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Exploring the Influence of Basic Cognitive Skills on the Relation Between Math Performance and Math Anxiety

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Abstract

What causes math anxiety? According to a cognitive deficits view, early weaknesses in basic number and spatial skills lead to poor performance and hence negative affect. A strong version of this view suggests that the relation between math anxiety and math performance among adults will be explained by deficits in spatial and basic number skills. In the present research, we tested a model to account for the relations among math anxiety, math performance, and cognitive skills (i.e., working memory, basic number and spatial skills) among adults (N = 90). We replicated the modest correlations observed between math anxiety and these cognitive skills. However, we did not find a direct link between basic number and spatial skills and math anxiety; instead, these relations were mediated by complex math performance. We conclude by rejecting the hypothesis that math anxiety in adults is linked directly to individual differences in spatial and basic numerical skills and suggest instead that the present results are consistent with the alternative view in which even basic numerical tasks, under certain conditions may evoke an anxiety response and mask skill proficiency. Finally, we note that caution should be applied when extrapolating correlational results to make causal claims about whether cognitive skills may be precursors in the development of math anxiety.

Keywords: Math anxiety, cognition, basic number skills, spatial skills, cognitive deficits, working memory

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Math anxiety is a negative response to participation in mathematical activities that has consequences for adults' behavior (Ashcraft & Ridley, 2005; Hembree, 1990; Richardson & Suinn, 1972; Suárez-Pellicioni, Núñez-Peña, & Colomé, 2016). Math-anxious students avoid courses that involve mathematics (Ashcraft & Ridley, 2005; Hembree, 1990; Suárez-Pellicioni et al., 2016), they rate themselves as less skilled in math, have less intention to pursue further mathematics, and have lower math confidence than their peers (e.g., Hembree, 1990; LeFevre, Kulak, & Heymans, 1992). Notably, correlations between math anxiety and math performance are moderate and, thus in some models, reduced math competence is assumed to be a consequence of avoiding math-related courses and activities (e.g., Ashcraft & Ridley, 2005) rather than the cause of the anxiety. Recently, however, Maloney and colleagues have proposed a *cognitive deficits* model which links math anxiety more directly to individual differences in basic number and spatial competencies (Ferguson, Maloney, Fugelsang, & Risko, 2015; Maloney, Ansari, & Fugelsang, 2011; Maloney, Risko, Ansari, & Fugelsang, 2010; Maloney, Waechter, Risko, & Fugelsang, 2012). According to Maloney (2016), "…a cognitive predisposition to the development of math anxiety that starts with a small deficit in the foundational skills and snowballs into a larger and emotion-laden difference" (p. 408). Support for a cognitive deficits model of math anxiety in adults is limited to the identification of moderate correlations between basic numerical and spatial abilities and math anxiety, without consideration of other relevant correlates. In the present research, we explored a cognitive deficits model by simultaneously assessing multiple cognitive competencies (i.e., spatial and numerical abilities), math anxiety, and mathematical performance. This approach allowed us to explore how the various measures of cognitive and mathematical skill were interrelated for adults.

Models of the Relations Between Math Anxiety and Math Performance

Suárez-Pellicioni et al. (2016) identified three general explanations for the relation between math anxiety and math performance: (a) A cognitive deficits model, in which early weaknesses in fundamental quantitative and spatial skills lead to poor performance and hence negative affect; (b) an attentional/working memory model in which math-anxious individuals' susceptibility to distraction leads to on-line performance difficulties in mathematics that may cause or, exacerbate math anxiety, and (c) an experiential explanation, in which negative experiences during math learning in the home and school environments accumulate to produce avoidance and ongoing negative feelings. These causal paths are not mutually exclusive, however, the extent to which each contributes to math anxiety may vary. Until recently, many researchers assumed that the attentional/working memory model provided the best explanation for the correlation between math anxiety and math performance among adults. Specifically, math anxiety consumes attentional resources during complex math tasks and thus contributes to declines in math performance, a relationship that is exacerbated in situations with high cognitive loads (e.g., Ashcraft & Krause, 2007; Ashcraft & Moore, 2009; Beilock, 2008; Beilock & Decaro, 2007; Lyons & Beilock, 2012).

Ashcraft and Kirk (2001) found support for an attentional locus of the math anxiety-performance connection. Participants completed 2-column addition problems while maintaining a memory load of up to six letters. As the letter-load increased, high math-anxious participants performed worse on the math task than less math-anxious participants. Similarly, Beilock et al. (2004) found that participants in a high-pressure group where anxiety was induced (e.g., they were told their performance was being videotaped, there were monetary incentives, and they were responsible for a partner's winning or losing) performed worse on difficult math problems than those in a low-pressure control group. These results support the view that anxiety compromises the availability of working memory resources during on-line mathematical activity.

Crucially, Ashcraft and colleagues (see Ashcraft & Kirk, 2001; Faust, Ashcraft, & Fleck, 1996) explicitly rejected difficulties with basic number skills as a causal explanation of the relation between math anxiety and performance in adults – in their studies, there were no differences in arithmetic skills between the high- and low-math-anxious groups when anxiety was controlled.

Suárez-Pellicioni et al. (2014, 2016) have updated the attentional/working memory model by applying attention control theory (ACT) to describe the math anxiety and mathematical performance relation. According to ACT (Eysenck, Derakshan, Santos, & Calvo, 2007), anxious individuals are more vulnerable to distractions and less influenced by goal-directed processes. Thus, their attentional resources can be consumed by both distracting internal (i.e. worrisome thoughts and ruminations) and external (i.e. task-irrelevant distractors) content making it more difficult for them to focus on the given task. This can lead to performance deficits on both complex tasks with high working memory demands and tasks that involve inhibitory control. On this view, math anxiety may lead to performance deficits in both complex mathematical tasks (as described above) and basic numerical tasks where an inhibitory response is provoked. Support for the effect of math anxiety on inhibitory control comes from studies looking at the effect of anxiety on performing a numerical Stroop task (Hopko, Hunt, & Armento, 2005; Suárez-Pellicioni et al., 2014). In the numerical strop, participants must inhibit physical-size information to compare magnitudes of two digits; for example,

2 to **5** or **3** to 7

Researchers found that high math-anxious individuals were more vulnerable to distraction when performing a numerical Stroop task than low math-anxious individuals. Suarez-Pellicioni and colleagues concluded that this effect is related to an anxiety-provoked deficit in attentional control.

A *cognitive deficits model* is a complementary theory of the link between math anxiety and math performance (Maloney, Ansari, & Fugelsang, 2011; Maloney et al., 2010). According to this model, difficulties with basic number skills, such as counting, number recognition, or symbolic number comparison, or with other fundamental cognitive skills, such as spatial processing, result in performance difficulties which may influence children's affective responses to learning mathematics and lead to the development of math anxiety (Maloney, 2016; Maloney & Beilock, 2012). Some support for this model was found by Ma and Xu (2004) in a longitudinal cross-lagged study of American high school students. They observed that prior low math achievement predicted later math anxiety, supporting a potential causal path from early math skills to later math anxiety. Furthermore, research with young children suggests that math anxiety may begin as early as first and second grade, which supports a close relation between fundamental number skills and math anxiety (Krinzinger, Kaufmann, & Willmes, 2009; Vukovic, Kieffer, Bailey, & Harari, 2013; Wu, Barth, Amin, Malcarne, & Menon, 2012). However, not all research with young children has shown a relation between mathematical performance and self-reported math anxiety (Dowker, Bennett, & Smith, 2012; Hill et al., 2016; Krinzinger et al., 2009) and there are no longitudinal studies which follow children from the early years. Thus, the research with younger children does not provide strong support for a cognitive deficits model of math anxiety among older children and adults. Furthermore, the correlations between math performance and math anxiety are moderate, and thus can only form part of the explanation for persistent math anxiety among adults.

Notably, basic number skills correlate highly with adults' mathematical performance on complex mathematical tasks (Castronovo et al., 2012; De Smedt, Noël, Gilmore, & Ansari, 2013; Lyons & Beilock, 2011). Thus, a cognitive deficits hypothesis may provide an explanation of the relation between math anxiety and performance if basic skills mediate the relation between math anxiety and complex skills. Basic number skills that are correlated with math anxiety include counting (Maloney et al., 2010) and symbolic number comparison (Maloney et al., 2011; Núñez-Peña & Suárez-Pellicioni, 2014); spatial abilities are also correlated with math anxiety (Ferguson et al., 2015). Maloney and colleagues have proposed a cognitive deficits hypothesis as one interpretation of these correlations between math anxiety and basic cognitive skills (see Maloney & Beilock, 2012). For example, in reference to their research with adults, Ferguson et al. (2015) concluded that "these novel findings provide evidence for a practical spatial impairment in math anxious individuals … and suggest that small-scale spatial skill may be especially relevant as a predictor of math anxiety. This insight deepens our understanding of the cognitive basis of math anxiety, provides new clues about the etiology of the impairment, and provides guidance on the optimal approach to remediation" (p. 12). Despite these strong conclusions, the moderate correlations between math anxiety and complex math performance have a variety of alternative possible interpretations.

