math anxiety scores.

Number line estimation

Children were shown a horizontal line anchored with 0 on the left and 100 or 1000 on the right. To respond, children drew a hatch mark through the number line indicating their estimate of the position of each requested number. Our measure – including the counter-balancing of the two number line tasks and the numbers requested – mirrored the measure developed and used by Siegler and Opfer (2003). Children were randomly assigned to receive Order A or B at all time points.[2] Order A included a 0–1000 scale first (230, 71, 4, 780, 18, 6) and a 0–100 scale second (42, 6, 71, 18, 2, 4). Order B included a 0–100 scale first (3, 25, 86, 6, 2, 67) and a 0–1000 scale second (390, 2, 810, 86, 6, 25). Children received a new blank number line for each trial. Number line estimation was scored by converting children's estimates to the equivalent numerical values and finding the percentage of variance explained (R^2) by the best-fitting linear model that related their estimates to the requested numbers (linear R^2). We focused on linear R^2 – as opposed to other measures such as percent absolute error (PAE) – in our analyses because this index captures internally consistent placements of children's responses. In other words, linear R^2 captures the linearity of children's estimation of the location of the numbers requested in relation to each other, even if these estimations were not necessarily mapped onto the number line in an accurate manner (Mix et al., 2016). However, we also ran analyses using PAE, which was

[1]In the achievement session, students were randomly assigned to either complete the number line task first followed by measures of academic performance including the Applied Problems subtest and a Vocabulary subtest, or to complete measures of academic performance first followed by the number line task. Students were equally likely to receive the 0–100 or 0–1000 number line tasks first, regardless of whether they started the session by completing the number line task. In the emotion session, students first completed measures of emotions toward a variety of academic subjects, including Theories of Intelligence. Students then completed measures of domain-specific anxiety (math, reading, and spatial), with the order of the domain randomized across students.

[2]Although subjects were supposed to receive the same number line order throughout all five time points, this was not the case for six subjects due to experimenter error. These six subjects received one of the following orders over the five time points: AAABA, ABBBB, BBABB, BBBAB. Additionally, one child only completed five out of the six trials on the 0–1000 scale due to experimenter error during 1st grade fall, and that child's number line estimation was measured based on those five trials.

scored using the following formula: |Participant estimate – number requested|/scale of estimates, with scale of estimates being 100 or 1000.

Math achievement

Children completed the Applied Problems subtest of the Woodcock-Johnson III (Woodcock, McGrew, & Mather, 2001). This subtest requires children to answer math word problems of increasing difficulty. Subsequent analyses examined students' W scores, a transformation of raw scores into a Rasch-scaled score of equal interval measurements that represents the child' ability and the task difficulty, which is recommended to measure individual growth. A one-point W score increase roughly represents approximately a half month of learning during a school year. A score of 500 is the approximate average performance of a 10-year-old.

Results

Descriptive statistics

There was variability in children's performance on all tasks at all time points (see Table 1). During 1st grade fall, math anxiety on average was intermediate, about half-way between low math anxiety and high math anxiety (M = 2.55, *SD* = 0.72) and ranged from about two standard deviations below to three standard deviations above the mean. Performance on Applied Problems (M = 457.87, *SD* = 17.47) ranged from about four standard deviations below to three standard deviations above the mean. Performance on the 0–100 number line task, as assessed by linear R^2 (M = 0.74, *SD* = 0.21) was significantly higher than performance on the 0–1000 number line task (M = 0.58, *SD* = 0.19); t(161) = 8.6, *p = <0.001*. The linearity of children's number line estimation on the two scales at various time points is similar to that reported in other studies (e.g., Booth & Siegler, 2006; Opfer & Siegler, 2007; Siegler & Booth, 2004; Siegler & Opfer, 2003).

Children who completed the 0–100 number line task first performed better on that scale (M = 0.81, *SD* = 0.14) than children who completed the 0–1000 number line task first (M = 0.68, *SD* = 0.024); t(160) = −4.31, *p = <0.001*). Similarly, children who completed the 0–1000 number line task first performed marginally better on that scale (M = 0.61, *SD* = 0.17) than children who completed the 0–100 number line task first (M = 0.55, *SD* = 0.21); t(160) = 1.97, *p = .051*).

