Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

Original Article

Testing the specificity of links between anxiety and performance within mathematics and spatial reasoning

Richard J. Daker,[1] Véronic Delage,[2] Erin A. Maloney,[2] and Ian M. Lyons[1]

[1]Department of Psychology, Georgetown University, Washington, DC. [2]School of Psychology, University of Ottawa, Ottawa, Ontario, Canada

Address for correspondence: Richard J. Daker, Department of Psychology, Georgetown University, 306N White-Gravenor Hall, 37th and O Streets, N.W., Washington, DC 20057. rjd107@georgetown.edu

Anxiety within the domains of math and spatial reasoning have consistently been shown to predict performance within those domains. However, little work has focused on how specific these associations are. Across two studies, we systematically tested the degree of specificity in relations between anxiety and performance within math and spatial reasoning. Results consistently showed that anxiety within a cognitive domain predicted performance in that domain even when controlling for other forms of anxiety, providing evidence that cognition-specific anxieties are valuable for understanding cognition-specific performance. We also found that general trait anxiety did not explain a significant portion the anxiety–performance link in either math or spatial reasoning, suggesting that these anxiety–performance associations are not due to the propensity to feel anxious generally. Interestingly, while spatial anxiety did not explain any of the anxiety–performance association in math, math anxiety did explain a significant portion of the anxiety–performance link in spatial reasoning. These results suggest that, while links between anxiety and performance cannot be reduced to a single underlying general anxiety construct, there may nevertheless be overlap between domain anxieties. We end by calling for a more detailed examination of the unique and shared mechanisms linking anxiety and performance across disparate cognitive domains.

Keywords: math anxiety; spatial anxiety; math performance; spatial reasoning

Introduction

Ability in the domains of mathematics and spatial reasoning have emerged as important prerequisites to securing a career in science, technology, engineering, and math (STEM) fields.[1–5] Despite the importance of these fields for societal advancement, and despite the relatively high pay offered by STEM as compared to non-STEM jobs, many STEM jobs around the world go unfilled.[6] Spurred on by this, researchers have put a great deal of effort into understanding ways to foster math and spatial ability. One of the key barriers to successful math and spatial performance that researchers have identified is feelings of anxiety specific to each form of cognition—that is, math anxiety and spatial anxiety. Past work has found that individuals who are high in math anxiety reliably underperform in math compared to their less-anxious peers,[7–9] and the same is true for spatial anxiety and spatial underperformance.[10–12] Better understanding the nature of associations between anxiety and performance within these cognitive domains can provide insights that could prove key in alleviating these barriers to successful performance.

An important question that has not yet been fully addressed in the literatures on math and spatial anxiety is the following: how specific are associations between anxiety and performance within a domain? In other words, how specific is the link between math anxiety and math performance, and how specific is the link between spatial anxiety and spatial performance? Past review papers and meta-analyses in the math anxiety literature have generally made

doi: 10.1111/nyas.14761

the case that math anxiety is specific to math by relying on findings that math anxiety is only moderately correlated with general trait anxiety, which indicates that there is a meaningful difference between the two constructs.[9,13,14] Other work has made use of factor analysis to provide evidence that anxieties toward specific types of reasoning are distinct from one another.[10,15–17] These findings provide evidence that anxiety toward math and spatial reasoning are specific in an important sense—they are separate constructs from one another and general anxiety.

Another important test of the specificity of these cognition-specific anxieties, like math anxiety and spatial anxiety, concerns predictive specificity. One of the core reasons why math anxiety, for instance, has received so much research attention is because it has been found to be reliably negatively correlated with math ability and is thought to be a barrier to successful math performance.[7–9,18] However, if associations between math anxiety and math performance could be fully accounted for by individual differences in, for instance, general trait anxiety, this would (more or less) negate the usefulness of math anxiety as a construct. If, on the other hand, math anxiety continued to predict unique variance in outcomes we care about, like math performance, even when controlling for other forms of anxiety, this would lend support to the idea that "math anxiety," specifically, is a useful construct and should not be disregarded in favor of more general constructs like general trait anxiety. Confirming that anxieties about specific forms of cognition predict differences in the target cognitive ability even when other forms of anxiety are controlled for is, therefore, an important test of the idea that these anxieties are specific. A handful of previous studies have begun to address this question. A recent study by Di Lonardo Burr and LeFevre,[19] for instance, found that, controlling for general trait anxiety and literacy anxiety, math anxiety is predictive of math performance but not of literacy performance, and the same is true of literacy anxiety and literacy performance. Other studies have shown that math anxiety continues to predict math performance even when controlling for general anxiety.[11,20] Interestingly, other work found that math anxiety was a significant predictor of math achievement when controlling for general anxiety in secondary school students, but for primary school students, math anxiety fails to predict unique variance in math achievement when general anxiety is controlled for.[21] And in Lyons *et al.*,[10] specific subtypes of spatial anxiety (i.e., anxiety toward mental manipulation, navigation, and mental imagery) were found to predict performance on spatial tasks that tapped into the relevant ability even when controlling for the other forms of spatial anxiety and general anxiety. Additionally, a recent meta-analysis by Caviola and colleagues[22] used a different approach to address questions about predictive specificity by showing that the meta-analytic association between math anxiety and math achievement ($r = -0.30$) was significantly stronger than the association between test anxiety and math achievement ($r = -0.23$), providing additional evidence that assessing anxiety toward math, in particular, can add predictive value.

In the present work, we make use of two different samples to build on this previous work by systematically investigating how specific the associations between anxiety and performance within the domains of math and spatial reasoning are. We tested whether math anxiety continues to predict unique variance in math performance when holding constant general trait anxiety and spatial anxiety (and vice versa with a focus on the spatial anxiety–spatial performance link). There is substantial evidence that the cognitive domains of math and spatial reasoning are closely linked.[23–26] There is a great deal of work showing that mathematical thinking often relies on spatial strategies,[27–29] suggesting that spatial reasoning plays an important role in supporting mathematical thinking. Some work even suggests that people associate specific numerical properties (e.g., addition and subtraction) with spatial directions (e.g., left and right).[30,31] Likely owing to this tight association between math and spatial reasoning, abilities within these domains are routinely positively correlated with one another.[23–25,32,33] As a result of this interconnectedness, examining whether math anxiety and spatial anxiety uniquely predict performance in their respective domains constitutes a particularly strict test-case for determining the specificity of within-domain anxiety–performance associations.

In this work, in addition to testing whether, for instance, math anxiety continues to predict unique variance in math performance when controlling for general trait anxiety and spatial anxiety, we also directly quantify the extent to which these associations can be accounted for by these other forms of anxiety (e.g., how much of the math anxiety–math performance link can be explained by general trait anxiety?), and how much cannot be. As we discuss above, there is already evidence that math anxiety predicts math performance even when controlling for general anxiety. However, no work we are aware of has ever quantified how much of the association between math anxiety and math performance general anxiety can explain. This is consequential—if it were the case that general anxiety explained a substantial portion of the math anxiety–math performance association, it would suggest that targeting general anxiety could boost the math performance of math-anxious individuals. However, if we found that general anxiety did not explain any of the math anxiety–math performance association, it would suggest that targeting general anxiety would not boost math performance of those who are math-anxious. (Of course, any such findings would need to be followed up with experimental evidence to afford any causal claims.) This approach also allows us to quantify the effect sizes of *cross-domain effects*, that is, to what extent, for instance, does math anxiety explain the association between spatial anxiety and spatial performance? From a practical standpoint, if results showed that math anxiety could explain a significant portion of the spatial anxiety–spatial performance association, it would suggest that reducing math anxiety could have the potential to boost spatial performance; the same would be true if results showed that spatial anxiety could explain a portion of the math anxiety–math performance association. From a theoretical standpoint, this type of analytic approach provides a means of examining another side of specificity, that is, how much do cognition-specific anxieties predict performance in other cognitive domains? Conducting such an analysis with a focus on anxiety and performance within the domains of math and spatial reasoning—domains that are closely related—can provide a stringent initial test case for the idea that links between anxiety and performance in a domain are truly specific and not explainable by anxiety toward other domains.

In the present work, we addressed these questions by examining two different samples with a range of different math and spatial performance measures. In study 1, we simplified our approach by analyzing an existing dataset that included only a single canonical measure (i.e., widely used in the literature) each of math and spatial performance. In contrast, in study 2, we made use of an existing dataset that included five different measures each of math and spatial performance. We then extracted factor scores for each domain to represent the broader constructs of math performance and spatial performance. By asking the same research questions of two datasets with differing measures, we can assess whether the core findings from one study generalize to the other. If we observe a given result across both studies, it can augment our confidence in the robustness of that finding and provide evidence that the result is not dependent on the design idiosyncrasies of one study. Conversely, if a given result differs across studies, this may suggest that result is less robust and thus should perhaps be interpreted with additional caution.