One major limitation of the recent body of work on cognitive deficits and math anxiety is no single study has included a full range of cognitive predictors, that is, basic number skills, working memory, and spatial abilities, nor has mathematical performance been assessed. An alternative explanation of the correlations between basic number skills and math anxiety is that it reflects what we might call general number avoidance: Adults who are math anxious may show performance decrements in any task that involves numbers, especially in mildly stressful situations (e.g., speeded tasks). Rather than reflecting cognitive and spatial deficits, on this view, the correlations between basic numerical processes and math anxiety may reflect a generalized negative response to numerical tasks that has been acquired over the course of many years.

Alternative explanations for the inter-relations between cognitive skills and math anxiety are shown in Figure 1, 2 and 3. First, the relations shown in Figure 1 represent a "strong view" of cognitive deficits that should hold if cognitive deficits account for the relations between complex mathematical skills and math anxiety. On this strong view, basic number and cognitive skills should mediate the relations between complex mathematical skills and math anxiety.

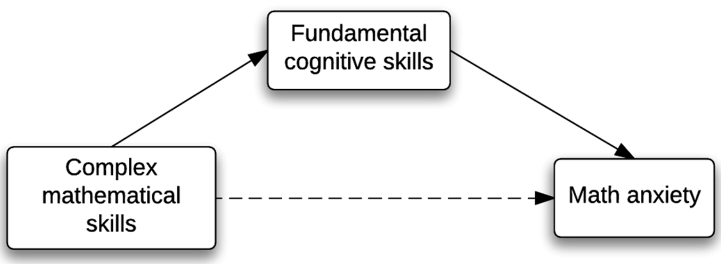

Figure 1. Strong version of the cognitive deficits model showing fundamental cognitive skills (specifically basic number and spatial skills) fully mediating the math-performance and math-anxiety relation.

Second, as shown in Figure 2, spatial skills may mediate the relations between either basic or complex mathematical skills and math anxiety if Ferguson et al. (2015)'s claims about the importance of spatial skills are correct.

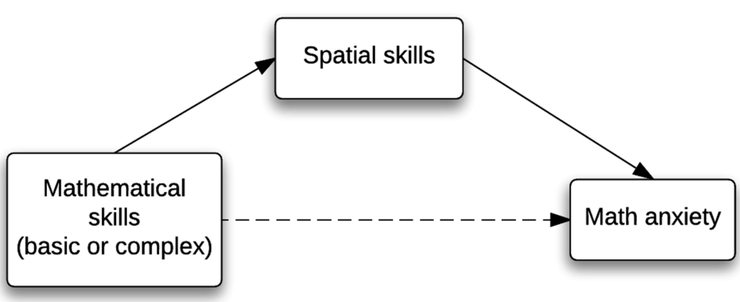

Figure 2. The spatial deficits model showing spatial skills mediating the relation between mathematical skills and math anxiety.

In contrast, if acquired negative responses to number tasks explain the concurrent relations among these variables, then the relations shown in Figure 3 may hold, that is, complex mathematical skills/performance may mediate the relation between basic number skills and math anxiety. In the present research, we assessed these

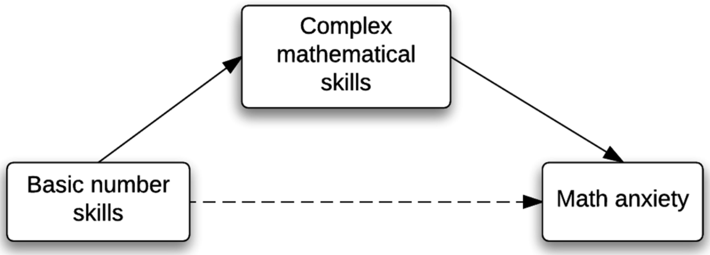

Figure 3. The negative exposure explanation showing the relation between basic number skills and math anxiety is mediated by the relation between complex mathematical skills and math anxiety.

predictions about the relations between math anxiety and math performance, cognitive, and number skills and subsequently developed and tested a more complete model to account for the observed interrelations.

The Present Research

Some of the confusion and inconsistency in the literature on the relations between math anxiety and math performance has occurred because researchers have not clearly defined or assessed basic numerical competencies separately from more complex mathematical skills. Thus, in the present research we assessed both basic number skills and complex mathematical skills. To further refine the cognitive deficits hypothesis, we also measured spatial skills and basic number skills. To avoid the possibility that a single measure of basic number skills has some privileged relation with math anxiety, in the present research basic number skills were modeled as a latent factor with three indicator variables; symbolic magnitude comparison (Nosworthy, Bugden, Archibald, Evans, & Ansari, 2013), number ordering (Lyons & Beilock, 2011) and the number sets test (Geary, Bailey, & Hoard, 2009). In other research, these measures were related to complex mathematical skills in both children and adults (e.g., Dietrich et al., 2015; Holloway & Ansari, 2009; Lyons & Beilock, 2011; Lyons, Price, Vaessen, Blomert, & Ansari, 2014; Nosworthy et al., 2013; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013). Complex math performance was assessed with two measures, one focused on multi-digit calculations (cf. Lyons & Beilock, 2011) and the other on use of fraction and whole number arithmetic as well as algebraic computation and procedures (Steiner & Ashcraft, 2012). Accordingly, we independently assessed the relations between math anxiety and both simple and complex mathematics skills, and we assessed the role of spatial abilities in these relations. Based on these independent assessments (i.e., testing Hypotheses 1 to 3), we then developed an integrated model to simultaneously account for the observed relations.

> *Hypothesis 1: As shown in Figure 1, the relation between math anxiety and math performance will be mediated by fundamental cognitive skills.*

According to a *strong* version of the cognitive deficits model, the relation between math anxiety and performance will be fully accounted for by shared variance with fundamental cognitive skills, specifically basic number and spatial skills.

> *Hypothesis 2: As shown in Figure 2, the relations between math anxiety and math performance will be mediated by spatial skills.*

This hypothesis is a specific implementation of the strong cognitive skills hypothesis in which spatial skills are assumed to capture the shared variability between math performance and math anxiety.

Hypothesis 3: As shown in Figure 3, the relation between math anxiety and basic number skills will be mediated by complex mathematical skills.

As an alternative to a strong cognitive deficits model, the negative exposure explanation suggests that the correlation between basic number skills and math anxiety will be shared with complex skills. Shared relations between basic skills and complex math performance may account for some variance in math anxiety but more complex mathematical skills will also uniquely predict math anxiety. Importantly, this view holds that relations between math anxiety and math performance among adults will not be accounted for by deficits in basic cognitive and numerical skills.

In summary, the goal of the present research was to capture the observed correlations among the various cognitive predictors of math performance, and provide a more integrated description of how math anxiety is related to these predictors, as well as to complex mathematical performance. Young adults completed two mathematical performance measures, three tests of basic number skills, two small-scale spatial tasks, and control measures of verbal, visual-spatial, and executive working memory. Working memory is strongly related to math performance among adults (Ashcraft & Kirk, 2001; DeStefano & LeFevre, 2004; Raghubar, Barnes, & Hecht, 2010; Wiley & Jarosz, 2012) and was controlled to ensure that any relations between fundamental number skills and math anxiety were independent of working memory abilities. Math anxiety was assessed using the Abbreviated Math Anxiety Scale (i.e., AMAS; Hopko, Mahadevan, Bare, & Hunt, 2003) which has been used extensively in other studies with adults (e.g., Ferguson et al., 2015; Maloney et al., 2011, 2010).

Method

Participants

Ninety adults were recruited from a Canadian university and the surrounding area (*Median* age = 21 years; range 16 to 54 years; 59 women). Participants received either $15 ($n$ = 41) or course credit for participating in the study. English was the first language for 70.0% of participants (n = 63) and all participants spoke fluent English. The most frequent other first languages were Chinese (n = 12), Arabic (n = 5) and French (n = 4). Approximately one-third of the sample (n = 33) were pursuing degrees in the sciences.

Materials and Procedures

Participants were tested in a quiet space either individually or in pairs. Total testing took approximately one hour. The order of the tests was: Math surveys, memory measures, magnitude comparison, mental rotation task, order judgement, number sets task, hidden figures and mathematical outcomes. This ordering was designed to provide a mix of short and simple tasks with more complex and time-demanding tasks, with the goal of minimizing fatigue and maximizing attention. Several additional measures were administered but are not discussed in the present analysis. Information about these tasks can be found in Douglas (2015).

Math Anxiety

Math anxiety was assessed with the 9-item Abbreviated Math Anxiety Scale (i.e., the AMAS; Hopko, Mahadevan, Bare, & Hunt, 2003). Participants rated their anxiety during specified tasks such as, “Listening to a lecture in math class.” The response scale ranges from 1 (low anxiety) to 5 (high anxiety) with total scores ranging from 9-45. The AMAS has high internal consistency and validity. Hopko et al. (2003) reported excellent test-retest reliability (r = 0.85) and internal consistency was high with the current sample (Cronbach's α = 0.93).

Cognitive Measures

Memory measures — Three memory measures were administered; forward digit span, backward digit span, and spatial span.