Correlations

Correlations between measures during 1st grade fall are reported in Table 2. Math anxiety was negatively correlated with performance on the 0–100 number line task but not the

Table 2. Pearson correlations for variables in 1st grade fall. (N = 162).

1st grade fall measures	1.	2.	3.
1. Math Anxiety			
2. Lin R^2 (0–100)	−.163*		
3. Lin R^2 (0–1000)	−.049	.249**	
4. AP (W Score)	−.355**	.316**	.327**

$*p < 0.05$, $**p < 0.01$

0–1000 number line task. Performance on Applied Problems was correlated with performance on both number line tasks, and the scores on the two number line tasks were correlated.

As shown in Table 3, math anxiety in 1st grade fall was positively correlated with math anxiety at all later time points. Similarly, number line estimation on the 0–100 scale in 1st grade fall was positively correlated with number line estimation on both the 0–100 and 0–1000 scales at all later time point. In contrast, 0–1000 number line estimation in the fall of 1st grade was not correlated with later 0–100 number line estimation except at one time point (2nd grade spring) but was correlated with 0–1000 number line estimation at all later time points. Of note, within each time point, linearity and PAE were highly correlated on both the 0–100 scale ($r = -0.695$ to -0.79), and the 0–1000 scale ($r = -0.774$ to -0.872).

Does 1st grade fall math anxiety predict future math achievement, controlling for number line estimation?

In these subsequent analyses examining whether fall math anxiety predicts later math achievement controlling for number line estimation, we used the Hierarchical Linear Modeling (HLM) program (Raudenbush, Bryk, & Congdon, 2004) to account for the nested nature of the data (i.e., time within children) and the maximum likelihood methods in the program to account for missing data. Math anxiety and number line estimation were z-scored and kept as continuous variables. Order of administration of the two number line tasks was analyzed as a centered contrast and coded −1 for order A (0–1000 scale was first) and +1 for order B (0–100 scale was first). Time was coded as 0–4 with 0 being the first time point (1st grade fall) and 4 being the last time point (3rd grade fall).

We also wanted to control for initial performance on the Applied Problems subtest, to ensure that any observed association between initial math anxiety and future Applied Problems would not be explained by the association between initial math anxiety and initial Applied Problems. Because initial performance on the Applied Problems subtest was highly correlated with initial math anxiety and initial number line estimation (0–100 and 0–1000, see Table 2), we controlled for shared variance by regressing Applied Problems on math anxiety and number line estimation (0–100 and 0–100) and saved the residuals. This approach has been used to deal with overlapping variance issues (Durik, Shechter, Noh, Rozek, & Harackiewicz, 2015). These Applied Problems residuals capture the variance in Applied Problems that does not overlap with math anxiety or number line estimation in 1st grade fall. Applied Problems residuals were z-scored and used as a continuous variable.

In model 1, we examined whether math anxiety in 1st grade fall predicted future Applied Problems scores, controlling for number line estimation (0–100 and 0–1000 scale) in 1st

Table 3. Pearson correlations between variables at initial time point (1st fall) and later time points (1st spring through 3rd fall).

1st fall measure	1st spring	2nd fall	2nd spring	3rd fall
Math Anxiety	.489**	.449**	.311**	.491**
Lin R^2 (0–100) correlation with Lin R^2 (0–100)	.220**	.358**	242**	.338**
Lin R^2 (0–100) correlation with Lin R^2 (0–1000)	.324**	.203**	.345**	.360**
Lin R^2 (0–1000) correlation with Lin R^2 (0–100)	.145	.072	.212*	.149
Lin R^2 (0–1000) correlation with Lin R^2 (0–1000)	.336**	.206*	.207*	.247*

*$p < 0.05$, **$p < 0.01$

grade fall, and Applied Problems residuals in 1st grade fall. Because the order in which children completed the number line tasks influenced their number line estimation (i.e. 0–100 or 0–1000 scale first), we also controlled for order of the number line tasks in model 2. In model 3, we examined whether there was a time x math anxiety interaction effect, a time x number line estimation interaction effect, and a time x Applied Problems residuals effect on future Applied Problems, to test whether these relations changed over time. The results for models 1–3 are reported in Table 4.