Study 1

Study 1 assessed the extent to which associations between math anxiety and math performance could be explained by individual differences in general trait anxiety and/or spatial anxiety. We used the same approach to examine specificity in the association between spatial anxiety and spatial performance. Study 1 made use of a sample of first-year undergraduate students at the University of Western Ontario (London, Canada). Performance measures were based on a canonical math and a canonical spatial task widely used in the literature.

Materials and methods

Participants. A total of 186 first-year undergraduate students (118 females, 68 males; mean age = 18.56, SD = 0.42) at the University of Western Ontario participated during their first semester on campus. Participants were recruited widely throughout campus via flyers. It should be noted that these data analyzed here are part of a larger dataset used in other papers.[2,34,35] The theoretical questions, analyses, and reports addressed in this paper are original.

Procedure. Participants provided written consent to participate, and the University of Western Ontario Ethics Review Board approved all procedures. Each participant completed a battery of computer-based questionnaires and cognitive tasks in the lab that lasted 2 h and were compensated $20 CAD. The order of all measures was randomized.

Details on the relevant measures to the current work can be found below.

Math anxiety. Math anxiety was measured using the short math anxiety rating scale (sMARS[36]). Participants rated how anxious they would feel in 25 math-related situations (e.g., "being given a set of division problems to solve on paper") on a scale from 0 (not at all) to 4 (very much). The items on the sMARS are adapted from a longer scale called the Math Anxiety Rating Scale (MARS[37]). Possible math anxiety scores range from 0 to 100. Cronbach's α for this measure was 0.96.

Spatial anxiety. Spatial anxiety was measured using the Spatial Anxiety Scale (SAS[10]). The SAS measures anxiety toward three subtypes of spatial reasoning: mental manipulation, spatial navigation, and spatial imagery. Because this study is specifically interested in associations involving anxiety about and performance in mental manipulation, the mental manipulation subscale was used as spatial anxiety variable of interest. In this scale, participants indicate how anxious they would feel in situations involving mental manipulation (e.g., "asked to imagine and mentally rotate a 3-dimensional figure") on a scale from 0 (Not at all) to 4 (Very much). There were eight items in the mental manipulation subscale, yielding a range of possible scores from 0 to 32; greater values indicate greater anxiety. Cronbach's α for this measure was 0.87.

General trait anxiety. General trait anxiety was measured using the trait component of the State-Trait Anxiety Inventory (STAI[38]). Participants respond to statements like "I worry too much over something that doesn't really matter" on a scale from 1 (almost never) to 4 (almost always) based on how they generally feel. The scale contains a total of 20 items, and possible scores range from 20 to 80, where higher scores indicate greater general anxiety. General trait anxiety was included as a covariate to control for general anxiety that is not specific to math. Cronbach's α for this measure was 0.93.

Math performance. Participants completed difficult mental arithmetic problems adapted from the Kit of Factor-Referenced Cognitive Tests.[39,40] Trials included all four basic arithmetic operations: addition (three 2-digit numbers, e.g., $45 + 72 + 87$), subtraction (a 2- or 3-digit minuend and a 2- or 3-digit subtrahend, e.g., 354–87), multiplication (one 2-digit number and one 1-digit number, e.g., 64×6), and division (a 1-digit divisor into a 2- or 3-digit dividend, e.g., $432 \div 9$). Problems were open-ended, and participants responded by typing their answer using the number pad on the keyboard. They were required to calculate the answer mentally, that is, pencil and paper or other devices were not permitted to aid with calculation. As such, the task was relatively difficult for arithmetic (mean accuracy = 81.2%, mean RT = 9.91 s). Operation types were presented in separate blocks, and in each block, participants completed as many problems as they could in 3 minutes. Participants were not aware that there was a time limit, and the block ended once a participant completed the trial they were at once 3 min had passed (this final trial was not included as part of their score because the 3-min time limit had expired). A math performance score was computed for each participant by summing the total number of problems answered correctly across all four operation types, where higher scores indicate greater math performance. Past work has shown that performance on this task is correlated with performance on several basic numerical tasks (including numerical ordering and numerical comparison tasks[40]). Internal reliability for this task was computed using participants' scores for each of the four operation types; Cronbach's α was 0.89.

Spatial performance. Spatial performance was measured via the Mental Rotation Task (MRT[41]). Participants saw two two-dimensional drawings of three-dimensional objects made of cube-shaped blocks. In half of the trials, the two objects were the same object, just rotated along one of the x, y, and z axes. The degree to which objects were rotated varied across trials. In the other half of the trials, the two objects were different objects and could not be rotated to match the same shape. Participants were asked to determine as quickly and accurately as possible whether the block figures were the same or different objects, and participants made their response via the keyboard. Each trial had a maximum duration of 12 seconds. Participants completed five practice trials, and the main task was comprised of 50 trials. Accuracy was used as the measure of spatial performance. Cronbach's α was 0.82.

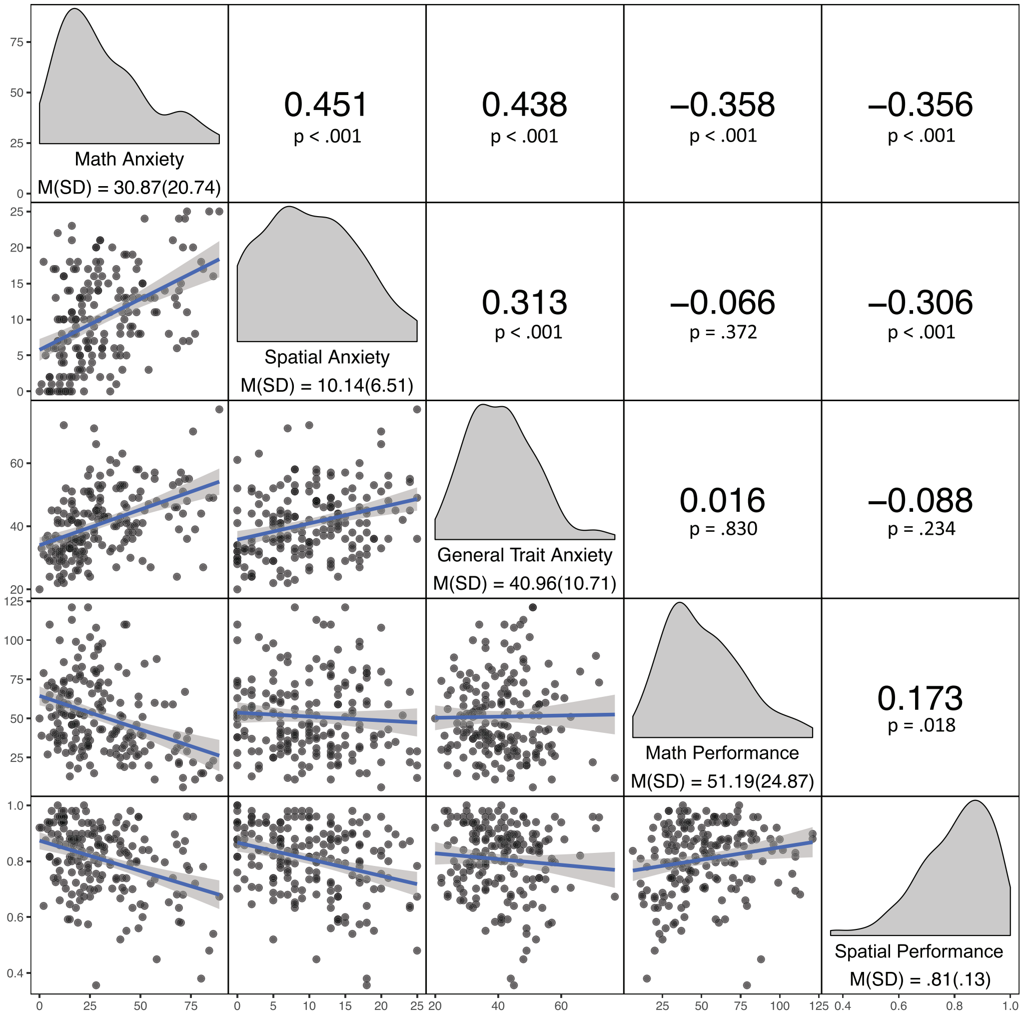

Figure 1. **Density plots of each variable (on the diagonal), scatterplots with lines of best fit and 95% confidence intervals for each bivariate association (below the diagonal), and Pearson's correlation coefficients and associated *P* values for each bivariate association (above the diagonal).**

Results

Figure 1 shows zero-order correlations between all measures, scatterplots that visualize these associations, and density plots showing the distributions of all variables alongside descriptive statistics. Consistent with past work, math anxiety showed a significant negative zero-order association with math performance ($r(184) = -0.358$, $t = -5.20$, $P = 5\text{e-}7$). Likewise, spatial anxiety showed a significant negative zero-order association with spatial performance ($r(184) = -0.306$, $t = -4.35$, $P = 2\text{e-}5$).