Forward digit span. In the forward span the tester reads a sequence of numbers. The participant repeats that sequence in order. There are two trials for each sequence length, starting with a sequence of three digits. If one of the two sequences for a given length is recalled correctly, the tester increases the sequence length by one digit. Testing continues until the participant is unable to recall both trials for a given sequence length. Score is the highest sequence length with at least one sequence recalled correctly. Reliability was calculated by summing across first versus second trials for all sequences (Cronbach's α = 0.84).

Backward digit span. In the backward span the experimenter recites a list of numbers (e.g., 2-7-4). The participant then repeats the numbers in reverse order, starting from the last number and ending with the first number recited (e.g., 4-7-2). The task begins with two sequences of 2 digits. Performance was scored as the highest sequence with one trial correctly recalled. The same procedure as the forward digit span was used to determine when the test was terminated. Reliability was calculated by summing across first versus second trials for all sequences (Cronbach's α = 0.86).

Spatial span. Spatial span is an index of spatial working memory capacity (Baddeley, 2003). In this iPad version, *PathSpan,* there is pseudo-random array of nine green circles. For each trial, these circles light up in a sequence. The participant watches and then copies the forward pattern by touching the circles in the order in which they flashed. Following task instructions, the participant completes a practice trial with a sequence length of 2. There are three trials for each span length and testing ends when all three trials are recalled incorrectly. The participant was scored on the maximum sequence length with one correct trial. This task takes approximately 4 min. to administer. Reliability was calculated by summing across the first, second, and third trials across sequence lengths (Cronbach's α = 0.80).

Basic number skills — Three measures of basic number skills were administered; magnitude comparison, order judgment, and the number sets task.

Symbolic magnitude comparison. In this timed paper and pencil task, participants compare single digit pairs where digits range from 1 to 9. Participants cross out the larger of the two digits and are timed as they complete the task. Placement of the larger digit is counterbalanced in this version and all thirty-six two-digit combinations are used. The test consists of two pages (forms A and B), each with 15 items. Scoring was based on the number of correct items completed per second and averaged between the 2 pages. Reliability comparing forms A and B was very high (α = 0.96) for the test sample. The measure is based on the design of a similar task used by Nosworthy and colleagues (2013) and adapted by Sowinski (2016). It is available on the website https://carleton.ca/cacr/math-lab/measures

Order judgment. The order judgment task required participants to decide whether a series of three numbers were ordered, either increasing (e.g., 1 2 3) or decreasing (e.g., 3 2 1) or if they were unordered (e.g., 3 1 2). This timed paper and pencil task was created by the author and based on work by Lyons and Beilock (2011) and Bourassa (2014). Two pages (Forms A and B) with 32 sequences per page were created. There were eight examples of four different types of sequences per page. Ordered counting sequences are consecutive numbers (e.g., 1 2 3 or 3 2 1). Half of the ordered counting sequences were ascending and half were descending. Unordered counting sequences included the same digits as counting sequences (e.g., 2 1 3, 1 3 2). Ordered neutral sequences were non-consecutive numbers that did not form familiar patterns (e.g., 7 6 3, 3 6 7). Unordered neutral sequences included the same digits as the neutral sequences (e.g., 6 3 7, 7 3 6). The same stimuli were re-arranged for the second page. For example, an ascending sequence became a descending sequence and an unordered sequence where the first two digits increased, became an un-ordered sequence where the first two digits decreased and vice versa. Reliability comparing Forms A and B was very high (Cronbach's α = 0.97). This task is available on the website https://carleton.ca/cacr/math-lab/measures

Participants were instructed to place a check mark beside ordered sequences and an X beside unordered sequences. After a demonstration and practice, the participant was instructed to complete the task as quickly and accurately as possible. Scoring followed the same procedure as the magnitude comparison task, number correct per second. Results reported are the number of correct items per second averaged between Forms A and B.

Number sets. Participants completed the number sets task developed by Geary et al. (2009). In this timed pencil and paper task, the set stimuli are presented as either 2 or 3-squared dominoes with a digit, a set of shapes or a blank in the domino squares. Participants circle the dominos that sum to a target number (i.e., 5 or 9). The participant completed a practice trial for the target number of 3. The participant then completed two pages with a target number of 5 and two pages with a target number of 9. Each page had 18 test items and was completed separately and timed. The participant was instructed to complete the page as quickly and accurately as possible. Scoring was based on a sensitivity measure (d') - the number of correct responses minus the false alarms where false alarms are circled number sets that do not add up to the target number. This measure was then divided by the time required to complete the page. Reliability comparing across the four pages was very high (Cronbach's α = 0.91). A principle components factor analysis (PCA) was used to reduce the results of the four pages into one number sets score. The PCA produced a one-component structure that accounted for 82% of the variance in the scores and factor loadings were high ranging from 0.87 to 0.94.

Spatial processing measures — Participants completed two small-scale spatial processing tasks: Mental rotation and hidden figures.

Mental rotation. A redrawn version by Peters et al. (1995) of the Shepard and Metzler (1971) mental rotation task was administered. In this task, participants view four test figures and one target figure. They are expected to mentally rotate the four test figures to choose the two that match the target figure. The researcher guided the participants through four practice items. Participants were then given seven minutes to complete up to 24 questions. Items were scored correct if the two matched test figures were correctly identified. This test has both strong internal consistency (KR-20 = .88) and test-retest reliability (r = 0.83) as reported in Peters et al. (1995).

Hidden figures. In the Hidden Figures test (Ekstrom, French, & Harman, 1976) participants are asked to identify which of five simple geometric figures is embedded within a complex figure. Test-retest reliability is high (0.78 to 0.92; Kepner & Neimark, 1984) in a group-administered version of the task. Participants were guided through two practice questions. They were then given eight minutes to complete the 16 questions. Participants were scored on the number of correct responses.

Mathematical outcomes — Two arithmetic assessments were used to index mathematical performance.

Calculation fluency. Fluency of multi-digit arithmetic was measured using the *Calculation Fluency Test* (CFT; Sowinski, Dunbar, & LeFevre, 2014). This pencil and paper test (available on https://carleton.ca/cacr/math-lab/measures) consists of one page each of double-digit addition (e.g., 28 + 13), double-digit subtraction (e.g., 89 - 60) and multiplication (e.g., 16 x 8). Participants first complete two practice questions for each operation. Following this, they are given one minute per page to quickly and accurately complete as many questions as they can. Scoring is based on the total number correct. Reliability was high (Cronbach's α = 0.90) across the three operations/pages.

Procedural arithmetic. The Brief Math Assessment 3 was developed by Steiner and Ashcraft (2012) based on the Wide Range Achievement Test: Third Edition (WRAT3). In this un-timed paper and pencil test, participants complete ten progressively more difficult questions ranging from whole number addition and subtraction to fractions, decimals and algebra. Scoring is based on the total number correct.

Results

Descriptive Statistics

The means, standard deviations and ranges for all measured variables are reported in Table 1.

Table 1

Descriptive Statistics for All Measures

Measure	*M*	*SD*	Skew	Min	Max
Math Anxiety (AMAS)	22.60	8.51	0.60	9	45
Working Memory					
Forward Digit Span	6.73	1.28	-0.01	4	9
Backward Digit Span	4.88	1.46	0.51	2	9
Spatial Span	7.56	1.29	-0.48	4	10
Number Skills					
Symbolic Magnitude Comparison[a]	1.46	.32	0.50	0.84	2.48
Order Judgement Task[a]	.54	.20	0.43	0.25	1.04
Number Sets Task[b]	1.60	.37	0.45	0.95	2.81
Spatial Skills					
Mental Rotation Task[c]	9.40	4.71	0.23	1	21
Hidden Figures Task[c]	4.49	3.12	1.08	0	16
Complex Mathematics Skills					
Addition[d]	15.26	6.87	0.84	4	35
Subtraction[d]	11.28	5.68	0.62	1	31
Multiplication[d]	6.69	5.33	0.91	0	22
Procedural Arithmetic – BMA3[c]	6.89	2.42	0.08	1	11

[a][number correct/sec.]. [b][#correct-false alarms/sec.]. [c]number correct. [d][number correct/min.].

The math anxiety measure (AMAS) had an observed mean of 22.6 (SD = 8.31) which was not significantly different from Hopko et al.'s (2003) undergraduate replication sample (M = 23.2), $t(89) = 0.85$, $p = 0.40$.

Correlations

Correlations among the individual tests are shown in Appendix A. As anticipated, individuals who were more math anxious performed worse than less-anxious participants on all basic number skills and math performance measures. For the spatial tasks, participants with higher math anxiety performed worse on the hidden figures task than low math anxious participants whereas anxiety was not significantly correlated with performance on the mental rotation task. Women performed moderately worse than men on both these spatial tasks and also self-reported somewhat higher math anxiety than men. Math anxiety was not significantly related to the individual working memory measures (digit span backwards and spatial span).

