Cognition 182 (2019) 193–212

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

Original Articles

What explains sex differences in math anxiety? A closer look at the role of spatial processing

H. Moriah Sokolowski[a], Zachary Hawes[a], Ian M. Lyons[b,*]

[a] University of Western Ontario. London, Ontario, Canada
[b] Georgetown University, Washington, DC, USA

ARTICLE INFO

Keywords:
Math anxiety
Sex differences
Math skills
Spatial skills
Spatial anxiety

ABSTRACT

A large body of research has documented that females experience more math anxiety than males. Researchers have identified many factors that might explain the relation between sex and math anxiety. In the current study, we present a novel theoretical framework that highlights the importance of examining multiple aspects of processing across different cognitive domains. We use this framework to address the question of what best explains sex differences in math anxiety. One hundred and seventy-five undergraduate students completed a battery of cognitive tasks and affect questionnaires intended to measure actual math ability, perceived math ability, math anxiety, actual spatial ability, perceived spatial ability, and anxiety about situations requiring spatial mental manipulation (spatial anxiety). Results revealed that processes within the spatial domain but *not* in the mathematical domain mediated the relation between sex and math anxiety, controlling for general anxiety and cognitive ability. Moreover, within the spatial domain, spatial anxiety was the strongest mediator between sex and math anxiety, over actual and perceived spatial ability. Our findings point to spatial anxiety as a key contributor to the commonly reported sex differences in math anxiety. We conclude by raising the possibility that sex differences in math anxiety, may be rooted in sex-related differences in anxiety about or avoidance of spatial strategies in solving mathematical tasks.

1. Introduction

Human progress is fundamentally linked to advancements in science, technology, engineering, and mathematics (STEM). Thus, understanding the factors that influence whether a person decides to embark upon and eventually succeed in STEM is a major and pressing contemporary concern for researchers and policy makers alike. A related concern is the fact that women are less likely to express interest, enter, and succeed in STEM careers than their male peers (Dasgupta & Stout, 2014; Hango, 2013). The choice to enter a career in STEM likely involves complex interactions between cognitive and socio-emotional factors across several different cognitive domains (e.g., space, math and perhaps even reading). To complicate matters further, work in recent years has made clear that cognitive and affective processes are likely far more tightly intertwined than previously suspected (Brosch, Scherer, Grandjean, & Sander, 2013; Dolan, 2002; Storbeck & Clore, 2007). Thus, a seemingly simple question like, 'why do fewer women enter STEM disciplines' can catalyze a cascade of related questions from which it can be difficult to formulate a clear strategy for sorting through all potentially relevant factors. In the present study, we present a framework that, we hope, can aid research aimed at addressing complex questions regarding the interplay between cognitive and affective factors that may underlie STEM performance.

In addition to providing a theoretical framework, we present a practical example of how this framework may be applied. Specifically, we examine how cognitive and affective factors from spatial and mathematical domains contribute to significantly higher ratings of anxiety about mathematics in women than men. Understanding why more women are math anxious may help uncover why fewer women pursue STEM careers. This in turn may prove essential to better maximizing untapped female talent in STEM domains.

1.1. Sex differences in math anxiety

A large body of research has revealed sex differences in math anxiety, with women consistently reporting significantly more math anxiety than men (Ferguson, Maloney, Fugelsang, & Risko, 2015; Hembree, 1990; Maloney, Waechter, Risko, & Fugelsang, 2012), even when controlling for other kinds of anxiety such as general trait and test anxiety (Devine, Fawcett, Szűcs, & Dowker, 2012; Ferguson et al.,

* Corresponding author.
E-mail address: ian.lyons@georgetown.edu (I.M. Lyons).

https://doi.org/10.1016/j.cognition.2018.10.005
Received 7 November 2017; Received in revised form 5 October 2018; Accepted 8 October 2018

2015). Math anxiety is defined as the experience of negative emotions or affect in thinking about or engaging in numerical and mathematical tasks (Ashcraft & Moore, 2009; Hembree, 1990). Importantly, math anxiety has been shown to negatively impact mathematics performance. For example, individuals with high math anxiety perform worse than their low math anxious peers on basic mathematical tasks, such as counting and comparing numbers (Maloney, Ansari, & Fugelsang, 2011; Maloney, Risko, Ansari, & Fugelsang, 2010), as well as more advanced mathematics problems, including mental calculations (Ashcraft & Faust, 1994). Critically, math anxiety is related to the avoidance of mathematics related subject matter (Hembree, 1990), as well as decreased motivation and self-confidence in mathematics (Ashcraft, 2002). Furthermore, math anxiety has been shown to predict STEM career choice among high-achieving college women (Chipman, Krantz, & Silver, 1992). Therefore, math anxiety represents a promising source of lower female interest, involvement, and success in STEM (Ferguson et al., 2015). Given these detrimental effects of math anxiety, and the potential impact this has on career choice, specifically in STEM, an important question concerns why women are more likely than men to be math anxious.

Several studies have attempted to reveal the factors that might account for sex differences in math anxiety (Beilock, Gunderson, Ramirez, & Levine, 2010; Bieg, Goetz, Wolter, & Hall, 2015; Ferguson et al., 2015; Flessati & Jamieson, 1991; Hill, Corbett, & Rose, 2010; Maloney et al., 2011). However, prior research has focused separately on either cognitive factors or emotional factors to help explain the link between sex and math anxiety. Importantly, previous research in this area has provided several hypotheses that could explain why women are more likely than men to be math anxious. In the next section, we introduce a framework that integrates these various literatures into a comprehensive model of sex differences in math anxiety. More specifically, we examine how cognitive and affective differences in math and spatial domains may play a critical role in explaining sex differences in math anxiety.