To assess the extent to which (and thus also whether) associations between math anxiety and math performance can be accounted for by individual differences in general trait anxiety and/or spatial anxiety, we ran a series of regression models. In the first model (model A), we computed the bivariate association between math anxiety and math performance when no variables are controlled for. This is the same as the zero-order correlation reported in Figure 1, and it establishes a baseline level of association, allowing us to then ask what portion of this association can be accounted for by the various candidate covariates. Thus, we next ran three additional models in which we controlled for general trait anxiety (model B), spatial anxiety (model

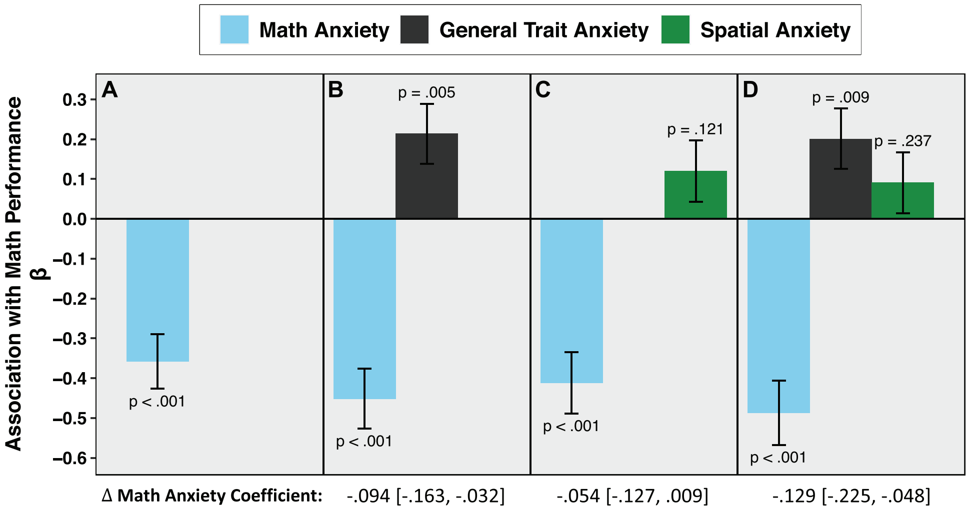

Figure 2. Results from four different regression models predicting math performance. All variables are standardized. Error bars reflect standard errors. Δ Math anxiety coefficient shows the extent to which the math anxiety coefficient changed compared to the zero-order model (model A). 95% confidence intervals were generated using the bootstrapping method with 10,000 iterations. Adjusted R^2 values: model A, 0.123; model B, 0.156; model C, 0.130; and model D, 0.158.

C), and both general trait anxiety and spatial anxiety (model D). In models B–D, we can (1) ask whether math anxiety continues to predict unique variance in math performance when adjusting for other measures of anxiety; (2) quantify the extent to which the strength of the association between math anxiety and math performance differs compared to the zero-order association, allowing us to ask how much of the association between math anxiety and math performance can be explained by these other anxiety measures; and (3) ask whether the other anxiety measures predict unique variance in math performance. To assess whether controlling for a given variable significantly affected the strength of the association between math anxiety and math performance, we computed the difference between the math anxiety coefficient in each model and in model A when no other variables were controlled for, and we labeled this difference Δ *math anxiety coefficient*. We used a bootstrapping method (10,000 iterations) to generate confidence intervals around the change in coefficient strength.[42] The results are visualized in Figure 2.

Results in Figure 2 show that math anxiety continued to predict unique variance in math performance regardless of what other anxiety measures were controlled for, providing evidence that anxiety specific to math adds predictive value over and above other measures of anxiety in predicting math performance. In fact, controlling for general trait anxiety (model B: Δ math anxiety coefficient = −0.094 [−0.163, −0.032]) and for both general trait anxiety and spatial anxiety (model D: Δ math anxiety coefficient = −0.129 [−0.225, −0.048]) caused the strength of the negative association between math anxiety and math performance to significantly increase by 26% and 36%, respectively, compared to the zero-order model (model A). This increase in the strength of the math anxiety coefficient when models include general trait anxiety suggests that general trait anxiety may act as a suppressor variable.[43] Controlling for spatial anxiety alone (model D) was associated with no significant change in the math anxiety–math performance association.

In these models, spatial anxiety did not predict unique variance in math performance over and above math anxiety. General trait anxiety, however, did predict unique variance in math performance when controlling for math anxiety alone and for math anxiety and spatial anxiety jointly, but here greater general trait anxiety was associated with better math performance (model B general trait anxiety $\beta(183) = 0.214$, $P = 0.005$; model D general trait anxiety $\beta(182) = 0.201$, $P = 0.009$).

Using the same analytic framework, we next asked whether the extent to which spatial anxiety predicts spatial performance could be explained by

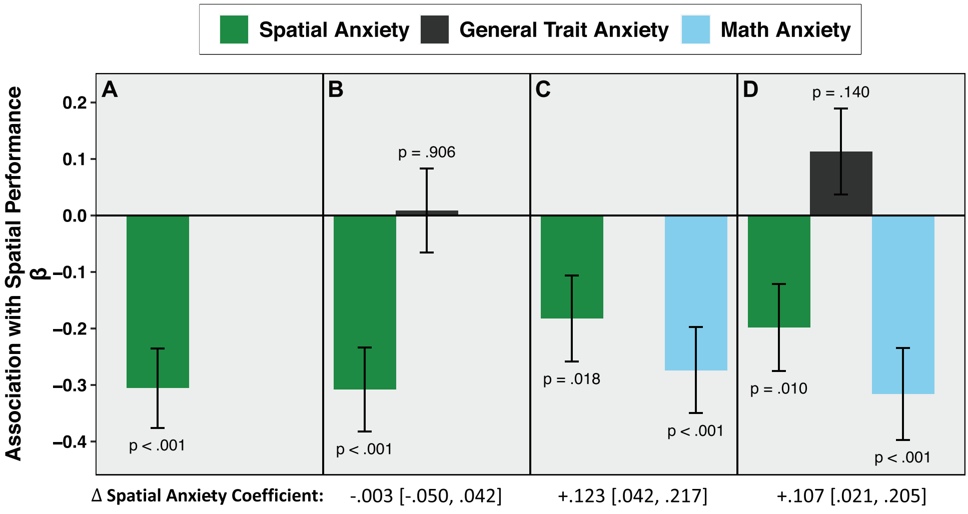

Figure 3. Results from four different regression models predicting spatial performance. All variables are standardized. Error bars reflect standard errors. Δ Spatial anxiety coefficient shows the extent to which the spatial anxiety coefficient changed compared to the zero-order model (model A). 95% confidence intervals were generated using the bootstrapping method with 10,000 iterations. Adjusted R^2 values: model A, 0.088; model B, 0.084; model C, 0.144; and model D, 0.149.

individual differences in general trait anxiety and/or math anxiety.

As was the case with math anxiety and math performance, results in Figure 3 show that spatial anxiety predicted unique variance in spatial performance even after controlling for general trait anxiety and math anxiety, providing evidence that anxiety specific to spatial reasoning adds predictive value over and above other measures of anxiety. However, models that included math anxiety alone (model C: Δ spatial anxiety coefficient = +0.123 [0.042, 0.217]) or math anxiety and general trait anxiety together (model D: Δ spatial anxiety coefficient = +0.107 [0.021, 0.205]) showed a decrease of 40% and 35%, respectively, in the strength of the negative association between spatial anxiety and spatial performance compared to the zero-order model (model A). By noting that model B (which included only general trait anxiety as a covariate) showed no such reduction, we can infer that the reduction seen in models C and D can largely be attributed to the presence of math anxiety.

Additionally, while general trait anxiety does not predict unique variance in spatial performance when included in a model with spatial anxiety, math anxiety does: (model C math anxiety $\beta(183) = -0.274$, $P = 4\text{e-}4$; model D general trait anxiety $\beta(182) = -0.316$, $P = 1\text{e-}4$). That math anxiety predicted unique variance in spatial performance even when holding constant spatial anxiety and general trait anxiety suggests that anxiety toward math can add predictive value of performance even on tasks that do not require any explicit math. That said, it is worth reiterating even after accounting for the unique contribution of math anxiety, spatial anxiety still accounted for a significant portion of spatial performance (green bars in Fig. 3C and D). Note also that a post-hoc Wald test indicated the spatial anxiety and math anxiety coefficients were not significantly different from one another in either model C or D (both $P > 0.05$).