To reliably characterize the constructs for further analysis, individual measures were used to create composite scores. For basic number skills, three tasks were available to capture the construct: Number order, magnitude comparison and the number sets task. A principal component analysis was used to create the number skills factor score. The correlations among the three memory measures (forward digit, backwards digit, and spatial span) were not very high. Spatial span and backwards digit span however had similar patterns of correlation with the basic number and complex mathematical measures whereas forward digit span was only correlated with math anxiety. Spatial span and backwards digit span were thus chosen to index working memory as they were related to mathematical performance. These two measures were standardized and averaged to create a working memory composite score. The two small-scale spatial measures, mental rotation and the hidden figures task were also standardized and averaged to create a spatial processing composite score.

The correlations among the composite variables are shown in Table 2. The pattern of correlations is consistent with our expectations and with previous research. Math anxiety was correlated with all the other measures except working memory. Gender, spatial skills and math anxiety were all weakly correlated and as anticipated, gender was not correlated with the basic number or complex mathematical measures.

Table 2

Correlations Among Composite Variables

		Cognitive Measures			Complex Mathematics	
Variable	**Gender**	**WM**	**NS**	**SS**	**CFT**	**BMA3**
Math Anxiety (AMAS)	.22*	-.05	-.30**	-.25*	-.37**	-.43**
Gender		.16	-.18	-.29**	.00	.01
Working Memory (WM)			.42**	.32**	.32**	.43**
Number skills (NS)				.43**	.72**	.55**
Spatial skills (SS)					.18	.36**
Calculation fluency (CFT)						.64**
Procedural Arithmetic (BMA3)						

*$p < .05$. **$p < .01$.

Mediation Analysis

Our first step in evaluating how best to model the observed correlations was to evaluate the hypotheses described in the introduction using the PROCESS mediation software for SPSS (Hayes, 2012). Mediation analysis allowed us to test the extent to which one of three correlated variables (i.e., the possible mediator) explained the relationship between the other two variables (Field, 2013). By testing these relationships in isolation, we were able to build a more complete model to account for the interrelations of variables. Causality is not implied by this use of mediation analysis.

> ***Hypothesis 1: The relation between math anxiety and math performance will be mediated by fundamental cognitive skills.***

To test Hypothesis 1, we conducted separate mediation analyses for the two complex mathematical measures (i.e., calculation fluency, procedural arithmetic). The question we addressed was whether basic number skills accounted for any of the relation between either complex mathematics measure and math anxiety. As shown in Table 3 and Figure 4, basic number skills did not mediate the relations between math anxiety and math performance because the indirect effects were not significant (i.e., the confidence intervals for the indirect effects included zero) whereas the direct effects of complex mathematics on math anxiety were significant (i.e., the confidence intervals did not include zero).

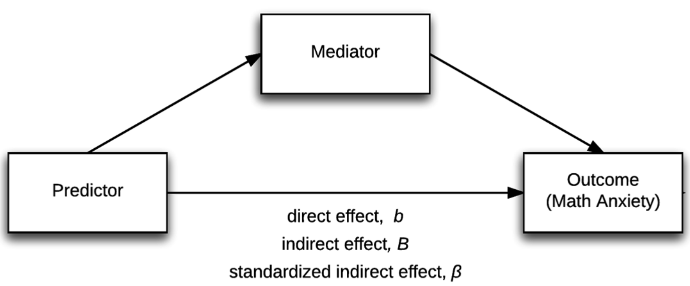

Figure 4. Illustration of the mediation effects reported in Table 3.

> ***Hypothesis 2: The relations between math anxiety and math performance will be mediated by spatial skills.***

To test Hypothesis 2, we used spatial skills as the mediating variable. As shown in Table 3, spatial skills did not mediate the relations between the complex mathematical skills and math anxiety, or between basic number skills and math anxiety. Thus, considering the results of testing both of these hypotheses, a strong version of the cognitive deficits hypothesis does not describe the current data. Although math anxiety was correlated with basic number skills and with spatial skills, similar to the results of other studies, these factors did not account for the relation between math anxiety and math performance.

Table 3

Summary of Mediation Analyses for Prediction of Math Anxiety

		Direct effect		Indirect effect (mediation)			
		unstandardized		unstandardized		standardized	
Predictor	**Mediator**	***b***	**95% CI**	***B***	**95% CI**	**β**	**95% CI**
Hypothesis 1							
(a) Calculation Fluency	Number skills	**-0.16****	**-0.30, -0.02**	-0.02	-0.12, 0.06	-0.05	-0.23, 0.11
(b) Procedural Arithmetic	Number skills	**-1.36****	**-2.17, -0.56**	-0.16	-0.59, 0.20	-0.05	-0.16, 0.05
Hypothesis 2							
(c) Calculation Fluency	Spatial skills	**-0.17****	**-0.27, -0.07**	-0.02	-0.06, 0.00	-0.03	-0.11, 0.00
(d) Procedural Arithmetic	Spatial skills	**-1.39****	**-2.11, -0.67**	-0.13	-0.48, 0.08	-0.04	-0.14, 0.02
(e) Number skills	Spatial skills	**-2.00***	**-3.89, -0.09**	-0.54	-1.38, 0.24	-0.06	-0.16, 0.03
Hypothesis 3							
(f) Number skills	Calculation fluency	-0.58	-2.30, 1.84	**-1.95***	**-3.54, -0.45**	**-0.23***	**-0.40, -0.05**
(g) Number skills	Procedural arithmetic	-0.71	-2.66, 1.25	**-1.82***	**-3.10, -0.90**	**-0.21***	**-0.35, -0.11**

Note. Bolded font indicates a statistically significant result. Confidence intervals are based on 5000 bootstrapped samples and the Sobel test was used to generate the *p*-value for the indirect effect.
**p* < .05. ***p* < .01. ****p* < .001.

Note, non-standardized coefficients are reported as suggested on the Process Macro website (http://processmacro.org/faq.html). A standardized indirect effect was also included to provide consistency with the path models shown in Figure 6 and 7.

Hypothesis 3: The relation between math anxiety and basic number skills will be mediated by complex mathematical skills (Figure 3)*.*

Hypothesis 3 tests a weak version of the Cognitive Deficits Model where relations between basic number skills and math anxiety are shared with relations between complex math skills and math anxiety. As shown in Table 3, the complex mathematics skills significantly mediated the relations between basic number skills and math anxiety. These analyses indicate that there is no direct relationship between basic number skills and math anxiety, once their relations with complex skills are taken into account. Thus, deficits in basic number skills do not explain the relation between math anxiety and math performance.

Our next step was to situate the results of our mediation analyses within a broader model where all measured cognitive predictors were included. First, however, we clarified the relations between spatial skills and gender. Ferguson et al. (2015) found that spatial skills partially mediated the correlation between gender and math anxiety (see also Maloney et al., 2012). Women and men do not typically differ in mathematics performance, even though women sometimes report being more anxious about their mathematical skills than men (Devine, Fawcett, Szűcs, & Dowker, 2012; Dowker, Sarkar, & Looi, 2016; Hembree, 1990; LeFevre et al., 1992) suggesting that the relation between gender and anxiety is not directly tied to number skills. In contrast, women typically perform worse than men on standardized measures of spatial skills (Maeda & Yoon, 2013; Reilly & Neumann, 2013; Uttal et al., 2013; Voyer et al., 1995). One explanation for these observations is that the relation between gender and anxiety may be tied to spatial skills rather than to number skills.

Hypothesis 4: Relations between math anxiety and gender will be mediated by spatial skills.

Spatial ability, gender, and math anxiety were all significantly (albeit weakly) inter-correlated (see Table 2). We evaluated a model in which spatial skills mediated the relation between gender and math anxiety using the PROCESS tool for mediation (Hayes, 2012). The results were not straightforward. On the one hand, 95% confidence interval for the indirect effect of gender on math anxiety (through spatial skills) did not include 0 (b = 1.04, 95% CI [0.17, 2.65]), suggesting that there was an indirect effect, however, the Sobel test on the indirect effect was not significant (p = .13). Ferguson et al. (2015) observed a small but significant indirect effect of gender on math anxiety through mental rotation for a large sample (N = 495). Unlike Ferguson et al. however, in the current sample the direct relation between spatial skills and math anxiety was not significant in this mediation model (b = -1.71, 95% CI [-3.52, .11]) likely explaining the Sobel test result. Thus, we concluded that spatial skills were not a direct predictor of math anxiety for the current sample when gender was included in the model. Nevertheless, spatial skills were significantly related to gender and to basic number skills in this data set and those relations were therefore incorporated into the model presented in the next section. Gender was also included as a direct predictor of math anxiety in the presented model.

Model Construction and Analysis

The analyses conducted to test Hypotheses 1 through 3 suggested that a model in which complex math skills mediate relations between number skills and math anxiety would be a reasonable fit for the present data. In the modified version, we show that weaknesses in basic numerical skills are related to math anxiety indirectly through complex math performance and that complex math performance accounts for additional unique variance in math anxiety. Spatial skills were not directly related to math anxiety, but may have an indirect relation through basic numerical skills. This model re-situates a cognitive deficit as specifically numerical, although the number skills themselves are linked to individual variability in domain-general cognitive skills. Further, this alternative model situates the connection between math performance and math anxiety at the level of more complex mathematical skills, while accounting for the patterns of simple correlations observed in previous research. This alternative model thus provides an integrated perspective on the pattern of relations among the cognitive variables, and shows that, among the range of potential predictors that we included in our study, complex math performance has the most direct connection to math anxiety. Note that this model does not include other possible predictors of math anxiety (specifically online working memory or specific negative experiences), but focuses solely on numerical and cognitive predictors and gender. The model was tested with structural equation modelling, as described below.