1.2. A cognitive-emotional framework of spatial and mathematical processing

When exploring factors that might account for the relation between sex and math anxiety, it is important to consider both cognitive and emotional factors (e.g. Ledoux, 1989; Pessoa, 2010). Moreover, it may be useful to consider the potential influence of related domains that have been found to share close relations with mathematical processing, such as spatial processing (e.g. Cheng & Mix, 2014; Mix & Cheng, 2012; Walsh, 2003). As shown in Fig. 1A, we present a novel theoretical framework that accounts for interplay between cognitive (ability) and emotional (self-perceived ability and anxiety) dimensions, both *within* and *between* the domains of mathematics and space. Moreover, as outlined in Fig. 1B, our theoretical framework conjectures multiple pathways between sex and math anxiety, considering both cognitive and emotional factors within and between the closely allied disciplines of spatial and mathematical processing. For example, it is possible that the path from sex to math anxiety is best explained by within domain factors related to actual and/or self-perceived *math* ability. However, the relation between sex and math anxiety might also be explained by considering cross-domain relations. For example, spatial and mathematics anxiety might be related in ways that are independent from within-domain relations (e.g., math ability and math anxiety). In other words, ability, self-perceived ability, and anxiety may share tighter cross-domain associations with one another at a single level than within-domain associations between levels.

Taken together, the potential pathways from sex to math anxiety are varied and might best be explained by within domain factors (i.e., either actual math ability and/or self-perceived math ability), between domain factors (i.e., spatial ability and/or spatial anxiety/self-perceived ability), or a combination of both within and between domain factors (e.g., sex differences in spatial and math ability might combine to provide the best explanation of sex differences in math anxiety). The framework in Fig. 1 provides a unified means of examining these possibilities, as well as a coherent theoretical background to aid in interpreting experimental results.

What follows is a brief review and discussion of the evidence to date on the various relations between each component of the framework and their potential to contribute to understanding the well-established – if problematic – link between sex and math anxiety.

1.2.1. Sex differences in mathematics abilities

The observed sex disparity in math anxiety could be explained by sex differences in mathematical competencies. In other words, perhaps on average, men are better than women at math and this difference in math ability explains why more women report higher levels of fear and anxiety towards math. However, to date, there is little empirical support for the presence of sex differences in mathematics abilities (e.g. Halpern et al., 2007; Hutchison, Lyons, and Ansari, 2018; Stoet & Geary, 2013). For example, a recent *meta*-analysis using international standardized test results (i.e., Trends in International Mathematics and Science Study [TIMSS] and Programme for International Student Assessment [PISA]) found little evidence for sex differences in mathematics performance amongst high school students from across sixty-nine countries (N = 493,495; Else-Quest, Hyde, & Linn, 2010). Even when sex differences did emerge in the data (in favor of males), the effect sizes were small ($ds < 0.15$). A meta-analysis by Hyde, Lindberg, Linn, Ellis, and Williams, (2008) revealed similar results. Specifically, Hyde et al. analyzed the test scores on state tests of over seven million American students and found only 'trivial' differences in mathematics performance, as indicated by uniformly small effect sizes across grades ($ds < 0.10$) (Hyde et al., 2008).

However, there is some evidence to suggest that while females tend to achieve better school grades in mathematics, males tend perform better on "high stakes" standardized tests, such as on the math sections of the SAT (Scholastic Aptitude Test) and GRE (Graduate Records Exam; Halpern et al., 2007). Further evidence for the "grade-test disparity" (Halpern et al., 2007), comes from studies showing that men outperform women on novel mathematics problems; that is, on questions that are not closely aligned with school mathematics (see Willingham & Cole, 1997 for details).

Although the evidence of sex differences in mathematics ability seems minimal and specific to novel mathematics problems, there is extensive, consistent evidence of sex differences in spatial abilities (Halpern et al., 2007; Levine, Foley, Lourenco, Ehrlich, & Ratliff, 2016; Voyer, Voyer, & Bryden, 1995); a point we will return to in further detail below. In view of this, one potential explanation for why sex differences emerge only when solving novel mathematics problems is that perhaps these novel problems rely on spatial processing to a greater extent than more traditional math tests. To this point, recent evidence suggests that spatial visualization, for example, plays an important role in solving novel mathematics tasks (e.g., see Mix et al., 2016).

In sum, with few exceptions (e.g., see Bull, Cleland, & Mitchell, 2013), sex differences in mathematics performance tend to be trivial or non-existent (Else-Quest et al., 2010; Halpern et al., 2007; Hutchison et al., 2018). However, there is some evidence to suggest that males and females may endorse different strategies to solve mathematical problems (e.g., see Battista, 1990; Gallagher et al., 2000; Heil & Jansen-Osmann, 2008; Pezaris & Casey, 1991). Overall, these results are difficult to reconcile with the view that females experience heightened math anxiety due to weaker mathematics ability compared to males.