Study 1 summary

Study 1 showed that both math anxiety and spatial anxiety continued to predict unique variance in performance in their respective cognitive domains even when controlling for each other and general trait anxiety, providing evidence for the value of cognition-specific anxieties in understanding cognition-specific performance. These analyses also showed that while associations between math anxiety and math performance were not explainable by differences in spatial anxiety, associations between spatial anxiety and spatial performance could, in part, be accounted for by differences in math anxiety. We next turn to study 2 to examine the extent to which these results (1) replicate in a separate sample, and (2) generalize to a more inclusive means of measuring (and thus a broader definition of) math and spatial performance.

Study 2

While study 1 provided new insights into specificity in associations between anxiety and performance within the domains of math and spatial reasoning, it is limited in that only a single measure of math performance and a single measure of spatial performance were included. As a result, the above conclusions alone cannot be generalized beyond measures of challenging mental arithmetic and spatial mental manipulation. To address this limitation, in study 2, participants completed five different measures each of math and spatial performance alongside measures of math anxiety, spatial anxiety, and general trait anxiety. Importantly, this allowed us to generate math performance and spatial performance factor scores that summarized overall performance in each cognitive domain, permitting more generalizable inferences about associations between anxiety and performance within those domains.

Materials and methods

Participants. Undergraduate students ($n = 425$) enrolled in a psychology course at University of Ottawa (Ottawa, Canada) participated. Of these, 65 participants failed to complete at least one measure used in this study, resulting in a total analytic sample size of 360 (246 females, 114 males; mean age = 19.18, SD = 2.62). This dataset has previously been used in other studies[27] to address different theoretical questions.

Procedure. Participants provided written consent to participate, and the University of Ottawa Ethics Review Board approved all procedures. Participants were recruited as part of the university's undergraduate student research pool. Each participant completed a battery of questionnaires and cognitive tasks in the lab that lasted approximately 1 h and were compensated with course credit. Participants completed the math tasks first, followed by the spatial tasks, and then followed by the questionnaires.

Questionnaires. Math anxiety was measured using the Abbreviated Math Anxiety Scale (AMAS[44]), which is made up of nine items from the Math Anxiety Rating Scale[37] (the same scale that the measure of math anxiety used in study 1, the sMARS, was adapted from). Participants rated how anxious they would feel in nine math-related situations (e.g., "Being given a homework assignment of many difficult problems that is due the next class meeting") on a scale from 0 (not at all) to 4 (very much). Possible math anxiety scores range from 0 to 36. Cronbach's α for this measure was 0.90.

Spatial anxiety. Spatial anxiety was measured using the Spatial Anxiety Scale (SAS[10]), as in study 1. While the current dataset has several different measures of spatial performance, not all of which are explicitly focused on spatial mental manipulation (see below for details), we opted to use the same approach as in study 1 and use the Mental Manipulation Anxiety subscale of the SAS as our measure of spatial anxiety. In addition to making the results from studies 1 and 2 more directly comparable, we made this decision because mental manipulation anxiety was more strongly correlated with math anxiety than the other subscales, allowing for a stricter test of specificity in associations between cognition-specific anxieties and performance. Cronbach's α for this measure was 0.92.

General trait anxiety. General trait anxiety was measured using the trait component of the State-Trait Anxiety Inventory (STAI[38]), as in study 1. Cronbach's α for this measure was 0.92.

Math tests. Participants completed five math tests designed to align with goals set in the Ontario mathematics curriculum by the Ontario Ministry of Education. The five math tests aimed to measure ability in the following areas set by the Ministry of Education: data management and probability (focusing on the ability to understand and reason about data), geometry and spatial sense (focusing on the ability to reason about geometrical shapes and graphs), number sense and numeration (focusing on basic arithmetic ability and word problem reasoning), measurement (focusing on the ability to reason about concepts like area and volume), and algebra (focusing on the ability to complete basic "solve for x" problems and correctly apply orders of operation). The goal of including these tests was (1) to collect math measures that are directly relevant to the kinds of tests students from this population are likely to have encountered in their actual schooling (rather than bespoke cognitive tasks often used by numerical cognition researchers), thus increasing ecological validity; (2) to collect measures of math ability that serve as the bedrock of more advanced math; and (3) to collect measures of a wide range of math knowledge and skills. Together, this approach allowed for more generalizable inferences about associations between math anxiety and math performance. Each test comprised 10 multiple choice items with four possible responses, and performance on each test was measured by overall accuracy. Problems appeared on the screen one-at-a-time, and there were no time limits. Participants received both paper and pencil and a calculator to work through the problems. Example items from each of the five tests can be found in Supplementary File S1: Appendix (online only). Cronbach's $\alpha > 0.85$ for all math tests.

Spatial tasks. Participants completed a series of five tasks of spatial performance. While we would have liked to use school-based measures in this case as well, few school districts explicitly teach (and fewer still directly assess) spatial skills with the same variety and specificity as they do math skills. Hence, to assess spatial skills, we instead relied on a battery of spatial tasks widely used in lab-based studies of spatial reasoning. Performance on each task was determined by overall accuracy. Tasks are described in greater detail below.

Mental rotation task. Mental manipulation performance was measured with a Mental Rotation Task,[45] similar to the task used in study 1. On each of 15 trials, participants were shown two 3D objects made of 10 adjoining cubes, which were oriented in different directions. The participants were asked to identify whether they thought the two objects shown were the same objects oriented differently or if they were two different objects by selecting "same" or "different" using the mouse. Cronbach's α for this measure was 0.89.

Spatial visualization. A modified computerized version of the Dot Localization task was used to evaluate participants' spatial visualization performance.[46] On each of 15 trials, the participant was first presented with a rectangle containing two dots for 125 milliseconds. Once this rectangle had disappeared, the participant was presented with another rectangle containing a grid and was asked to select locations within the grid to identify where the two dots would have been located if both rectangles had been superimposed. Cronbach's α for this measure was 0.89.

Imagery. Participants' spatial imagery performance was measured with a computerized and modified version of the embedded figures task.[10,47] On each of nine trials, a complex two-dimensional line drawing is shown to the participants, and they are asked to identify which figure out of five simple line figures is present in the complex drawing. The five simple figures presented on each trial were always the same. Cronbach's α for this measure was 0.84.

Perspective taking. To measure participants' spatial orientation performance, individuals were asked to complete the Hegarty perspective taking test.[48] For each of 15 trials, participants were shown a screen with a variety of common objects (e.g., cat, car, and house) and an arrow circle. The participants were asked to imagine that they were standing in the location of the object in question (e.g., object A in the middle of the circle) and facing a particular point (object B at the top of the circle). They were then asked to determine in which direction they would find a third object (e.g., object C) by using the mouse to click the appropriate area. Cronbach's α for this measure was 0.89.

Navigation. To measure participants' navigation performance, a modified and computerized version of the Road-Map Test of Directional Sense was used.[49,50] For this task, participants were presented a map that contained a dotted path. On each "street" corner, participants were shown the letter R (right turn) or the letter L (left turn) to demonstrate the direction they would be turning if they were walking along the dotted path. However, not every turn was labeled correctly. Therefore, participants were required to press "Y" or "N" to identify whether they agreed or disagreed with the direction provided. Three maps were presented with 3, 17, and 33 turns. Only the third map with 33 turns was used to score performance, and the other two were used as practice trials.[50] Participants received a score out of 33 that reflected the number of correct responses to each prompt. Cronbach's α for this measure was 0.92.