Model Testing

Two versions of the model were tested, one for each complex mathematical task, that is, calculation fluency and procedural arithmetic. Both basic number skills and calculation fluency were modelled as latent variables as shown in Figure 5. For the Model shown in Figure 5, fit was strong (χ^{2} = 10.26, p = .25) and factor loadings were all significant (p < .001) and strong (λ > 0.83), suggesting the two latent factors accurately captured these constructs.

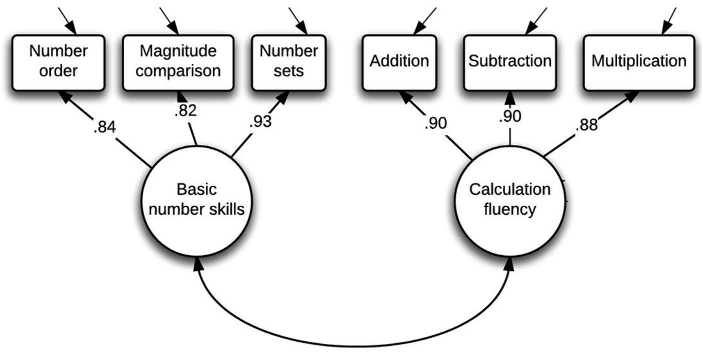

Figure 5. Measurement model of relations between indicator and latent variables representing basic number skills and calculation fluency.

As shown in Figure 6, working memory and spatial skills were assumed to be predictors of basic number skills, and were also allowed to covary. The further assumption was made that the relation between these cognitive factors and both math anxiety and calculation fluency was mediated through basic number skills. Gender was included as a predictor of spatial skills, given the strong support for this relation in the literature. The model included a path from gender directly to math anxiety, but also allowed for an indirect relation between gender and math anxiety that was mediated through spatial skills and basic number skills (following the results of testing Hypothesis 4). Basic number skills are shown as a predictor of math anxiety through complex math performance, reflecting a revised numerical knowledge model. A strong version would have included indirect relations between math performance and math anxiety through cognitive skills. Instead, this model includes a direct path from complex math performance to math anxiety. Note that there is empirical support for a reciprocal relationship between math anxiety and math performance in which poor performance triggers math anxiety and math anxiety triggers poor performance (Carey, Hill, Devine, & Szücs, 2016). Thus it is reasonable to assume that basic number deficits will not fully account for the relation between math performance and math anxiety.

Calculation fluency — The specific model including calculation fluency is shown in Figure 6. All fit statistics indicate a model that strongly fits the observed relations as described in Kline (2016, pp. 270-277). The χ^2 value was not significant indicating the model did not differ significantly from the observed data (Model $\chi^2(31) = 34.37$, $p = .31$), the Root Mean Square Error of Approximation (RMSEA) was less than .05 (Model $RMSEA = 0.03$), the Bentler Comparative Fit Index (CFI) was greater than .95 (Model $CFI = 0.99$), and the Standardized Root Mean Square Residual (SRMR) was less than .08 (Model $SRMR = 0.05$).

As shown in Figure 6, the predicted pathways were all significant with the exception of the direct path from working memory to calculation fluency. The R^2 for predicting basic number skills was 32% ($p < .001$), suggesting that there are other relevant predictors of basic number skills that need to be considered. Basic number skills are strongly related to calculation fluency and 57% ($p < .001$) of the variance in calculation fluency is accounted for in this model. In addition to the direct paths shown in Figure 6, several indirect paths were significant. As predicted, basic number skills are indirectly related to math anxiety through calculation fluency ($\beta = -0.33$, $p = .01$). Spatial skills were indirectly related to calculation fluency through basic number skills ($\beta = .26$, $p = .001$) and to math anxiety through calculation fluency ($\beta = -.11$, $p = .04$). Working memory was indirectly related to calculation fluency through basic number skills ($\beta = .25$, $p = .001$). Importantly, calculation fluency accounts for additional unique variance in math anxiety above and beyond gender and the fundamental cognitive skills (ΔR^2 = 0.079, p = .005). It should be noted however that this model only accounts for 21% of the total observed variance in math anxiety and thus there may be other important predictors not specified in the model.

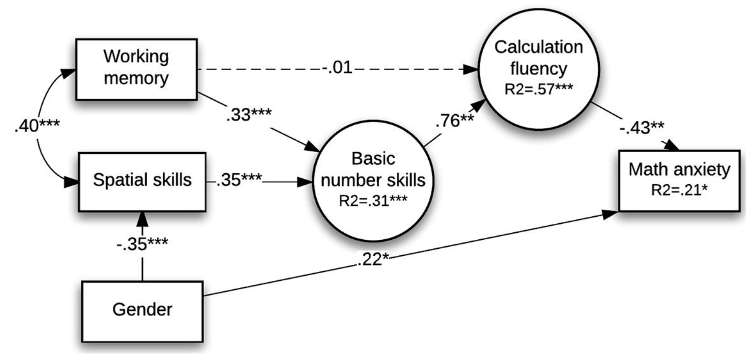

Figure 6. Path Model 1 representing the relations between math anxiety and mathematical performance. Hypothesized pathways shown with dotted lines were not statistically significant when tested within this model. The numbers shown for each line are the standardized coefficients

*p < .05. **p < .01. ***p < .001.

Procedural arithmetic — The model predicting math anxiety through procedural arithmetic (BMA3) is shown in Figure 7. Fit statistics indicate a strongly fitting model, $\chi^2(17)$ = 16.24, p = .51; RMSEA = 0.00; CFI = 1.00; SRMR = 0.05. This model accounted for 25% of the observed variance in math anxiety. As with calculation fluency, basic number skills predicted math anxiety indirectly through procedural arithmetic (β = -0.21, p = .002). Spatial skills were indirectly related to procedural arithmetic through basic number skills (β = 0.18, p = .002). and spatial skills were indirectly related to math anxiety through basic number skills and procedural arithmetic (β = -0.08, p = .014). Like calculation fluency in Figure 6, procedural arithmetic explained additional variance in math anxiety (ΔR^2 = 0.12, p < .001) above that accounted for by gender and basic cognitive skills.

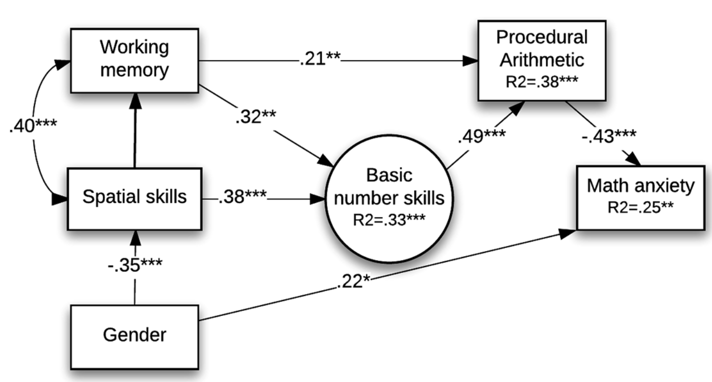

Figure 7. Path Model 2 representing the relations between math anxiety and procedural arithmetic. Pathways shown with dotted lines were not statistically significant. The numbers shown for each line are the standardized coefficients.

*p < .05. **p < .01. ***p < .001.

We note two key differences between the calculation fluency model (Model 1; Figure 6) and the procedural arithmetic model (Model 2: Figure 7). First, working memory was a direct predictor of procedural arithmetic but not of calculation fluency whereas working memory predicted calculation fluency indirectly through shared

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variance with basic number skills. This pattern is consistent with sources of variability in these tasks; procedural arithmetic is more cognitively demanding of working memory whereas skilled performance on calculation fluency occurs when performance is more automated and thus does not put as large a demand on working memory skills. Second, basic number skills were more strongly related to calculation fluency than to procedural arithmetic. In spite of these differences, the models effectively captured the observed co-variances and correlations in the data set thus providing a framework for future research.

Discussion

In the present study, we developed and tested a statistical model to account for the interrelations among math anxiety, math performance, basic number skills and domain-general cognitive factors (i.e., spatial ability and working memory). To develop this model, we first tested hypotheses from the literature that proposed relations between basic cognitive deficits and math anxiety. Next we integrated these results to clarify the direct and indirect relations among these variables. By fitting path models, we showed that adults' performance on calculation fluency and procedural arithmetic measures were moderately predictive of math anxiety. Most importantly, the relations between basic number skills and math anxiety were indirect in both models, that is, those relations were completely mediated by the more complex mathematics skills. Further, the relations between domain-general cognitive skills (i.e., spatial skills and working memory) and math anxiety were also indirect, mediated through either basic numerical and/or complex mathematical skills.