1.2.2. Sex differences in perceived mathematics abilities

Although math ability may not be a promising candidate for explaining the sex differences in math anxiety, reports of sex differences in *perceived* math ability (often referred to mathematical self-concept)

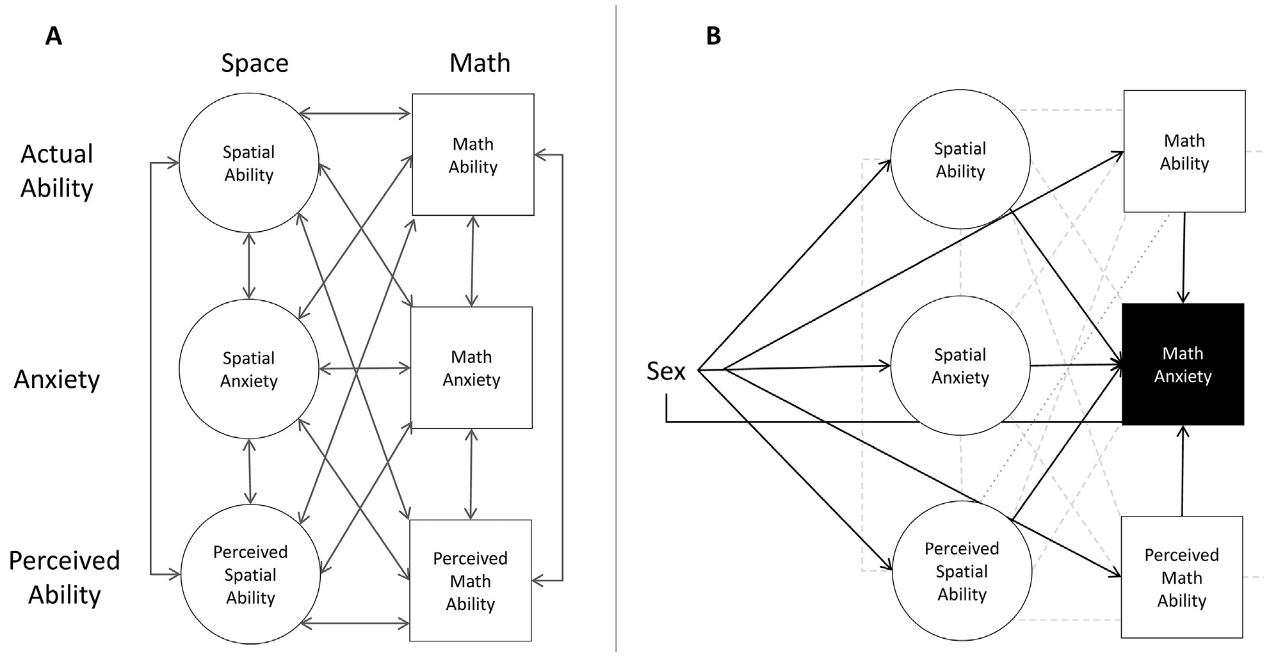

Fig. 1. An illustration of an overall framework presenting the possible theoretical relations between cognitive and emotional factors in the domains of spatial thinking and mathematics. (A) Depicts different aspects (actual ability, anxiety and perceived ability) of processing across two cognitive domains (spatial and mathematical). (B) Depicts the paths across the aspects of processing and cognitive domains that may explain the relation between sex and math anxiety.

have been more consistent. Self-concept refers to a collection of beliefs about one's own ability (Shavelson, Hubner, & Stanton, 1976). Mathematics self-concept refers specifically to an individual's perceived math ability. A large body of research has reported sex differences in math self-concept (e.g. Eccles & Harold, 1992; Nagy et al., 2010; Sáinz & Eccles, 2012).

A longitudinal cross-cultural study revealed that males have higher mathematical self-concept than females, and that this sex difference persists across time and is consistent across cultures (Nagy et al., 2010). However, when comparing mathematical self-concept to other domains such as language, studies find different patterns of results. For example, an early study of mathematical self-concept in a sample of gifted children showed that females reported higher self-concept for reading than math, whereas males reported higher self-concept for math than reading (Eccles & Harold, 1992). Another study that examined sex differences in self-concept related to math and computer skills revealed that males have a higher math and computer self-concept than females. Notably, this study reported no significant difference in math performance (measured by self-reported math grades) between males and females (Sáinz & Eccles, 2012).

Several studies have reported a link between math self-concept and math anxiety. For example, research has revealed a reciprocal relationship between math self-concept and math anxiety in school age children, with a larger magnitude of the path from math self-concept to math anxiety (Ahmed, Minnaert, Kuyper, & van der Werf, 2012). In line with this, the degree to which individuals integrate math into their sense of self (i.e. self-math overlap) has been linked to high math anxiety. Indeed, individuals who identify more with math are more likely to have lower math anxiety (Necka, Sokolowski, & Lyons, 2015).

In a similar vein, although the meta-analysis by Else-Quest et al. (2010) found little evidence of sex differences in actual math ability, the authors did find some evidence that males tend to have more positive attitudes towards math than females (d = 0.10–0.33) (Else-Quest et al., 2010). Together, this research indicates that perceived math ability (i.e. mathematical self-concept) varies as a function of sex; this variation in turn may be an important contributor to sex differences in math anxiety.

1.2.3. Sex differences in spatial abilities

While there is little evidence of sex differences in mathematics ability, there is extensive evidence of sex differences in ability within the domain of spatial cognition (Halpern et al., 2007; Levine et al., 2016; Voyer et al., 1995). Spatial ability is generally defined as the ability to generate, recall, maintain, and transform visual-spatial information (Lohman, 1996). Spatial ability can further be divided into small- and large-scale abilities (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006). Small-scale spatial skills are characterized by spatial tasks that require the mental manipulation or transformation of shapes or objects, such a mental rotation (Hegarty et al., 2006). Large-scale spatial skills are characterized by tasks that require physical or imagined movement through spatial environments, such as learning one's way through a new city (Hegarty et al., 2006).