In models 1–3, math anxiety negatively predicted future Applied Problems, controlling for number line estimation on the 0–100 scale, number line estimation on the 0–1000 scale, time, and Applied Problems residuals, which were also significant predictors. In models 2–3, the order in which students completed the number line tasks (0–100 or 0–1000 first) did not predict future Applied Problems performance. In model 3, time x math anxiety, time x number line estimation on the 0–100 scale, time x number line estimation on the 0–1000 scale did not significantly predict future Applied Problems.

In sum, children with higher math anxiety in 1st grade fall had lower scores on future Applied Problems, compared to children with lower math anxiety (see Figure 1).

Table 4. Hierarchical linear models predicting future Applied Problems (AP) W score over four time points from 1st spring through 3rd fall (N = 162).

Predictors	Model 1	Model 2	Model 3
	B (S.E. B), *p*	B (S.E. B), *p*	B (S.E. B), *p*
Math Anxiety 1st fall (z-score)	−5.50*** (0.84), *<.001*	−5.51*** (0.83), *<.001*	−5.79*** (0.93), *<.001*
Lin R^2 (0–100) 1st fall (z-score)	4.90 ** (0.79), *<.001*	4.93*** (0.86), *<.001*	3.38** (1.24), *.007*
Lin R^2 (0–1000) 1st fall (z-score)	4.32 *** (0.88), *<.001*	4.30*** (0.91), *<.001*	5.32*** (0.96), *<.001*
AP standardized residuals 1st fall (z-score)	11.06*** (0.79), *<.001*	11.06*** (0.79), *<.001*	11.62*** (0.99), *<.001*
Time (4 time points)	7.86*** (0.43), *<.001*	7.86*** (0.43), *<.001*	7.85*** (0.42), *<.001*
Order 1st fall (100s or 1000s first)		−0.07 (0.90), *.934*	−0.07 (0.91), *.931*
Time x Math Anxiety 1st fall			0.21 (0.47), *.652*
Time x Lin R^2 (0–100) 1st fall			1.25 (0.88), *.155*
Time x Lin R^2 (0–1000) 1st fall			−0.80 (0.46), *.086*
Time x AP standardized residuals 1st fall			−0.35 (0.40), *.380*

$^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

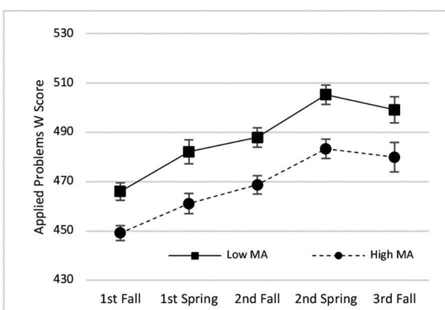
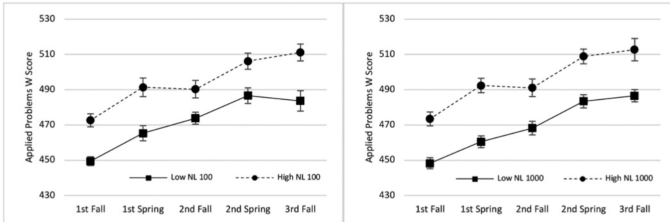


Figure 1. Math anxiety from 1st grade fall predicting Applied Problems W-Score over time. Math anxiety is plotted at 1 SD below the mean and 1 SD above the mean for visual purposes. This relation remained significant controlling for 1st grade number line estimation (0–100 and 0–100) as well as other factors (see Table 2).



a b

Figure 2a–b. Number line estimation in 1st grade fall predicting Applied Problems W-Score over time. Number line estimation is plotted at 1 SD below the mean and 1 SD above the mean for visual purposes.

Additionally, children with more linear number line representations in 1st grade fall had higher scores on future Applied Problems, compared to children with less linear number representations (see Figure 2).