Our results show that research in which correlations between any of the fundamental cognitive and numerical skills and math anxiety are observed needs to be considered carefully in terms of what those correlations may or may not imply about causes and sources of math anxiety. The current work addresses limitations of previous research because multiple indicators of basic number skills, spatial skills and mathematical performance were assessed and modelled simultaneously. However, the model is still limited in that it does not capture any environmental influences on math anxiety and only explains a moderate portion of the variance in math anxiety. These results suggest that the links between cognitive skills and math anxiety should be interpreted cautiously within a broader perspective.

Correlational studies of math anxiety and basic cognitive skills (i.e., magnitude comparison, counting and mental rotation) have been used by some researchers to support the hypothesis that deficits in basic spatial and number skills may be risk factors for the development of math anxiety (Ferguson et al., 2015; Maloney, 2016; Maloney et al., 2011, 2010, 2012). We tested a strong version of this theory where we hypothesized that any relation between math anxiety and complex math skills would be fully accounted for by individual differences in basic cognitive skills. Although we replicated the correlations between math anxiety and basic skills (numeric and spatial) found in other research, these basic cognitive skills did not mediate the relations between complex mathematical performance and math anxiety. Instead, complex math performance fully mediated the relations between basic cognitive skills and math anxiety. Critically, the view that basic number skills are central in understanding math anxiety that is based on research with adults (e.g., Maloney et al., 2010, 2012) was not supported because there was no direct relation between basic number skills and math anxiety. This finding aligns with previous empirical research (Ashcraft & Faust, 1994; Faust et al., 1996; Lyons & Beilock, 2012) providing further evidence that math anxiety is not necessarily closely linked with low levels of basic numeracy among adults.

Similarly, no support was found for the hypothesis that spatial ability mediates the relation between math anxiety and gender for adults (cf. Ferguson et al., 2015; Maloney et al., 2012). This prediction is related to the claim that numerical deficits arise from more general cognitive limitations in spatial abilities, therefore spatial abilities may be linked directly to anxiety about math and, as spatial abilities have been related to gender, spatial abilities may therefore account for any relation between gender and math anxiety. Although all three variables (gender, math anxiety, and spatial ability) were correlated in this sample, there was not a clear meditational pathway.

To provide an integrated account of the pattern of data, we proposed and tested path models of the relations among the variables. The analyses clearly show that individual differences in domain-general cognitive predictors (working memory and spatial skills) are related to math anxiety indirectly either through complex math skills or through basic number skills. The latter are, in turn, related to math anxiety indirectly through complex math skills. One interpretation of this model is that math anxiety is a consequence of deficits in basic number skills (i.e., in acquiring those skills) that, in turn, accounts for poor performance on the more complex mathematical outcomes. This interpretation assumes that the deficits observed in basic number skills precede and contribute to the development of math anxiety (Maloney, 2016).

Some support for the interpretation that numbers-based deficits precede math anxiety comes from research on children with developmental dyscalculia (i.e., deficits in basic number skills) who have much higher math anxiety levels than typically-developing children (Rubinsten & Tannock, 2010). We should however, use caution in extending theories from children with developmental disabilities to typically-developing children or to adults. Research with adults has also been interpreted as evidence that math anxiety arises, in part, as a consequence of deficits in basic number skills (Maloney et al., 2010, 2011; Núñez-Peña & Suárez-Pellicioni, 2014). However, for all research conducted with adults, including the present research, the development of math anxiety and of all mathematical skills preceded current measurement of these variables, and therefore it is not possible to make strong claims about the causal links between math anxiety and basic number skills. Further, our models accounted for under 25% of the variance in math anxiety; thus, even if early deficits do lead to later math anxiety, the present research allows for the strong possibility that other factors play equally or more important roles.

A second interpretation of our results is that the relation between basic number skills and math anxiety reflects the online attentional demands of the number tasks rather than a specific, long-standing deficit in number skills. This interpretation is consistent with the *working memory/attentional model* proposed by Ashcraft and colleagues (Ashcraft & Krause, 2007; Ashcraft & Moore, 2009; Hopko, Ashcraft, Gute, Ruggiero, & Lewis, 1998). Math anxiety influences any moderately stressful math-related task, for example, when there are time limits (Ashcraft & Moore, 2009; Faust et al., 1996) or when numerical information has to be inhibited or controlled (Núñez-Peña & Suárez-Pellicioni, 2014; Pletzer, Kronbichler, Nuerk, & Kerschbaum, 2015). As with other researchers (i.e., Maloney et al., 2011, 2010; Núñez-Peña & Suárez-Pellicioni, 2014) all our basic number tasks were timed and some may also involve inhibitory mechanisms (i.e., the number ordering task where participants must inhibit their responses to sequences that involve familiar numbers such as 1 3 2). It is possible that math-anxious participants responding to timed numerical tasks and numerical tasks that required inhibitory control experienced performance deficits that masked their true basic number skills.

The models also showed clearly that the relation between spatial skills and math anxiety is indirect for this adult sample; again, any claims about causality are not strongly supported by this pattern because basic and complex number skills fully mediated the relation between spatial skills and math anxiety. In contrast, Ferguson et al. (2015) proposed that deficits in basic spatial skills may be a root cause of math anxiety and they suggested that spatial skills training could potentially decrease math anxiety. However, Ferguson et al. did not test their claims directly and did not consider competing hypotheses. Furthermore, it seems premature to base conclusions about the relations between spatial abilities and math anxiety in children on work with adults. Overcoming math anxiety among adults likely requires a direct approach that involves either training weak number skills or attempting to reduce math anxiety directly (Khng, 2017; Lyons & Beilock, 2012; Morsanyi et al., 2014).

Finally, we found that the relation between spatial skills and mathematical performance was fully accounted for by shared relations with basic number skills. This finding adds to the literature on the relation between number and spatial skills. There is a strong body of research linking spatial skills, specifically visualization and mental rotation, to arithmetic performance in adults (see Mix & Cheng, 2012). Although this issue was not the focus of the current study, it is one that calls for more research on how spatial skills are related to children's acquisition of basic number knowledge, ideally starting from an early age (e.g., Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2017).

Conclusion

In the current study, deficits in domain-general spatial and working memory skills among adults did not account for the relation between math anxiety and math performance and were indirectly related to math anxiety through more complex mathematical skills. A *strong cognitive deficits hypothesis* was not supported for our adult participants. Moreover, consistent with other research on math anxiety among adults, the link between numerical processes and math anxiety was moderate (Ashcraft & Faust, 1994; Ashcraft & Moore, 2009; Faust et al., 1996; Maloney et al., 2011, 2010), further suggesting that other factors are equally, or perhaps more important, in the manifestation of math anxiety among adults. Future research is needed to test some of the relations suggested by the model in the current work. In particular, more information is required about the role of basic number skills in the development of math anxiety. One suggestion is to explore the effect of anxiety remediation on basic number skill performance. This approach could address whether math anxiety is masking basic number skill proficiency. An alternate approach is to develop measures of basic number skills that clearly do not evoke an anxiety response to clarify what aspect of performance is related to math anxiety; that is, are the performance differences numerical or do they reflect dynamic effects of math anxiety on performance?

In spite of the suggestion that math anxiety may arise in part from basic low-level deficits in numerical processing (Maloney, 2016; Maloney et al., 2010, p. 14) one cannot use correlations obtained for adults to make causal claims about the relations between math anxiety and fundamental skills, nor to conclude that low-level performance deficits may cause some children to develop math anxiety. Accordingly, our research does not tell us about the causes of math anxiety. An equally plausible conclusion for low performance on basic number tasks may be that these tasks elicit an anxiety response in math-anxious individuals because these tasks involve numbers and are timed. Furthermore, math anxiety may not be a stable individual difference in early childhood. Although Ma and Xu (2004) found that math anxiety became stable after grade 8, there are no longitudinal studies following children through elementary school. To ascribe causality, future research should focus on the changing relations among risk factors, math anxiety, and math performance over time. The current research is useful in that it clarifies the relations among the various measures for adults and because it cautions us not to make (backwards) causal predictions from adults' performance to that of children. Understanding the risk factors associated with math anxiety and how those factors may contribute to math performance is an important step in developing interventions to alleviate the effects of math anxiety on performance.

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Competing Interests

The authors have declared that no competing interests exist.

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Data Availability Statement

The underlying data for this article can be made available by contacting the authors.

References

Ashcraft, M. H., & Faust, M. W. (1994). Mathematics anxiety and mental arithmetic performance: An exploratory investigation. *Cognition and Emotion, 8*(2), 97-125. doi:10.1080/02699939408408931

Ashcraft, M. H., & Kirk, E. P. (2001). The relationships among working memory, math anxiety, and performance. *Journal of Experimental Psychology: General, 130*(2), 224-237. doi:10.1037/0096-3445.130.2.224

Ashcraft, M. H., & Krause, J. A. (2007). Working memory, math performance, and math anxiety. *Psychonomic Bulletin & Review, 14*(2), 243-248. doi:10.3758/BF03194059

Ashcraft, M. H., & Moore, A. M. (2009). Mathematics anxiety and the affective drop in performance. *Journal of Psychoeducational Assessment, 27*(3), 197-205. doi:10.1177/0734282908330580

Ashcraft, M. H., & Ridley, K. S. (2005). Math anxiety and its cognitive consequences: A tutorial review. In J. I. D. Campbell (Ed.), *Handbook of mathematical cognition* (pp. 315-327). New York, NY, USA: Psychology Press.