Math and spatial performance factor scores. For the present purposes, the goal of including several measures of math and spatial performance was to allow for more generalizable interferences to be made about the specificity of associations

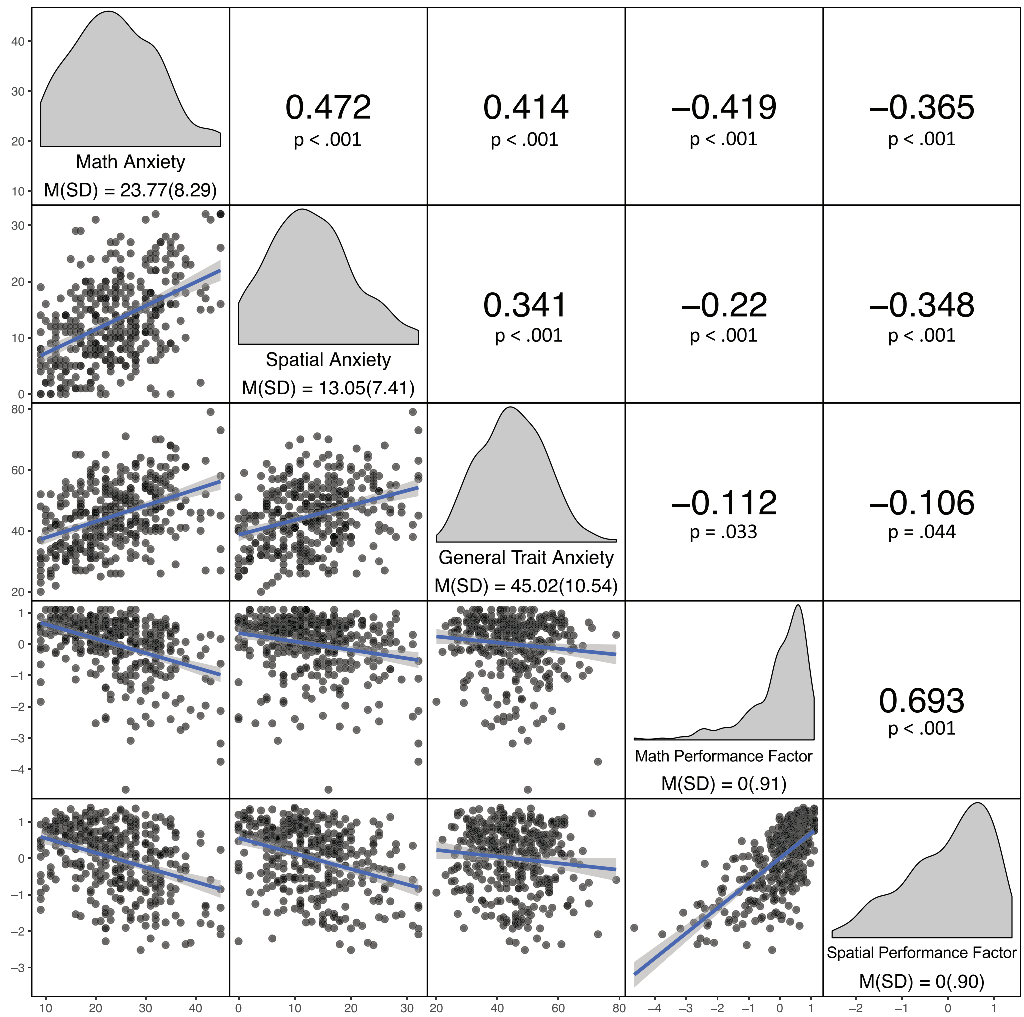

Figure 4. **Density plots of each variable (on the diagonal), scatterplots with lines of best fit and 95% confidence intervals for each bivariate association (below the diagonal), and Pearson's correlation coefficients and associated *P* values for each bivariate association (above the diagonal).**

between math anxiety and math performance and between spatial anxiety and spatial reasoning. To accomplish this goal, we ran two factor analyses, one using performance on all five math tasks and one using performance on all five spatial tasks. For both analyses, we computed a single factor solution using maximum likelihood estimation and promax rotation. Fit indices showed strong model fit for both factor analyses (math domain: RMSEA = 0.000 [0.000, 0.087]; spatial domain: RMSEA = 0.000 [0.000, 0.051]). This allowed us to generate math performance factor scores and spatial performance factor scores for each participant that reflect variance common to performance on each of the five math and spatial tasks, respectively. While we acknowledge that a perfect representation of math performance or spatial performance would require one to collect a theoretically infinite set of tasks in each domain, these factor scores made up of performance on several tasks allow for more generalizable inferences than are afforded by using a single measure of performance within each domain.

Results

Figure 4 shows zero-order correlations between all measures, scatterplots that visualize these

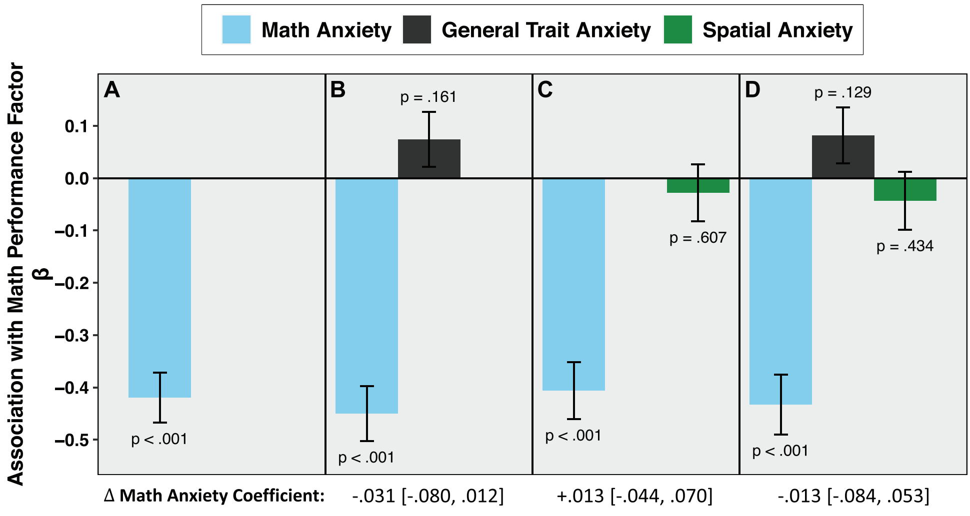

Figure 5. Results from four different regression models predicting math performance factor scores. All variables are standardized. Error bars reflect standard errors. Δ Math anxiety coefficient shows the extent to which the math anxiety coefficient changed compared to the zero-order model (model A). 95% confidence intervals were generated using the bootstrapping method with 10,000 iterations. Adjusted R^2 values: model A, 0.174; model B, 0.176; model C, 0.172; and model D, 0.175.

associations, and density plots showing the distributions of all variables alongside descriptive statistics. Results indicate that math anxiety shows a significant negative zero-order association with math performance factor scores ($r(358) = -0.419$, $t = -8.74$, $P < 2e\text{-}16$). Likewise, spatial anxiety shows a significant negative zero-order association with spatial performance factor scores ($r(358) = -0.348$, $t = -7.02$, $P = 1e\text{-}11$). Note that while math performance factor scores are left-skewed, we opted to retain all participants' data (i.e., we did not remove outliers). Some research opts to exclude outlier participants with very low accuracy on math tasks. However, in this case, we see near-chance responding as potentially informative—after all, one of the ways in which math anxiety is thought to negatively impact math performance is by leading highly math-anxious individuals to engage in avoidance behaviors like choosing to exert very little effort on a math task.[51,52] While we made the decision to retain these participants for theoretical reasons, note that removing outliers with math factor scores at more than 3 standard deviations below the mean does not appreciably change the inferences drawn by the present study. Additionally, note that compared to study 1, where the association between math and spatial performance was modest ($r(184) = 0.173$, $t = 2.39$, $P = 0.018$), here the association is quite strong: ($r(358) = 0.693$, $t = 18.17$, $P < 2e\text{-}16$). This is because factor scores that summarize performance across a number of tasks (the approach used in study 2) are typically more highly correlated with one another than performance on individual tasks (which were used in study 1).

To ask whether and the extent to which associations between math anxiety and math performance factor scores can be accounted for by individual differences in general trait anxiety and/or spatial anxiety (and vice versa with a focus on the association between spatial anxiety and spatial performance factor scores), we used the same analytic approach used in study 1. Figure 5 shows the effect of controlling for general trait anxiety, spatial anxiety, or both anxiety measures on the strength of the association between math anxiety and math performance factor scores.