Sex differences, typically in favor of males, have been found for both small and large-scale spatial abilities (Lawton, 2010; Voyer et al., 1995). However, perhaps the most robust and reliable sex differences occur on measures of 3D mental rotation (e.g. Masters & Sanders, 1993). Mental rotation ability is typically measured using a small-scale spatial task that involves mentally manipulating and comparing pictures of 3D figures to determine whether they are the same or different (i.e., mirror images; see Shepard & Metzler, 1971; Vandenberg & Kuse, 1978). In general, males are faster and more accurate than females on these tasks (Masters & Sanders, 1993) and outperform females in the range of 0.5 and 1 full standard deviations (Masters & Sanders, 1993; Nordvik & Amponsah, 1998; Silverman, Choi, & Peters, 2007; Voyer et al., 1995).

As spatial and mathematical abilities are strongly related, spatial ability is an important candidate to consider for explaining the link between sex and math anxiety (Mix & Cheng, 2012). Specifically, individuals with stronger spatial abilities tend to do better in mathematics (Mix & Cheng, 2012). Furthermore, spatial ability has also been shown to be a strong predictor of which high school students enter, enjoy, and succeed in STEM, even after controlling for quantitative and verbal skills (Wai, Lubinski, & Benbow, 2009).

Given the close relation between spatial thinking and mathematics, along with the sex differences in certain spatial abilities, it is possible that spatial abilities can help explain sex differences in math anxiety. In an early examination of this idea, Maloney et al. (2012) found evidence to suggest that spatial ability mediates the relation between sex and math anxiety. The authors concluded that women are likely to “be more math anxious than men on average because women are worse at spatial processing than men on average” (Maloney et al., 2012, p. 382). Although such a conclusion is plausible, it should be noted that the authors did not test for actual spatial ability per se. Instead, the authors used a subjective self-report measure that queried how good individuals believed themselves to be at various spatial skills. Thus, it is unclear from the Maloney et al. results whether it is spatial *ability* or one’s *perceptions* of one’s spatial ability (or both) that explains (mediates) the relation between sex and math anxiety.

To address this shortcoming, Ferguson et al. (2015) carried out a follow-up study that included both self-report measures of (large-scale) spatial abilities as well as objective behavioral measures of both small- and large-scale spatial skills. Although results varied somewhat between samples, the authors found evidence to suggest that small-scale spatial ability mediated the relation between sex and math anxiety. Notably, the authors also found that their measure of spatial anxiety mediated this relation. This point will be discussed further in the next section. These findings suggest that spatial ability may well play an important role in explaining sex differences in math anxiety (Ferguson et al., 2015).

One possibility is that sex differences in spatial skills result in increased spatial anxiety which in turn influences one’s overall anxiety towards mathematics. If one is anxious about spatial reasoning, it seems likely that they might also begin to feel anxious more generally about mathematics given that many math problems are inherently spatial or lend themselves to spatial reasoning or spatial strategies. Therefore, it would be surprising, but not inconceivable that the relationship between sex and math anxiety is best explained by processing within the spatial domain rather than the mathematical domain, as it is in the spatial domain where there are consistently reported sex differences.

1.2.4. Sex differences in affective factors of spatial processing

The majority of research on sex differences in spatial skills has operated under the assumption that these sex differences are attributable to fundamental differences in cognitive ability. However, an emerging body of research suggests that affective factors, such as attitude and beliefs, also play an important role in explaining sex differences in spatial processing. For example, recent research points to the potentially deleterious effects of the common societal belief that females are worse than males at spatial thinking (i.e. stereotype threat) (e.g., Beilock, Rydell, & McConnell, 2007; Maloney, Schaeffer, & Beilock, 2013; but see Flore & Wicherts, 2015; Ganley et al., 2013). Therefore, sex differences in spatial abilities might be partially attributable to the internalization of sociocultural norms and expectations. In keeping with this view, Tarampi, Heydari, and Hegarty (2016) found that sex differences in spatial ability may be due to differences in perceived rather than actual spatial ability. In this study, participants were given a spatial task that was framed as either a spatial condition or a social condition. In the spatial condition, the tasks were framed as measures of spatial ability, on which males had advantages. In the social condition, the task was framed as a measure of empathy, on which females had advantages. Results revealed that males performed better than females in the spatial condition but not the social condition.

The above evidence highlights the importance of perceived spatial ability in the performance of spatial reasoning tasks. This evidence drives the question: Does perceived spatial ability relate to an individual’s spatial anxiety, and potentially math anxiety as well? Previous work has shown that women tend to report higher levels of spatial anxiety compared to men (Else-Quest et al., 2010; Maloney et al., 2012). Moreover, as briefly noted above, Ferguson and colleagues found that spatial *anxiety* (in addition to actual small-scale spatial ability) mediated the relation between sex and math anxiety.

To our knowledge, only two studies have examined the contribution of affective and attitudinal factors within the spatial domain to the relation between sex and math anxiety: Ferguson et al. (2015) and Maloney et al. (2012). Maloney and colleagues found that self-reported spatial ability mediated the relation between sex and math anxiety. Critically, this study did not include a measure of actual spatial ability. By contrast, Ferguson et al. included measures of actual spatial ability, perceived spatial ability and spatial anxiety. Importantly, although the authors report that small-scale (and not large-scale) spatial ability mediated the relation between sex and math anxiety, measures of both perceived spatial ability and spatial anxiety focused exclusively on large-scale spatial situations. A more ideal approach to compare the mediational effects of cognitive and affective factors on the relation between sex and math anxiety would be to align these measures in terms of the type of spatial processing being assessed. Given the evidence that a strong relation exists between small-scale spatial skills (e.g., mental rotation, mental paper folding) and mathematics performance (Casey, Nuttall, Pezaris, & Benbow, 1995; Mix & Cheng, 2012), and because robust sex effects are routinely reported for small-scale spatial skills (e.g., Masters & Sanders, 1993; Nordvik & Amponsah, 1998; Silverman et al., 2007; Voyer et al., 1995), we propose examining different aspects of small-scale spatial processing (white circles in Fig. 1A). In addition, the potential explanatory role of both general cognitive factors (e.g., working memory capacity) and math processing (squares in Fig. 1) should be considered. For example, it may have been the case that actual spatial ability in Ferguson et al. was merely a proxy for either general cognitive or math processing abilities.