Baddeley, A. (2003). Working memory: Looking back and looking forward. *Nature Reviews Neuroscience, 4*(10), 829-839. doi:10.1038/nrn1201

Beilock, S. L. (2008). Math performance in stressful situations. *Current Directions in Psychological Science, 17*(5), 339-343. doi:10.1111/j.1467-8721.2008.00602.x

Beilock, S. L., & Decaro, M. S. (2007). From poor performance to success under stress: Working memory, strategy selection, and mathematical problem solving under pressure. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33*(6), 983-998. doi:10.1037/0278-7393.33.6.983

Beilock, S. L., Kulp, C. A., Holt, L. E., & Carr, T. H. (2004). More on the fragility of performance: Choking under pressure in mathematical problem solving. *Journal of Experimental Psychology: General, 133*(4), 584-600. doi:10.1037/0096-3445.133.4.584

Bourassa, A. (2014). *Numerical sequence recognition: Is familiarity or ordinality the primary factor in performance?* (Master's thesis, Carleton University, Ottawa, Canada). Retrieved from https://curve.carleton.ca/282e5db5-4f36-4e5f-93fa-7a47bbaf5640

Carey, E., Hill, F., Devine, A., & Szücs, D. (2016). The chicken or the egg? The direction of the relationship between mathematics anxiety and mathematics performance. *Frontiers in Psychology, 6*, Article 1987. doi:10.3389/fpsyg.2015.01987

Castronovo, J., Göbel, S. M., Seron, X., Humphreys, G., Popescu, T., & Price, C. (2012). Impact of high mathematics education on the number sense. *PLOS ONE, 7*(4), Article e33832. doi:10.1371/journal.pone.0033832

De Smedt, B., Noël, M.-P., Gilmore, C., & Ansari, D. (2013). How do symbolic and non-symbolic numerical magnitude processing skills relate to individual differences in children's mathematical skills? A review of evidence from brain and behavior. *Trends in Neuroscience and Education, 2*(2), 48-55. doi:10.1016/j.tine.2013.06.001

DeStefano, D., & LeFevre, J.-A. (2004). The role of working memory in mental arithmetic. *The European Journal of Cognitive Psychology, 16*(3), 353-386. doi:10.1080/09541440244000328 Retrieved from http://resolver.scholarsportal.info/resolve/09541446/v16i0003/353_trowmima.xml

Devine, A., Fawcett, K., Szűcs, D., & Dowker, A. (2012). Gender differences in mathematics anxiety and the relation to mathematics performance while controlling for test anxiety. *Behavioral and Brain Functions, 8*(1), Article 33. doi:10.1186/1744-9081-8-33

Dietrich, J. F., Huber, S., Moeller, K., & Klein, E. (2015). The influence of math anxiety on symbolic and non-symbolic magnitude processing. *Frontiers in Psychology, 6*(October), Article 1621. doi:10.3389/fpsyg.2015.01621

Douglas, H. (2015). *Math anxiety: Not just a numbers game* (Master's thesis, Carleton University, Ottawa, Canada). Retrieved from https://curve.carleton.ca/13fa5d8c-cf04-427e-9f0d-c8f449c6e1ad

Dowker, A., Bennett, K., & Smith, L. (2012). Attitudes to mathematics in primary school children. *Child Development Research, 2012*, Article 124939. doi:10.1155/2012/124939

Dowker, A., Sarkar, A., & Looi, C. Y. (2016). Mathematics anxiety: What have we learned in 60 years? *Frontiers in Psychology, 7*(April), Article 508. doi:10.3389/fpsyg.2016.00508

Ekstrom, R. B., French, J. W., & Harman, H. H. (1976, August). *Manual for Kit of Factor-Referenced Cognitive Tests.* Retrieved from https://www.ets.org/Media/Research/pdf/Manual_for_Kit_of_Factor-Referenced_Cognitive_Tests.pdf

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion, 7*(2), 336-353. doi:10.1037/1528-3542.7.2.336

Faust, M. W., Ashcraft, M. H., & Fleck, D. E. (1996). Mathematics anxiety effects in simple and complex addition. *Mathematical Cognition, 2*(1), 25-62. doi:10.1080/135467996387534

Ferguson, A. M., Maloney, E. A., Fugelsang, J. A., & Risko, E. F. (2015). On the relation between math and spatial ability: The case of math anxiety. *Learning and Individual Differences, 39*, 1-12. doi:10.1016/j.lindif.2015.02.007

Field, A. P. (2013). *Discovering statistics using IBM SPSS Statistics: And sex drugs and rock 'n' roll* (4th ed.). Los Angeles, CA, USA: SAGE.

Geary, D. C., Bailey, D. H., & Hoard, M. K. (2009). Prediciting mathematical achievement and mathematical learning disability with a simple screening tool. *Journal of Psychoeducational Assessment, 27*(3), 265-279. doi:10.1177/0734282908330592

Hayes, A. F. (2012). *PROCESS: A versatile computational tool for observed variable mediation, moderation, and conditional process modeling* [White paper]. Retrieved from http://www.afhayes.com/ public/process2012.pdf

Hembree, R. (1990). The nature, effects, and relief of mathematics anxiety. *Journal for Research in Mathematics Education, 21*(1), 33-46. Retrieved from http://www.jstor.org/stable/749455doi:10.2307/749455

Hill, F., Mammarella, I. C., Devine, A., Caviola, S., Passolunghi, M. C., & Szűcs, D. (2016). Maths anxiety in primary and secondary school students: Gender differences, developmental changes and anxiety specificity. *Learning and Individual Differences, 48*, 45-53. doi:10.1016/j.lindif.2016.02.006

Holloway, I. D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The numerical distance effect and individual differences in children's mathematics achievement. *Journal of Experimental Child Psychology, 103*(1), 17-29. doi:10.1016/j.jecp.2008.04.001

Hopko, D. R., Ashcraft, M. H., Gute, J., Ruggiero, K. J., & Lewis, C. (1998). Mathematics anxiety and working memory: Support for the existence of a deficient inhibition mechanism. *Journal of Anxiety Disorders, 12*(4), 343-355. doi:10.1016/S0887-6185(98)00019-X

Hopko, D. R., Hunt, M. K., & Armento, M. E. A. (2005). Attentional task aptitude and performance anxiety. *International Journal of Stress Management, 12*(4), 389-408. doi:10.1037/1072-5245.12.4.389

Hopko, D. R., Mahadevan, R., Bare, R. L., & Hunt, M. K. (2003). The abbreviated math anxiety scale (AMAS): Construction, validity, and reliability. *Assessment, 10*(2), 178-182. doi:10.1177/1073191103010002008

Kepner, M. D., & Neimark, E. D. (1984). Test-retest reliability and differential patterns of score change on the group embedded figures test. *Journal of Personality and Social Psychology, 46*(6), 1405-1413. doi:10.1037/0022-3514.46.6.1405

Khng, K. H. (2017). A better state-of-mind: Deep breathing reduces state anxiety and enhances test performance through regulating test cognitions in children. *Cognition and Emotion, 31*, 1502-1510. doi:10.1080/02699931.2016.1233095

Kline, R. B. (2016). *Principles and practice of structural equation modeling* (4th ed.). New York, NY, USA: The Guilford Press.

Krinzinger, H., Kaufmann, L., & Willmes, K. (2009). Math anxiety and math ability in early primary school years. *Journal of Psychoeducational Assessment, 27*(3), 206-225. doi:10.1177/0734282908330583

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LeFevre, J.-A., Kulak, A. G., & Heymans, S. L. (1992). Factors influencing the selection of university majors varying in mathematical content. *Canadian Journal of Behavioural Science, 24*(3), 276-289. doi:10.1037/h0078742

Lyons, I. M., & Beilock, S. L. (2011). Numerical ordering ability mediates the relation between number-sense and arithmetic competence. *Cognition, 121*(2), 256-261. doi:10.1016/j.cognition.2011.07.009

Lyons, I. M., & Beilock, S. L. (2012). Mathematics anxiety: Separating the math from the anxiety. *Cerebral Cortex, 22*(9), 2102-2110. doi:10.1093/cercor/bhr289

Lyons, I. M., Price, G. R., Vaessen, A., Blomert, L., & Ansari, D. (2014). Numerical predictors of arithmetic success in grades 1-6. *Developmental Science, 17*(5), 714-726. doi:10.1111/desc.12152

Ma, X., & Xu, J. (2004). The causal ordering of mathematics anxiety and mathematics achievement: A longitudinal panel analysis. *Journal of Adolescence, 27*(2), 165-179. doi:10.1016/j.adolescence.2003.11.003

Maeda, Y., & Yoon, S. Y. (2013). A meta-analysis on gender differences in mental rotation ability measured by the Purdue Spatial Visualization Tests: Visualization of Rotations (PSVT:R). *Educational Psychology Review, 25*(1), 69-94. doi:10.1007/s10648-012-9215-x

Maloney, E. A. (2016). Math anxiety: Causes, consequences, and remediation. In K. R. Wentzel & D. B. Miele (Eds.), *Handbook of Motivation at School* (2nd ed., pp. 408-423). New York, NY, USA: Routledge.