Results indicate that, as in study 1 (see Fig. 2 for comparison), math anxiety continued to predict unique variance in math performance factor scores regardless of which other anxiety measures were included in the model. Whereas study 1 showed that controlling for general trait anxiety significantly *increased* the strength of the math anxiety–math performance association, in study 2, this increase, while present, was not significant (models B and

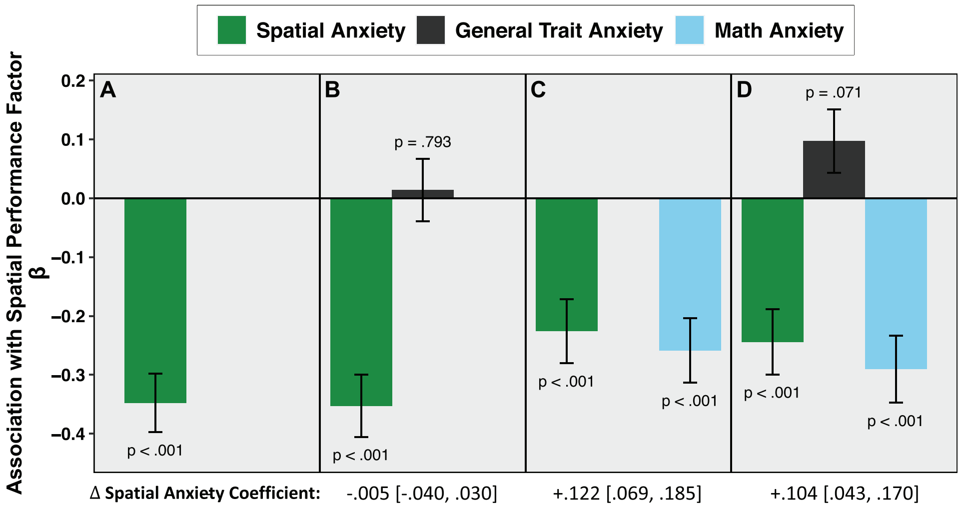

Figure 6. **Results from four different regression models predicting spatial performance factor scores. All variables are standardized. Error bars reflect standard errors. Δ Spatial anxiety coefficient shows the extent to which the spatial anxiety coefficient changed compared to the zero-order model (model A). 95% confidence intervals were generated using the bootstrapping method with 10,000 iterations. Adjusted R^2 values: model A, 0.119; model B, 0.116; model C, 0.169; and model D, 0.174.**

D), indicating that particular result from study 1 may not be robust to changes in measures between the studies. Similarly, while the unique contribution of general trait anxiety to math performance was in the same direction as in study 1, it was not significant here. Turning to spatial anxiety, consistent with study 1, controlling for spatial anxiety did not impact the association between math anxiety and math performance factor scores, nor did it predict unique variance in math performance factor scores. Note that the inferences from the results presented here do not change substantially if one uses as the dependent variable performance on just the number sense and numeration test, which focuses on calculation, similar to the math measure used in study 1. Broadly, these results provide converging evidence that associations between anxiety and performance within the domain of math cannot be explained by more general anxiety or anxiety toward a closely related cognitive domain (spatial reasoning), suggesting that math anxiety adds clear predictive value over and above other measures of anxiety.

We next asked whether the extent to which spatial anxiety predicts spatial performance factor scores could be explained by individual differences in general trait anxiety and/or math anxiety. Results are displayed in Figure 6 (see Fig. 3 for comparison with study 1). Results closely replicated findings from study 1. Spatial anxiety predicted unique variance in spatial performance factor scores no matter which other anxiety measures are controlled for. General trait anxiety did not predict unique variance in spatial performance factor scores, and controlling for it did not significantly change the spatial anxiety coefficient. Controlling for math anxiety was associated with a decrease in the magnitude of the spatial anxiety–spatial performance relation of 35% in model C (Δ spatial anxiety coefficient = +0.122 [0.069, 0.185]) and 30% in model D (Δ spatial anxiety coefficient = +0.104 [0.043, 0.170]) compared to the zero-order model (model A). And as in study 1, math anxiety also predicted unique variance in spatial performance factor scores. A post-hoc Wald test indicated the spatial anxiety and math anxiety coefficients were not significantly different from one another in either model C or D (both *P*s > 0.05). Please note that the inferences from the results presented here do not change substantially if one uses MRT performance as the dependent variable in place of the spatial performance factor scores as the dependent variable (i.e., more akin to study 1). Together, these results provide evidence that spatial anxiety adds predictive value over and above other measures of anxiety, but math anxiety explains an additional, significant portion of the spatial anxiety–spatial performance association.

Study 2 summary

Study 2 replicated each of the key findings from study 1. Namely, both math anxiety and spatial anxiety captured unique variance in math and spatial performance, respectively, and these results held after controlling for one another and general trait anxiety. Math anxiety accounted for a significant, unique portion of the spatial anxiety–spatial performance relation, but the reverse was not true. That each of these results replicated across different samples and using different measures of math and spatial performance lends substantial weight to the central conclusions that (1) links between anxiety and performance cannot be reduced to a single underlying general anxiety construct, and (2) there may nevertheless be overlap between cognition-specific anxieties.

General discussion

The goal of this work was to investigate the specificity of the associations between anxiety and performance within the domains of math and spatial reasoning. Across two studies using different samples and measures, we found consistent evidence that anxiety in a given cognitive domain (e.g., math) predicted differences in performance within that domain even when controlling for general trait anxiety and anxiety in a closely related cognitive domain (e.g., spatial reasoning). These results provide evidence for the value of cognition-specific anxieties in understanding cognition-specific performance. Namely, negative feelings toward a particular type of thinking are linked to poorer performance in that type of thinking, even after adjusting for negative emotionality more generally and for negative feelings toward other, related types of thinking. Below, we discuss our findings in additional detail and make recommendations for future work to better understand cognition-specific anxieties.

If anxiety toward specific types of thinking, like math anxiety and spatial anxiety, are to be useful constructs, they need to add predictive value over and above more general forms of anxiety. Our first test for each of these cognition-specific anxieties, then, was to assess whether links between anxiety and performance within each domain could be explained by individual differences in general trait anxiety. Across all analyses in the present work, we never found any evidence that accounting for general trait anxiety significantly reduced the extent to which math or spatial anxiety was predictive of math or spatial performance, respectively. This provides clear evidence against the idea that links between anxiety and performance within cognitive domains can be explained by reference to just anxiety. In other words, the specificity of the anxiety matters. In fact, in all analyses in the present work, controlling for general trait anxiety was associated with an *increase* in the cognition-specific anxiety–performance association, and in each case, the general trait anxiety coefficient was positive. To be sure, these augmenting effects of general anxiety were only significant in study 1 when examining the math domain, so caution is warranted. However, the same pattern was observed in all four key analyses (Figs. 2, 3, 5, and 6), strongly suggesting that general trait anxiety cannot explain associations between cognition-specific measures of anxiety and performance.

As a methodological point, the fact that controlling for general trait anxiety revealed stronger anxiety–performance associations (most notably for math in study 1) suggests that general trait anxiety acts as a suppressor variable.[43] A suppressor variable occurs when including a variable in a regression model enhances the predictive value of other predictors, and sometimes even itself.[53] Perhaps the most common explanation for this sort of phenomenon is that the suppressor variable accounts for measurement error in the predictor of interest, thereby absorbing noise associated with this measurement error and enhancing the predictive precision of other, relevant variables. One possibility is that the variance shared between, say, math anxiety and general trait anxiety (see Figs. 1 and 4) is not directly relevant for predicting math performance, but it *is* useful in more accurately apportioning the variance *specifically* attributable to each anxiety measure. By measuring and including both measures, one can more accurately separate these sources of (performance relevant) variance, thus improving the predictive accuracy of both measures. Therefore, while general anxiety did not reduce the predictive value of either math or spatial anxiety, we nevertheless strongly recommend researchers collect and account for general trait anxiety in their models, as doing so is likely to improve the precision of one's estimate of how cognition-specific anxieties contribute to cognition-specific performance.

Our second test of the specificity of anxiety–performance links was to assess whether they held when controlling for a cognition-specific anxiety in a closely related cognitive domain. Results showed that, in all cases, math anxiety continued to explain unique variance in math performance, and spatial anxiety continued to explain unique variance in spatial performance. However, across both studies, results also showed that while spatial anxiety did not account for a significant portion of the link between math anxiety and math performance, math anxiety did account for a substantial portion of the anxiety–performance link within spatial reasoning. These results partially replicate findings from work done in children by Lauer *et al.*[11] In that study, math anxiety predicted unique variance in math performance when controlling for spatial anxiety and other anxiety measures, but neither math anxiety nor spatial anxiety predicted unique variance in spatial performance, even though both were predictive of spatial performance when no variables were controlled for. It is possible that the more specific links between anxiety and performance within cognitive domains found in the present work, which used university students as participants, emerge only after significant exposure to and experience with disparate forms of cognition.