Taken together, the research reviewed above suggests that spatial skills, one’s self-evaluation of mathematical and spatial skills (i.e. perceived ability), and spatial anxiety, are all potential contributors to sex differences in math anxiety. However, further work is needed to better specify the unique contributions of each of these factors.

1.3. Current study

In the current paper, we examine the extent to which both affective and cognitive factors in the mathematical and spatial domains contribute to sex differences in math anxiety (see Fig. 1B). More specifically, our first aim was to replicate the often-reported sex difference in math anxiety (e.g. Hembree, 1990). Our second aim was to examine the respective potential of math ability, perceived math ability, spatial ability, perceived spatial ability, and spatial anxiety to mediate the relation between sex and math anxiety (Fig. 1B). Our third aim was to test the relative *unique* contributions of candidate mediators from the previous step in explaining the relation between sex and math anxiety. To foreshadow the results, spatial anxiety proved to be the most robust unique mediator of the relation between sex and math anxiety. Hence, we then ran post-hoc analyses to examine how different components of spatial anxiety may or may not mediate the relation between sex and math anxiety.

2. Materials and methods

2.1. Participants

One hundred and eighty-six first-year undergraduate students at the University of Western Ontario were recruited for a study examining predictors of academic decisions in University. Participants were recruited through posters and flyers distributed randomly throughout the University campus and through social media channels such as Facebook and networking groups for first year students at the University of Western Ontario. There was no mention of mathematics in the recruitment materials or the consent form. Of the 186 participants, nine were excluded. Two participants were excluded because they were not first year students, three participants were excluded because they incorrectly answered more than one third of instructional manipulation questionnaire check items (an a-priori exclusion criteria) and four participants were excluded because their errors on the mental rotation task were greater than chance (error-rate > 0.45). This resulted in a total of 175 participants (109 females, 66 males, ages 17–20, M = 18.55, SD = 0.39).

2.2. Procedure

Data included in this study are part of a larger data set. All included measures were collected during a two-hour behavioural session, wherein participants completed a battery of surveys and several cognitive tasks.[1] The order of the survey battery and cognitive tasks was counterbalanced and randomized across participants. Participants completed all measures and identified their biological sex. The University of Western Ontario Ethics Review Board approved all procedures. Participants provided written consent. Participants were tested while sitting at a desk approximately 60–70 cm from a flat-screen LCD monitor. Surveys were presented using Qualtrics (Provo, UT, USA) and all cognitive tasks were presented using EPrime 2.0 software. The surveys and working memory task were computed using mouse input; all other tasks were completed using keyboard input. Participants were compensated $20 CAD for their time.

2.3. Materials

Descriptive statistics of survey battery and cognitive tasks are presented in Table 1.

2.3.1. Math anxiety

Participants completed the short math-anxiety rating scale (sMARS; Alexander & Martray, 1989). In this survey, participants rated how anxious they would feel in 25 situations related to math such as, "signing up for a math course" or "walking to math class". Participants answered the 25 items on a 0–4 likert scale, with a higher number indicating more anxiety. Total scores ranged from 0 to 100 with 0 being the lowest possible math anxiety score and 100 being the highest possible math anxiety score. This score was used as a measure of math anxiety (middle square in Fig. 1A); it was the outcome measure in all mediation models. The survey has a Cronbach's α of 0.96.

2.3.2. Math ability

Participants completed challenging mental arithmetic problems (MATH). Task trials were adapted from the Kit of Factor-Referenced Cognitive Tests (Ekstrom, French, & Harman, 1976; Lyons & Beilock, 2011). Trials were one of four different operation types: addition (three 2-digit numbers; e.g., 67 + 95 + 52), subtraction (a two- or three digit minuend and a 2- or three digit subtrahend; e.g., 283–97), multiplication (one 2-digit number and one 1-digit number; e.g., 36 × 7) and division (a 1-digit divisor into a 2- or 3-digit dividend; e.g., 522 ÷ 9). Participants freely responded with the answer using the number-pad of the keyboard. Participants were not allowed to use a pencil or paper during this task. As such, for arithmetic, the task was relatively difficult (mean RT = 9.91 s, mean accuracy = 81.2%). Operation types were presented in separate blocks. The order of the blocks was randomized across participants. Each block lasted approximately 3 min. The trial ended when the participant completed the trial they were at when 3 min elapsed. Participants were unaware that there was a time limit. Math ability was scored as the total number of problems solved correctly within the each 3-min time span, and then summed across the 4 operation blocks. A higher score indicates higher math ability. This score was used as an indicator of math ability (top square in Fig. 1A).

2.3.3. Perceived math ability

Participants reported their perceived math ability by indicating their level of agreement with the statement "I am just not good at math" (adapted from the PISA index of mathematics self-concept, SCMAT; OECD, 2012). The item was scored on a scale of 0–3 and reverse-coded (a higher score thus indicates higher self-rated math ability). This score was used as an indicator of perceived math ability (the bottom-most square in Fig. 1A). While this was a single-item measure, the correlation between perceived math ability and actual math ability in the current data of (r = 0.37) is in fact slightly higher than that which is typically reported in the literature for multi-item assessments of perceived math ability ($r = 0.33$, Freund & Kasten, 2012), thus indicating good validity for the measure used here.