Maloney, E. A., Ansari, D., & Fugelsang, J. A. (2011). The effect of mathematics anxiety on the processing of numerical magnitude. *Quarterly Journal of Experimental Psychology, 64*(1), 10-16. doi:10.1080/17470218.2010.533278

Maloney, E. A., & Beilock, S. L. (2012). Math anxiety: Who has it, why it develops, and how to guard against it. *Trends in Cognitive Sciences, 16*(8), 404-406. doi:10.1016/j.tics.2012.06.008

Maloney, E. A., Risko, E. F., Ansari, D., & Fugelsang, J. A. (2010). Mathematics anxiety affects counting but not subitizing during visual enumeration. *Cognition, 114*(2), 293-297. doi:10.1016/j.cognition.2009.09.013

Maloney, E. A., Waechter, S., Risko, E. F., & Fugelsang, J. A. (2012). Reducing the sex difference in math anxiety: The role of spatial processing ability. *Learning and Individual Differences, 22*(3), 380-384. doi:10.1016/j.lindif.2012.01.001

Mix, K. S., & Cheng, Y. L. (2012). The relation between space and math: Developmental and educational implications. *Advances in Child Development and Behavior, 42*, 197-243. doi:10.1016/B978-0-12-394388-0.00006-X

Morsanyi, K., Busdraghi, C., & Primi, C. (2014). Mathematical anxiety is linked to reduced cognitive reflection: A potential road from discomfort in the mathematics classroom to susceptibility to biases. *Behavioral and Brain Functions, 10*(1), Article 31. doi:10.1186/1744-9081-10-31

Nosworthy, N., Bugden, S., Archibald, L., Evans, B., & Ansari, D. (2013). A two-minute paper-and-pencil test of symbolic and nonsymbolic numerical magnitude processing explains variability in primary school children’s arithmetic competence. *PLOS ONE, 8*(7), Article e67980. doi:10.1371/journal.pone.0067918

Núñez-Peña, M. I., & Suárez-Pellicioni, M. (2014). Less precise representation of numerical magnitude in high math-anxious individuals: An ERP study of the size and distance effects. *Biological Psychology, 103*, 176-183. doi:10.1016/j.biopsycho.2014.09.004

PsychOpen
publishing psychology

Peters, M., Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., & Richardson, C. (1995). A redrawn Vandenberg and Kuse Mental Rotations Test: Different versions and factors that affect performance. *Brain and Cognition, 28*, 39-58. doi:10.1006/brcg.1995.1032

Pletzer, B., Kronbichler, M., Nuerk, H. C., & Kerschbaum, H. H. (2015). Mathematics anxiety reduces default mode network deactivation in response to numerical tasks. *Frontiers in Human Neuroscience, 9*(April), Article 202. doi:10.3389/fnhum.2015.00202

Raghubar, K. P., Barnes, M. A., & Hecht, S. A. (2010). Working memory and mathematics: A review of developmental, individual difference, and cognitive approaches. *Learning and Individual Differences, 20*(2), 110-122. doi:10.1016/j.lindif.2009.10.005

Reilly, D., & Neumann, D. L. (2013). Gender-role differences in spatial ability: A meta-analytic review. *Sex Roles, 68*(9-10), 521-535. doi:10.1007/s11199-013-0269-0

Richardson, F. C., & Suinn, R. M. (1972). The Mathematics Anxiety Rating Scale: Psychometric data. *Journal of Counseling Psychology, 19*(6), 551-554. doi:10.1037/h0033456

Rubinsten, O., & Tannock, R. (2010). Mathematics anxiety in children with developmental dyscalculia. *Behavioral and Brain Functions, 6*, Article 46. doi:10.1186/1744-9081-6-46

Sasanguie, D., Göbel, S. M., Moll, K., Smets, K., & Reynvoet, B. (2013). Approximate number sense, symbolic number processing, or number-space mappings: What underlies mathematics achievement? *Journal of Experimental Child Psychology, 114*(3), 418-431. doi:10.1016/j.jecp.2012.10.012

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*(3972), 701-703. doi:10.1126/science.171.3972.701

Sowinski, C. (2016). *Numerical building blocks: Exploring domain-specific cognitive predictors of mathematics* (Doctoral thesis, Carleton University, Ottawa, Canada). Retrieved from https://curve.carleton.ca/ee6b6815-6c69-4bb8-bc97-7cbb6c822f1f

Sowinski, C., Dunbar, K., & LeFevre, J. (2014). *Calculation Fluency Test* (Unpublished technical report). Math Lab, Carleton University, Ottawa, Canada.

Steiner, E. T., & Ashcraft, M. H. (2012). Three brief assessments of math achievement. *Behavior Research Methods, 44*, 1101-1107. doi:10.3758/s13428-011-0185-6

Suárez-Pellicioni, M., Núñez-Peña, M. I., & Colomé, À. (2014). Reactive recruitment of attentional control in math anxiety: An ERP study of numeric conflict monitoring and adaptation. *PLOS ONE, 9*(6), Article e99579. doi:10.1371/journal.pone.0099579

Suárez-Pellicioni, M., Núñez-Peña, M. I., & Colomé, À. (2016). Math anxiety: A review of its cognitive consequences, psychophysiological correlates, and brain bases. *Cognitive, Affective & Behavioral Neuroscience, 16*(1), 3-22. doi:10.3758/s13415-015-0370-7

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin, 139*, 352-402. doi:10.1037/a0028446

PsychOpen
publishing psychology

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. S. (2017). II. Methods for longitudinal study of preschool spatial and mathematical skills. *Monographs of the Society for Research in Child Development, 82*(1), 31-55. doi:10.1111/mono.12281

Voyer, D., Voyer, S., Bryden, M. P., Bigelow, A., Brooks, G. P., Bulman-Fleming, B., . . . Johnson, R. W. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin, 117*(2), 250-270. doi:10.1037/0033-2909.117.2.250

Vukovic, R. K., Kieffer, M. J., Bailey, S. P., & Harari, R. R. (2013). Mathematics anxiety in young children: Concurrent and longitudinal associations with mathematical performance. *Contemporary Educational Psychology, 38*(1), 1-10. doi:10.1016/j.cedpsych.2012.09.001

Wiley, J., & Jarosz, A. F. (2012). How working memory capacity affects problem solving. *Psychology of Learning and Motivation, 56*, 185-227. doi:10.1016/B978-0-12-394393-4.00006-6

Wu, S. S., Barth, M., Amin, H., Malcarne, V., & Menon, V. (2012). Math anxiety in second and third graders and its relation to mathematics achievement. *Frontiers in Psychology, 3*, Article 162. doi:10.3389/fpsyg.2012.00162

Appendices

Appendix A: Correlations Among Measured Variables

										Mathematics Outcomes				
		Memory Spans			Basic Number Skills			Spatial Skills			Calculation fluency			
Variable	**AMAS**	**DSF**	**DSB**	**SS**	**MC**	**Order**	**# sets**	**MRT**	**HFT**	**SF**	**add**	**sub**	**mult**	**BMA3**
gender	.22*	.11	.07	.19	-.12	-.16	-.22*	-.21*	-.27*	-.09	-.01	.00	.02	.01
AMAS		-.26*	-.09	-.01	-.25*	-.28**	-.29*	-.12	-.29**	-.33**	-.30**	-.39**	-.35**	-.43**
DS forward			.36**	.14	.01	.14	.06	.06	.23*	.16	.08	.08	-.02	.20
DS back				.24*	.18	.28**	.29**	.19	.24*	.40**	.22*	.19	.19	.35**
Spatial span					.36**	.31**	.37**	.30**	.11	.37**	.33**	.25*	.21	.32**
Mag compar						.66**	.78**	.23*	.28**	.69**	.64**	.58**	.56**	.41**
ordering							.79**	.27*	.41**	.72**	.66**	.64**	.58**	.55**
Number set								.46**	.32**	.76**	.64**	.59**	.57*	.55**
Rotation									.36**	.25*	.07	.01	.04	.33**
Hidden fig.										.22*	.23*	.27*	.20	.27**
Simple Flu											.63**	.64**	.55**	.54**
CF Addition												.82**	.79**	.58**
CF Subtract													.80**	.60**
CF Multiply														.61**

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

Appendix B: Standardized Indirect Effects of Interest not Shown in the Path Models

Model	**Spatial skills on AMAS through number and complex math**	**Number skills on AMAS through complex math**	**WM on AMAS through number and complex math**	**WM on complex math through number**	**Gender on AMAS through spatial, number and complex math**
Model 1: Calculation Fluency	-.11*	-.33*	-.11*	.25**	.04
Model 2: Procedural Arithmetic	-.08*	-.21**	-.16**	.48**	.03*

Note. WM = Working Memory score. AMAS = Abbreviated Math Anxiety Scale score.

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

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