Our results suggest that links between spatial anxiety and spatial performance may be less specific than links between math anxiety and math performance. Interestingly, it also suggests that anxiety toward math can add predictive value even on tasks that do not require any explicit math. Future work should endeavor to understand why it is that math anxiety can explain a portion of the spatial anxiety–performance association, but not vice versa. One reason why this might be is that our measures of math anxiety may be capturing anxiety related to academics more generally, given that many items in both math anxiety measures used in this work involve studying, reading textbooks, doing homework, or taking tests.[36,44] A useful way of testing this idea would be to conduct a study in which measures of anxiety and performance within several different cognitive domains are collected; if math anxiety continues to explain a portion of the association between anxiety and performance within an array of cognitive domains, this would provide evidence in favor of this possibility that the math anxiety scales used here are, in part, capturing anxiety toward academic assessment situations more broadly. Another possible explanation for these findings has to do with participants' perceptions of the math and spatial tasks themselves. It is possible that participants tend to perceive the spatial tasks as involving elements of what they consider to be math, but not vice versa. If this were the case, individuals who are anxious about math may also become anxious when performing spatial tasks (which they may also consider to be similar to math), which could in turn impair performance. Future work would be needed to distinguish between these and other possible explanations. It is also worth considering why spatial anxiety did not explain additional unique variance in math performance (over and above math and general anxiety). One potential explanation for this finding is that while many math tasks (including the ones used in this work) can be completed using spatial strategies, math often affords nonspatial, verbal strategies as well.[27,54] As a result, it is possible that spatial anxiety does not predict unique variance in math performance because those who are anxious about spatial reasoning can simply rely on nonspatial skills to complete math problems (the idea that those who are anxious about spatial reasoning may be more likely to use nonspatial strategies when completing math was first suggested, to our knowledge, by Sokolowski and colleagues[34]). We believe directly testing this idea would be worthwhile. Additionally, this study was conducted in university populations; it is possible that spatial anxiety could be more impactful for math performance earlier in development, when children may use spatial skills to scaffold their development of math skills.[33,55]

The findings of this work have potential implications for interventions. We found that general trait anxiety explained no portion of the anxiety–performance association within math and spatial reasoning. This suggests that finding ways to reduce general trait anxiety without also reducing either of these cognition-specific anxieties is unlikely to result in boosted math or spatial performance. The finding that math anxiety explains a significant portion of the spatial anxiety–spatial performance association but that spatial anxiety does not explain the math anxiety–math performance association suggests that finding ways to lower trait-level math anxiety may result in both gains to math performance and spatial performance (for a review of interventions to reduce math anxiety, see Ramirez *et al.*[56]). Lowering spatial anxiety, on the other hand, should not be expected to impact math performance. Future intervention work would need to be done to directly test these ideas.

Limitations

We turn now to the limitations of this work. To address the present research questions, we made use of two existing datasets that used different measures of math anxiety, math performance, and spatial performance. This approach of using multiple datasets with different measures comes with significant strengths, namely, it greatly increases our confidence in findings that are common to both datasets by allowing for an internal conceptual replication. We found that our core findings replicated across both datasets: (1) both math anxiety and spatial anxiety continued to predict performance in their respective domains even after controlling for general anxiety and one another; (2) general trait anxiety did not explain any significant portion of associations between anxiety and performance within either math or spatial reasoning; and (3) while spatial anxiety did not explain a significant portion of the association between math anxiety and math performance, math anxiety did partially explain the spatial anxiety–spatial performance link. Our approach of using different datasets with different measures allows for greater confidence that these are robust, replicable findings not dependent upon the idiosyncrasies of a single study design. However, the major limitation of this approach is that it is difficult to interpret discrepancies between the studies. Though it was not the goal of this paper to identify such discrepancies, we should note that the one difference we found between the studies was that, in study 1, controlling for general trait anxiety was associated with a significant increase in the strength of the math anxiety–math performance association, but this increase was not significant in study 2. This discrepancy could be because we used different measures between the studies, or it could be that this finding is simply not as replicable as the key results (1–3) from above. The fact that we observed this finding in one dataset but not the other suggests that this finding is not as robust as the core findings described above, and we urge readers to take caution when interpreting this result.

Another limitation concerns the nature of the claims this study is able to make about predictive specificity of cognition-specific anxieties. In the present work, we made use of anxiety and performance within two closely related domains—math and spatial reasoning—and tested whether anxiety–performance associations within a domain would hold when controlling for general anxiety and anxiety in the other closely related cognitive domain. We believe that this provides a strict test case of the predictive specificity of these constructs: given that math anxiety continued to predict unique variance in math performance even after controlling for general anxiety and spatial anxiety, we believe it is likely that math anxiety would continue to predict math performance even if, for instance, creativity anxiety (or any anxiety about a theoretically more distinct construct in comparison to spatial anxiety) were controlled for. However, in the present work, we did not have the data to directly test whether the associations we observe here would hold even controlling for a variety of different cognition-specific anxieties. In addition to providing additional insight into the constructs of math and spatial anxiety, a future investigation in which anxiety and performance within several different cognitive domains are collected in the same samples could allow for a broader test of the predictive specificity that cognition-specific anxieties, considered together, possess. We believe the present work can help to lay the foundation for such an investigation, and we hope to see more work that considers different cognition-specific anxieties together moving forward.

Conclusion and future directions

Taken together, the present results provide clear evidence that cognition-specific anxieties can add value for predicting cognition-specific performance over and above more general anxiety or anxiety specific to other, even related types of cognition. This work also demonstrates that links between math anxiety and cognitive performance are specific in some ways (links between math anxiety and math performance cannot be explained by the other forms of anxiety examined here) but nonspecific in others (math anxiety predicts unique variance in spatial performance over and above spatial anxiety). While the present work speaks most directly to links between anxiety and performance within the domains of math and spatial reasoning, we suggest that future work should aim to better understand the conditions in which cognition-specific anxieties more generally should be expected to predict cognitive performance, considering as many domains as possible. In this work, we used tasks specifically designed to measure math ability and spatial ability, but many important real-world tasks involve a combination of several types of cognition-specific abilities. Writing computer code, for instance, is likely to include elements of math, spatial, and even verbal reasoning, and as such, it is possible that anxiety about each of these types of thinking would contribute to predicting and understanding performance on such a task. Developing a framework that explains when and how cognition-specific anxieties, considered broadly, impact cognitive performance would represent an important advance in our understanding of links between emotion and cognition. We believe the literatures on math and spatial anxiety could play a key role in the development of such an account.

Acknowledgments

This work was funded by the National Science Foundation (CAREER-2041887) and Georgetown University (New Faculty Start-Up Funds) to I.M.L. and a Natural Sciences and Engineering Research Council of Canada Discovery Grant to E.A.M.

Author contributions

R.J.D. and I.M.L. conceptualized the manuscript. R.J.D. wrote the manuscript under the supervision of I.M.L., and V.D. and E.A.M. suggested revisions. V.D. and R.J.D. reviewed the literature. R.J.D. completed the data analysis. I.M.L., E.A.M., and V.D. planned and executed initial data collection.

Supporting information

Additional supporting information may be found in the online version of this article.

Supplementary File S1: Appendix

Competing interests

The authors declare no competing interests.

Data availability statement

Data supporting this research are openly available at the following Open Science Framework link: https://osf.io/p2amc/?view_only=a99aa44659064b47b637bc66fbcc4dff.

Peer review

The peer review history for this article is available at: https://publons.com/publon/10.1111/nyas.14761

References

1. Humphreys, L.G. & G. Yao. 2002. Prediction of graduate major from cognitive and self-report test scores obtained during the high school years. *Psychol. Rep.* **90:** 3–30.
2. Daker, R.J., S.U. Gattas, H.M. Sokolowski, *et al.* 2021. First-year students' math anxiety predicts STEM avoidance and underperformance throughout university, independently of math ability. *Npj Sci. Learn.* **6:** 1–13.
3. Benbow, C.P. & J.C. Stanley. 1982. Consequences in high school and college of sex differences in mathematical reasoning ability: a longitudinal perspective. *Am. Educ. Res. J.* **19:** 598–622.
4. Wai, J., D. Lubinski & C.P. Benbow. 2009. Spatial ability for STEM domains: aligning over 50 years of cumulative psychological knowledge solidifies its importance. *J. Educ. Psychol.* **101:** 817–835.
5. Uttal, D.H. & C.A. Cohen. 2012. Spatial thinking and STEM education: when, why, and how? In *The Psychology of Learning and Motivation*, Vol. **57**. B.H. Ross (Ed.): 147–181. Elsevier.
6. Watt, H.M., J.S. Eccles & A.M. Durik. 2006. The leaky mathematics pipeline for girls: a motivational analysis of high school enrolments in Australia and the USA. *Equal Oppor. Int.* **25:** 642–659.
7. Barroso, C. *et al.* 2021. A meta-analysis of the relation between math anxiety and math achievement. *Psychol. Bull.* **147:** 134–168.
8. Ma, X. 1999. A meta-analysis of the relationship between anxiety toward mathematics and achievement in mathematics. *J. Res. Math. Educ.* **30:** 520–540.
9. Hembree, R. 1990. The nature, effects, and relief of mathematics anxiety. *J. Res. Math. Educ.* **21:** 33–46.
10. Lyons, I.M. *et al.* 2018. Spatial anxiety: a novel questionnaire with subscales for measuring three aspects of spatial anxiety. *J. Numer. Cogn.* **4:** 526–553.
11. Lauer, J.E., A.G. Esposito & P.J. Bauer. 2018. Domain-specific anxiety relates to children's math and spatial performance. *Dev. Psychol.* **54:** 2126.
12. Atit, K. & K. Rocha. 2021. Examining the relations between spatial skills, spatial anxiety, and k-12 teacher practice. *Mind Brain Educ.* **15:** 139–148.
13. Ashcraft, M.H. 2002. Math anxiety: personal, educational, and cognitive consequences. *Curr. Dir. Psychol. Sci.* **11:** 181–185.
14. Dowker, A., A. Sarkar & C.Y. Looi. 2016. Mathematics anxiety: what have we learned in 60 years? *Front. Psychol.* **7:** 508.
15. Pizzie, R.G. & D.J. Kraemer. 2019. The Academic Anxiety Inventory: evidence for dissociable patterns of anxiety