2.3.4. Spatial manipulation ability

Participants completed the Mental Rotation Task (MRT; derived from Shepard & Metzler, 1971). This task is a standard measure of an individual's ability to mentally manipulate objects. In this version of the task, participants saw two 2-dimensional drawings of 3-dimensional objects. In half of the trials, the two objects were the same object, just rotated along one of the x-, y-, 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. Participants were asked to determine as quickly and accurately as possible whether the block figures were the same or different objects. The instructions were "Your task is to decide if two objects are in fact the same object - with one object simply rotated in space. The alternative is that the two objects, even if rotated, are indeed different. If the objects are the same, press the C key. If the objects are different press the M key." The participant was given 12 s to answer each trial. Participants saw 5 practice trials and 50 experimental trials. Experimental trial order was randomized across participants. Performance was determined using accuracy (proportion correct); hence, a higher score indicated better mental rotation ability. This score was used as a measure of spatial ability (top-most circle in Fig. 1A). Participants with an accuracy rate < 0.55 were assumed to be guessing at chance and were excluded.

2.3.5. Perceived spatial ability

Participants completed the Object-Spatial Imagery Questionnaire (OSIQ; Blajenkova, Kozhevnikov, & Motes, 2006). This survey is a 30-item questionnaire that consists of two 15-item subscales: The Spatial Imagery Questionnaire (SIQ) and the Object Imagery Questionnaire (OIQ). The SIQ is a measure of an individual's self-rated ability to process spatial relations between objects. Here, we refer to this as perceived spatial (manipulation) ability (bottom-most square in Fig. 1). We used the SIQ portion of the questionnaire as a measure of perceived spatial ability (bottom-most circle in Fig. 1A). Cronbach's alpha for the spatial scale is 0.83. The OIQ is a measure of an individual's self-rated ability to process detailed picture-like images. Here, we refer to the OIQ portion of the questionnaire as perceived imagery ability, which we used as a control measure (i.e. to control for self-rated ability in general). Cronbach's alpha for the Object scale is 0.79. Scores on each subscale range from 15 to 75 (lower score indicates lower self-rated ability).

2.3.6. Spatial anxiety (manipulation, recognition, navigation)

Participants completed a spatial anxiety questionnaire (Lyons et al., in press). This survey examined how anxious the participant would feel in 24 situations related to spatial processing. There were eight situations (i.e., 8 items) that related to spatial manipulation (SAM), spatial recognition (SAR), and spatial navigation (SAN). The primary measure of interest was anxiety about spatial manipulation (SAM, corresponding to the middle circle in Fig. 1). The other two spatial anxiety measures

[1] Additional cognitive measures included a processing speed task, vocabulary ability, and a visual imagery task. Additional questionnaires included various other demographic, academic and personality assessments relevant to goals of other aspects of the broader project. These measures are not included here as they do not bear directly on the hypotheses of primary theoretical interest in the present manuscript.

Table 1
Descriptive statistics and bivariate correlations.

	M	*SD*	Sex[a]	SMARS[b]	MATH[c]	PMATH[d]	MRT[e]	SIQ[f]	SAM[g]	R-Span[h]	OIQ[i]	TAI[j]	SAR[k]	SAN[l]
Sex[a]	***0.62***	***0.49***	**—**	**1.0E−06**	**0.104**	**0.011**	**3.0E−06**	**3.6E−04**	**1.5E−04**	0.124	0.025	1.3E−05	0.702	3.0E−06
SMARS[b]	***29.52***	***19.67***	**0.355****	**—**	**5.0E−06**	**6.9E−28**	**2.6E−04**	**3.1E−07**	**1.7E−09**	0.545	3.1E−04	1.7E−09	0.248	2.5E−12
MATH[c]	***50.95***	***24.37***	**−0.123**	**-0.339****	**—**	**4.9E−07**	**0.024**	**0.684**	**0.780**	0.106	0.116	0.693	0.054	0.085
PMATH[d]	***1.90***	***1.05***	**−.191***	**−0.708****	**0.369****	**—**	**0018**	**3.8E−03**	**0.004**	0.700	0.013	5.1E−05	0.994	6.8E−05
MRT[e]	***0.18***	***0.11***	**−0.344****	**−0.273****	**0.170***	**0.178***	**—**	**1.8E−04**	**3.5E−04**	0.015	0.020	0.675	0.296	1.1E−04
SIQ[f]	***45.13***	***7.59***	**−0.267****	**−0.375****	**0.031**	**0.306****	**0.280****	**—**	**3.6E−04**	4.8E−01	2.8E−03	7.0E−03	3.1E−01	4.2E−05
SAM[g]	***10.07***	***6.45***	**0.283****	**0.435****	**−0.021**	**−0.218****	**−0.267****	**−0.429****	**—**	0.299	0.798	1.2E−05	2.8E−11	4.6E−10
R-Span[h]	*46.13*	*15.47*	−0.117	−0.046	0.106	−0.029	0.184*	−0.053	−0.079	—	0.702	0.320	0.969	0.604
OIQ[i]	*50.85*	*9.67*	0.170*	0.270**	−0.119	−0.187*	−0.175*	−0.225**	−0.019	0.029	—	0.921	9.5E−12	0.958
TAI[j]	*40.71*	*10.82*	0.323**	0.436**	0.030	−0.301**	−0.032	−0.203**	0.324**	−0.076	0.008	—	0.013	6.2E−05
SAR[k]	*11.39*	*6.11*	0.029	0.088	0.146	−0.001	0.079	0.077	0.476**	−0.003	−0.486**	0.187*	—	9.7E−08
SAN[l]	*11.93*	*7.82*	0.343**	0.498**	−0.130	−0.296**	−0.289**	−0.304**	0.449**	−0.040	−0.004	0.298**	0.390**	—