We also examined whether math anxiety in 1st grade fall explained variation in future Applied Problems performance, over and above number line estimation (0–100, 0–1000) in 1st grade fall, after covarying out Applied Problems residuals from 1st grade fall. We ran three sets of four regression models with Applied Problems residuals predicting future Applied Problems at each of the four future time points (see Table 5). Initial Applied Problems residuals accounted for 30.1% to 35.1% of the variation in future Applied Problems performance. Next we added initial number line estimation (0–100 and 0–1000) as predictors to each regression model. After covarying out Applied Problems residuals, number line estimation accounted for an additional 13.2% to 23.2% of the variation in future Applied Problems. Finally, we added math anxiety as a predictor to each regression model, which accounted for an additional 7.1% to 8.9% of the variation in future Applied Problems performance.

Does the relation of math anxiety to number line estimation change over time, depending on the scale?

Similar to our previous analyses, in these subsequent analyses, we used the HLM program (Raudenbush et al., 2004) and the maximum likelihood methods in the program. Math anxiety was z-scored and kept as a continuous variable. Number line scale was analyzed as a centered contrast and coded −1 for the 0–100 scale and +1 for the 0–1000 scale.

Table 5. Adding (a) number line estimation (0–100 and 0–1000) from 1st grade fall, and then (b) math anxiety from 1st grade fall to regression models with Applied Problems residuals from 1st grade fall predicting future Applied Problems W-scores.

Future AP	AP standardized residuals	Lin R^2 (0–100 & 0–1000)		Math Anxiety	
W Score	1st fall	1st fall		1st fall	
	R^2	R^2 change	Sig. F. change	R^2 change	Sig. F. change
1st spring	0.351	0.162***	*<0.001*	0.082***	*<0.001*
2nd fall	0.337	0.154***	*<0.001*	0.089***	*<0.001*
2nd spring	0.313	0.132***	*<0.001*	0.079***	*<0.001*
3rd fall	0.301	0.232***	*<0.001*	0.071***	*<0.001*

***p < 0.001

Similarly, order of administration of the number line tasks was analyzed as a centered contrast and coded −1 for order A (0–1000 scale was first) and +1 for order B (0–100 scale was first). Time was coded as 0–4 with 0 being the first time point (1st grade fall) and 4 being the last time point (3rd grade fall). Since possible scores for our outcome measure of linear R^2 range from 0 to 1, for ease of interpretation Beta and standard error values were multiplied by 100.

In model 1, we examined whether math anxiety in 1st grade fall predicted number line estimation over time and tested the following interactions: math anxiety x time, math anxiety x scale, time x scale, and math anxiety x time x scale. In model 2, we controlled for number line order. The results for models 1–2 are reported in Table 6. In models 1–2, there was a significant math anxiety x time x scale interaction effect on number line estimation, such that the relation between math anxiety and number line estimation changed over time depending on the scale. Additionally, math anxiety, time, and number line scale significantly predicted number line estimation. Math anxiety x time, math anxiety x scale, and time x scale did not predict number line estimation. In model 2, number line order significantly predicted number line estimation.

To unpack the three-way interaction, we examined how math anxiety related to number line estimation on the 0–100 scale specifically and on the 0–1000 scale specifically (see Tables 7 and 8). Overall, math anxiety significantly predicted number line estimation on the 0–100 scale, but not the 0–1000 scale. However, there was a significant effect of time on number line estimation for both the 0–100 scale and the 0–1000 scale, and importantly, there was a significant math anxiety x time interaction effect on number

Table 6. Hierarchical linear models predicting number line estimation over time (N = 162).

Predictors of number line estimation	Model 1	Model 2
	B (SE B), *p*	B (SE B), *p*
Math Anxiety 1st fall (z-score)	−2.7007* (1.1361), *.019*	−2.4559* (1.1245), *.030*
Time (5 time points)	4.9974*** (0.2861), *<.001*	4.9982*** (0.2856), *<.001*
Scale (0–100 or 0–1000)	−9.4063*** (0.7463), *<.001*	−9.4063*** (0.7463), *<.001*
MA x Time	−0.0017 (0.2901), *.995*	0.0022 (0.2902), *.994*
MA x Scale	1.0698 (0.7832), *.172*	0.1967 (0.7832), *.172*
Time x Scale	0.1967 (0.2904), *.498*	0.1967 (0.2904), *.498*
MA x Time x Scale	−0.8491** (0.3089), *.006*	−0.8491** (0.3089), *.006*
Order 1st fall (100s or 1000s first)		1.9143* (0.7759), *.015*

**p* < .05, ***p* < .01, ****p* < .001
Beta values and S.E. values were multiplied by 100 (since linear R^2 scores can range from 0–1) for ease of interpretation.