related to math and other sources of academic stress. *Front. Psychol.* **9:** 2684.
16. Malanchini, M., K. Rimfeld, N.G. Shakeshaft, *et al.* 2017. The genetic and environmental aetiology of spatial, mathematics and general anxiety. *Sci. Rep.* **7:** 4221.
17. Daker, R.J., R.A. Cortes, I.M. Lyons & A.E. Green. 2020. Creativity anxiety: evidence for anxiety that is specific to creative thinking, from STEM to the arts. *J. Exp. Psychol. Gen.* **149:** 42–57.
18. Beilock, S.L. & E.A. Maloney. 2015. Math anxiety: a factor in math achievement not to be ignored. *Policy Insights Behav. Brain Sci.* **2:** 4–12.
19. Di Lonardo Burr, S.M. & J.-A. LeFevre. 2021. The subject matters: relations among types of anxiety, ADHD symptoms, math performance, and literacy performance. *Cogn. Emot.* **35:** 1334–1349.
20. Justicia-Galiano, M.J., M.E. Martín-Puga, R. Linares & S. Pelegrina. 2017. Math anxiety and math performance in children: the mediating roles of working memory and math self-concept. *Br. J. Educ. Psychol.* **87:** 573–589.
21. Hill, F. *et al.* 2016. Maths anxiety in primary and secondary school students: gender differences, developmental changes and anxiety specificity. *Learn. Individ. Differ.* **48:** 45–53.
22. Caviola, S. *et al.* 2021. Math performance and academic anxiety forms, from sociodemographic to cognitive aspects: a meta-analysis on 906,311 participants. *Educ. Psychol. Rev.* **34:** 1–37
23. Cheng, Y.-L. & K.S. Mix. 2014. Spatial training improves children's mathematics ability. *J. Cogn. Dev.* **15:** 2–11.
24. Mix, K.S., S. C. Levine, Y.-L. Cheng, *et al.* 2016. Separate but correlated: the latent structure of space and mathematics across development. *J. Exp. Psychol. Gen.* **145:** 1206.
25. Mix, K.S. & Y.-L. Cheng. 2012. The relation between space and math: developmental and educational implications. *Adv. Child Dev. Behav.* **42:** 197–243.
26. Tosto, M.G., K.B. Hanscombe, C.M.A Haworth, *et al.* 2014. Why do spatial abilities predict mathematical performance? *Dev. Sci.* **17:** 462–470.
27. Hegarty, M. & M. Kozhevnikov. 1999. Types of visual–spatial representations and mathematical problem solving. *J. Educ. Psychol.* **91:** 684–689.
28. Bruce, C.D. & Z. Hawes. 2015. The role of 2D and 3D mental rotation in mathematics for young children: what is it? Why does it matter? And what can we do about it? *ZDM* **47:** 331–343.
29. Hawes, Z. & D. Ansari. 2020. What explains the relationship between spatial and mathematical skills? A review of evidence from brain and behavior. *Psychon. Bull. Rev.* **27:** 465–482.
30. Cipora, K., Y. He & H.-C. Nuerk. 2020. The spatial–numerical association of response codes effect and math skills: why related. *Ann. N.Y. Acad. Sci.* **1477:** 5–19.
31. Toomarian, E.Y. & E.M. Hubbard. 2018. On the genesis of spatial–numerical associations: evolutionary and cultural factors co-construct the mental number line. *Neurosci. Biobehav. Rev.* **90:** 184–199.
32. Gilligan, K.A., E. Flouri & E.K. Farran. 2017. The contribution of spatial ability to mathematics achievement in middle childhood. *J. Exp. Child Psychol.* **163:** 107–125.
33. Geary, D.C., M.K. Hoard & L. Nugent. 2021. Boys' visuospatial abilities compensate for their relatively poor in-class attentive behavior in learning mathematics. *J. Exp. Child Psychol.* **211:** 105222.
34. Sokolowski, H.M., Z. Hawes & I.M. Lyons. 2019. What explains sex differences in math anxiety? A closer look at the role of spatial processing. *Cognition* **182:** 193–212.
35. Necka, E.A., H.M. Sokolowski & I.M. Lyons. 2015. The role of self-math overlap in understanding math anxiety and the relation between math anxiety and performance. *Front. Psychol.* **6:** 1543.
36. Alexander, L. & C. Martray. 1989. The development of an abbreviated version of the Mathematics Anxiety Rating Scale. *Meas. Eval. Couns. Dev.* **22:** 143–150.
37. Richardson, F.C. & R.M. Suinn. 1972. The Mathematics Anxiety Rating Scale: psychometric data. *J. Couns. Psychol.* **19:** 551–554.
38. Spielberger, C.D., Gorsuch, R.L. & Lushene, R.E. 1970. *Manual for the State-Trait Anxietry, Inventory*. Palo Alto, CA: Consulting Psychologists Press.
39. Ekstrom, R., J. French, H. Harman & D. Dermen. 1976. *Manual for kit of factor referenced cognitive tests*. Princeton New Jersey Educational Testing Service.
40. Lyons, I.M. & S.L. Beilock. 2011. Numerical ordering ability mediates the relation between number-sense and arithmetic competence. *Cognition* **121:** 256–261.
41. Shepard, R.N. & J. Metzler. 1971. Mental rotation of three-dimensional objects. *Science* **171:** 701–703.
42. Preacher, K.J. & A.F. Hayes. 2008. Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behav. Res. Methods* **40:** 879–891.
43. Watson, D., L.A. Clark, M. Chmielewski & R. Kotov. 2013. The value of suppressor effects in explicating the construct validity of symptom measures. *Psychol. Assess.* **25:** 929–941.
44. Hopko, D.R., R. Mahadevan, R.L. Bare & M.K. Hunt. 2003. The Abbreviated Math Anxiety Scale (AMAS) construction, validity, and reliability. *Assessment* **10:** 178–182.
45. Shepard, R.N. & J. Metzler. 1971. Mental rotation of three-dimensional objects. *Science* **171:** 701–703.
46. Manna, C.B.G. *et al.* 2010. EEG hemispheric asymmetries during cognitive tasks in depressed patients with high versus low trait anxiety. *Clin. EEG Neurosci.* **41:** 196–202.
47. Ekstrom, R.B., J.W. French & H.H. Harman. 1976. *Manual for kit of factor-referenced cognitive tests*.
48. Hegarty, M. & D. Waller. 2004. A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence* **32:** 175–191.
49. Money, J., D. Alexander & H.T. Walker. 1965. *A Standardized Road-Map Test of Direction Sense: Manual*. Johns Hopkins Press.
50. Ferguson, A.M., E.A. Maloney, J. Fugelsang & E.F. Risko. 2015. On the relation between math and spatial ability: the case of math anxiety. *Learn. Individ. Differ.* **39:** 1–12.

51. Faust, M.W., M.H. Ashcraft & D.E. Fleck. 1996. Mathematics anxiety effects in simple and complex addition. *Math. Cogn*. **2:** 25–62.
52. Choe, K.W., J.B. Jenifer, C.S. Rozek, *et al.* 2019. Calculated avoidance: math anxiety predicts math avoidance in effort-based decision-making. *Sci. Adv.* **5:** eaay1062.
53. Horst, P. *et al.* 1941. The prediction of personal adjustment: a survey of logical problems and research techniques, with illustrative application to problems of vocational selection, school success, marriage, and crime. Social Science Research Council.
54. Battista, M.T. 1990. Spatial visualization and gender differences in high school geometry. *J. Res. Math. Educ.* **21:** 47–60.
55. Mix, K.S. 2019. Why are spatial skill and mathematics related? *Child Dev. Perspect.* **13:** 121–126.
56. Ramirez, G., S.T. Shaw & E.A. Maloney. 2018. Math anxiety: past research, promising interventions, and a new interpretation framework. *Educ. Psychol.* **53:** 145–164.