Note: Descriptive statistics and correlation matrix of survey and behavioral measures. Variables of interest are bolded. Covariates are shown in normal font. Post-hoc variables are grey. The values to the left of the diagonal are the bivariate correlation coefficients (*r*). The values to the right of the diagonal are the p-values of each correlation in reported using scientific notation. $N = 175$. $^{*}p < .05$, $^{**}p < .01$.
[a]Sex: Males were coded as 0 and females were coded as 1.
[b]Short math-anxiety rating scale (sMARS): Higher scores mean higher math anxiety.
[c]Mental Arithmetic Task (MATH): Higher scores mean higher mental arithmetic ability.
[d]Perceived Math ability (PMATH): Higher scores mean higher perceived math ability.
[e]Mental Rotation Task (MRT): Higher scores mean better spatial manipulation ability.
[f]Spatial Imagery Questionnaire (SIQ): Higher scores mean better perceived spatial manipulation ability.
[g]Spatial Anxiety Manipulation Subtest (SAM): Higher scores mean higher anxiety for spatial manipulation.
[h]Reading-Span task (R-span): Higher scores means greater working memory capacity.
[i]Object Imagery Questionnaire (OIQ): Higher scores mean better perceived spatial recognition ability.
[j]Trait anxiety inventory (TAI): Higher scores mean more general anxiety.
[k]Spatial Anxiety Recognition Subtest (SAR): Higher scores mean higher anxiety for spatial recognition.
[l]Spatial Anxiety Navigation Subtest (SAN): Higher scores mean higher anxiety for spatial navigation.

(SAR and SAN) were examined as post-hoc variables. Participants answered 24 items on a 0–4 likert scale, with a higher number indicating higher anxiety. Participants' scores on each of the three subscales (SAM, SAR, SAN) ranged from 0 to 32 with 0 indicating the lowest possible degree of anxiety. The SAM score was used as a measure of spatial anxiety ability (middle circle in Fig. 1A). Reliability is good to excellent for all three subscales ($\alpha s > 0.86$).

2.3.7. Trait anxiety

Participants completed the trait anxiety inventory (TAI; Spielberger, Gorsuch, & Lushene, 1970). This 20-item survey assessed how frequently participants experience general feelings of anxiety. Participants indicated how often they experience statements such as, "I feel calm" and "I feel tense" using a 1–4 likert scale with 1 labeled "not at all" and 4 labeled "very much so." Participants' scores ranged from 20 to 80 with a higher value indicating higher general anxiety. The TAI was included as a covariate to account for anxiety that is not specific to mathematical or spatial processing. This measure has a Cronbach's α of 0.93.

2.3.8. Working memory

Participants completed the Automated Reading-Span (R-SPAN) task (Conway et al., 2005; Unsworth, Heitz, Schrock, & Engle, 2005) to determine individual working memory capacity. This is a complex span task with two components: a processing component and a memory component. On each sub-trial, the participant verifies the semantic sensibility of a grammatically valid English sentence. The participant is then presented with a single letter. This procedure is repeated 3–7 times, after which participants must recall the letters in the order they saw them. This constitutes a single trial. The score for a trial is either the number of letters correctly recalled on said trial or zero if any recall errors were made. Total scores are summed across trials and range from 0 to 75, with a higher value indicating higher working memory capacity. This measure was included as a covariate to account for general cognitive capacity when examining mathematical ability and spatial ability scores. This measure has a Cronbach's α of 0.78.

3. Results

All analyses were performed in SPSS v. 24. Results are presented in five sub-sections. (1) Bivariate correlations assessed associations between all variables included in the main analyses (sex, math anxiety, math ability, perceived math ability, spatial manipulation ability, perceived spatial manipulation ability, spatial manipulation anxiety), covariates (working memory, perceived object imagery ability, trait anxiety), and post-hoc variables (spatial recognition anxiety, spatial navigation anxiety). (2) Independent samples t-tests were computed to examine sex differences between scores on all variables. (3) Single mediation analyses were computed to determine whether math ability, perceived math ability, spatial manipulation ability, perceived spatial manipulation ability, and spatial manipulation anxiety mediated the relation between sex and math anxiety (i.e. to examine whether each indirect path in Fig. 1B was significant). (4) A combined, multiple-mediation analysis examined whether spatial manipulation ability, perceived spatial manipulation ability, and spatial manipulation anxiety (the three circles in Fig. 1B) were unique mediators of the relation between sex and math anxiety. (5) Post-hoc mediation analyses were included to a) perform quality checks on the data b) examine whether spatial recognition anxiety and spatial navigation anxiety mediated the relation between sex and math anxiety and c) examine whether spatial manipulation ability and spatial manipulation anxiety sequentially mediated the relation between sex and math anxiety.

3.1. Correlations between measures

3.1.1. Bivariate correlations

All summary statistics of survey and cognitive measures as well as statistics from the bivariate correlations are presented in Table 1. All five variables of interest (bolded entries in Table 1) were significantly correlated with math anxiety.

3.2. Sex differences

Independent samples *t*-tests were run for all included variables to

Table 2
Sex differences.