Table 7. Hierarchical linear models predicting number line estimation (0–100) over time (N = 162).

	Model 1	Model 2
Predictors of number line estimation	B (SE B), *p*	B (SE B), *p*
Math Anxiety 1st fall (z-score)	−3.7803* (1.5460), *.016*	−3.3215* (1.4569), *.024*
Time (5 time points)	4.7817*** (0.3466), *<.001*	4.7902*** (0.3468), *<.001*
MA x Time	0.8510* (0.4178), *.042*	0.8546* (0.4205), *.043*
Order 1st fall (100s or 1000s first)		3.5091*** (0.7533), *<.001*

**p* < .05, ***p* < .01, ****p* < .001
Beta values and S.E. values were multiplied by 100 (since linear R^2 scores can range from 0–1) for ease of interpretation.

Table 8. Hierarchical linear models predicting number line estimation (0–1000) over time (N = 162).

	Model 1	Model 2
Predictors of Math Achievement (from 1st fall)	B (SE B), *p*	B (SE B), *p*
Math Anxiety 1st fall (z-score)	−1.5996 (1.2002), *.185*	−1.5742 (1.2061), *.194*
Time (5 time points)	5.2479*** (0.4669), *<.001*	5.2479*** (0.4668), *<.001*
MA x Time	−0.8822* (0.4398), *.045*	−0.8815* (0.4400), *.046*
Order 1st fall (100s or 1000s first)		0.1997 (1.0031), *.842*

*p < .05, **p < .01, ***p < .001
Beta values and S.E. values were multiplied by 100 (since linear R^2 scores can range from 0–1) for ease of interpretation.

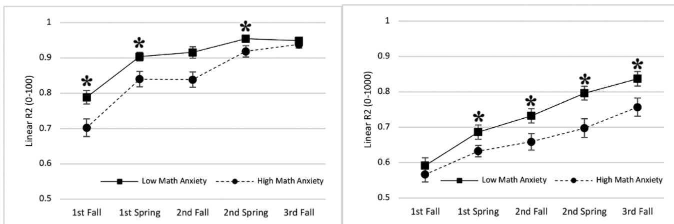


Figure 3a–b. Math anxiety from 1st grade fall predicting number line estimation on the 0–100 scale (Figure 3a) and 0–1000 scale (Figure 3b) over time. Math anxiety is plotted at 1 SD below the mean and 1 SD above the mean for visual purposes, but it is analyzed as a continuous variable in our HLM analyses. *Significant relation ($p < .05$) between children's math anxiety and their number line estimation on a 0–100 or 0–1000 scale at a particular time point.

Table 9. Pearson correlations between 1st grade math anxiety and number line estimation at all time points.

	1st fall	1st spring	2nd fall	2nd spring	3rd fall
NL (0–100, lin R^2)	−.163*	−.224**	−.123	−.174*	−.045
NL (0–1000, lin R^2)	−.049	−.186*	−.217*	−.270**	−.216*

*p < .05, **p < .01

line estimation for both the 0–100 scale and the 0–1000 scale. For a visual representation of the relation between math anxiety and number line estimation (0–100 and 0–1000) over time see Figure 3.

To further test our hypothesis about math anxiety being most detrimental to math tasks at the cusp of the child's ability, we examined the relation between math anxiety and number line estimation on both scales (0–100 and 0–1000) during each of the five time points (see Table 9). Math anxiety in 1st grade fall negatively related to 0–100 number line estimation at the earlier time points (from 1st grade fall through 2nd grade spring, with the exception of 2nd grade fall) but not during the last time point (3rd grade fall). In contrast, math anxiety in 1st grade fall did not relate to 0–1000 number line estimation linearity at the fall 1st grade time point but did at all the later time points.[3]

[3]Results were similar with PAE as the index of number line estimation, with a few exceptions. First, in model 3 of Table 4 PAE on the 0–100 scale marginally predicted (p=–0.051) future Applied Problems. Second, although the critical three-way

Discussion

Regarding our first question, children's early math anxiety from 1st grade fall predicted their future math achievement up to two years later when they were in the fall of 3rd grade, and this relation remained significant controlling for their early number line estimation – a foundational cognitive math skill. To our knowledge, the present study is the first to control for a foundational numerical representation in examining the relation between children's early math anxiety and their future math achievement over the course of the early elementary school years. Our findings contradict those of Skagerlund, Östergren, Västfjäll, and Träff (2019), in which adults' math anxiety indirectly related to arithmetic through symbolic number comparison. Further, regardless of whether math anxiety stems from poor math skills, math anxiety leads to low math skills, or this relation is bidirectional, our findings suggest that it is important to consider both foundational math skills and emotional factors – in particular, math anxiety – in supporting children's math learning and achievement. In other words, there is more to children's math learning than their math skills alone; and fostering positive emotions toward math, in addition to math skills, is likely to be an effective approach to promoting strong math achievement.

Regarding our second question, math anxiety was more predictive of number line performance when the number line task was appropriately complex (i.e. not too easy or too difficult) as shown by the significant three-way interaction between math anxiety, time, and scale on number line estimation. In particular, math anxiety in 1st grade was associated with number line estimation on the 0–100 scale in 1st and 2nd grade, but as this task became easy for children in 3rd grade, math anxiety no longer predicted performance. In contrast, math anxiety in 1st grade was associated with number line estimation on the 0–1000 scale from 1st grade spring through 3rd grade fall when this task was challenging but not too difficult, but not during 1st grade fall when the task was likely too difficult regardless of children's math anxiety. Number line estimation was an ideal task to capture this developmental trajectory, as the structure of the task remained the same but the complexity of the task changed when the rightmost anchor was larger. Our results suggest that math anxiety was particularly harmful when the number line estimation task was not too easy and not too difficult. This finding suggests that perhaps math anxiety plays a reverberating role in children's math learning in school – a place where children are consistently introduced to new concepts and skills that are at the cusp of their learning level.

One limitation of our study is its correlational design, which impedes us from making causal claims. Further, we show that math anxiety is a significant predictor of future math achievement controlling for an important foundational number representation (linearity of number line estimation), but we do not know what the relation between math anxiety and later math achievement would be controlling for additional foundational math skills (e.g., magnitude comparison). Nonetheless, the robust relation between number line estimation and math competence provides evidence that math anxiety matters for children's math achievement, over and above this important foundational numerical representation.

interaction effect of math anxiety x time x scale on PAE was significant in Table 6, in models 1-2 of Table 8 math anxiety significantly predicted PAE on the 0–1000 scale, and there was not a significant math anxiety x time interaction effect on PAE on the 0–1000 scale (p = 0.160 to 0.175). Third, in Table 9 math anxiety marginally predicted PAE on a 0–100 scale in 1st grade spring (p = 0.056) and did not significantly predict PAE on a 0–100 scale in 2nd grade spring.

Further research should examine whether intervening on math anxiety alone, foundational math skills alone, or both math anxiety and foundational math skills simultaneously would most positively influence children's short-term and long-term math achievement. While some interventions have focused on improving number line estimation (Siegler & Ramani, 2009), and others have targeted the negative effects of anxiety on math performance (Ramirez & Beilock, 2011; Rozek, Ramirez, Fine, & Beilock, 2019), intervening on both of these predictors simultaneously might have a greater impact on math achievement. Further, having educators, as opposed to researchers administer these interventions might prove most fruitful and be a more sustainable way to foster children's positive feelings about math. Future research should examine whether there is a particular age at which math anxiety interventions might be most beneficial, and whether administering these interventions at one time point or administering them across multiple time points might differentially impact math performance.

In conclusion, our findings support the theory that math anxiety does not simply stem from poor math ability, but rather is separable from math ability as it predicts math achievement over and above a foundational math skill – number line performance. Furthermore, math anxiety appears to be most predictive of math performance on tasks that are appropriately complex (i.e., tasks that are at the cusp of children's knowledge), suggesting that math anxiety can have reverberating effects as children encounter new and challenging math tasks. Taken together, our findings suggest that children's math achievement depends not only on fostering foundational cognitive skills, but also on fostering their positive emotions toward math.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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