Measure	Sex	*Mean*	*SD*	*t*	*df*	*p*	M_Δ
sMARS	**M**	**20.58**	**14.46**	**−5.42****	**168.8**	**2.0E−07**	**−14.36**
	F	**34.94**	**20.47**				
MATH	**M**	**54.80**	**22.33**	**1.64**	**173.0**	**0.104**	**6.19**
	F	**48.61**	**25.34**				
P-MATH	**M**	2.17	0.99	**2.57***	**173.0**	**0.011**	**0.41**
	F	1.75	1.06				
MRT	**M**	**0.13**	**0.09**	**5.08****	**159.3**	**1.0E−06**	**−0.08**
	F	**0.21**	**0.11**				
SIQ	**M**	**47.73**	**6.58**	**3.64****	**173.0**	**3.6E−04**	**4.17**
	F	**43.56**	**7.76**				
SAM	**M**	**7.73**	**5.78**	**−3.89****	**173.0**	**1.5E−04**	**−3.76**
	F	**11.49**	**6.45**				
R-Span	M	48.44	14.49	1.55	173.0	0.124	3.71
	F	44.72	15.94				
OIQ	M	48.74	8.20	−2.39*	160.4	0.018	−3.38
	F	52.12	10.3				
TAI	M	36.23	7.94	−4.90**	169.8	2.0E−06	−7.19
	F	43.42	11.45				
SAR	M	11.17	5.25	−0.38	173.0	0.702	−0.37
	F	11.53	6.59				
SAN	M	8.48	5.80	−5.22**	168.6	5.3E−07	−5.52
	F	14.01	8.17				

Note: T-tests quantifying sex-differences. Variables that are part of the main analyses are bolded, covariates are in normal font and post-hoc variables are in grey. Levene's test of homogeneity of variance was computed for each measure. A t-statistic not assuming homogeneity of variance was used for measures that violated the assumption (SMARS, MRT, OIQ, TAI and SAN). See Section 2 for a description of how each measure was scored. $^{*}p < .05$, $^{**}p < .01$. Results did not change when analyses were run with standardized scores. M_Δ: difference between means.

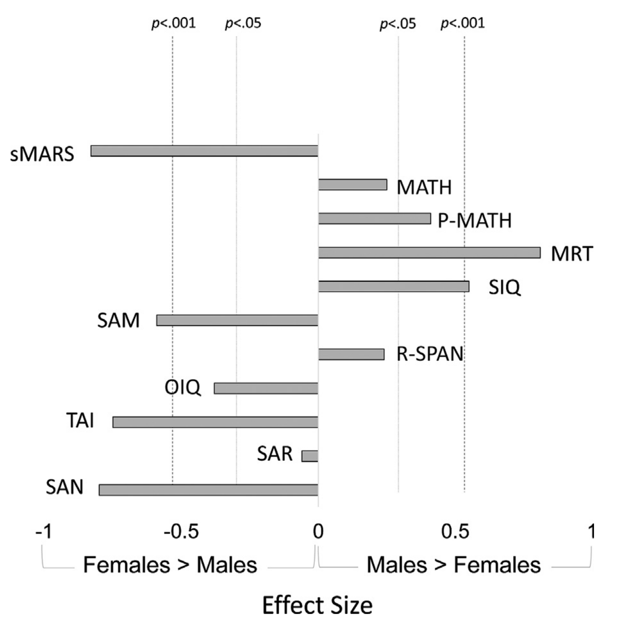

Fig. 2. A visual illustration of the effect sizes of the sex differences for all variables in the current study. Negative effect sizes represent scores where females have higher scores than males. Females scored higher than males on math anxiety (sMARS), spatial manipulation anxiety (SAM), perceived spatial recognition ability (OIQ), general anxiety (TAI), spatial recognition anxiety (SAR), and spatial navigation anxiety (SAN). Positive effect sizes represent scores where males have higher scores than females. Males scored higher than females on math ability (MATH), perceived math ability (PMATH), spatial manipulation ability (MRT), perceived spatial manipulation ability (SIQ), and working memory ability (WM).

test sex differences for each measure (see Table 2 for details; effect-sizes are shown in Fig. 2). Women reported significantly higher math anxiety, spatial manipulation anxiety, spatial navigation anxiety, and trait anxiety. Women also reported significantly lower perceived spatial manipulation ability, and perceived math ability, but higher perceived spatial recognition ability. Women performed significantly worse on the mental rotation task. There were no significant sex differences on working memory, math ability, perceived spatial recognition ability and spatial recognition anxiety. Notably, math ability, and working memory approached significance, with effect-sizes > 0.20.

3.3. Mediation analyses

The current study examined whether the relation between sex and math anxiety is mediated through different aspects of mathematical and spatial processing depicted in Fig. 1B. Specifically, the two variables within the mathematical domain including math ability and perceived math ability (represented by white squares in Fig. 1B) were each examined as potential mediators between sex and math anxiety. Subsequently, variables within the spatial domain including actual spatial manipulation ability, perceived spatial manipulation ability, and spatial manipulation anxiety (represented by the circles in Fig. 1B) were each examined as potential mediators in the relation between sex and math anxiety.

Mediation analyses were computed to examine whether each of the five variables mediated the relation between sex and math anxiety while controlling for covariates (working memory, perceived spatial recognition ability, trait anxiety). Working memory was included as a covariate to control for general cognitive processing to improve the specificity of our ability mediators. Perceived spatial recognition ability was included as a covariate to control for self-perceived ability in general. Trait anxiety was included as a covariate to ensure that the mediational effects were specific to spatial and/or math anxiety rather than attributable to high anxiety in general. The variables included in all mediation analyses were standardized. This was to ensure that predictors, mediators, and covariates were on the same scale and could thus be compared within the model.

All mediation analyses were computed using the PROCESS macro v. 2.15 in SPSS. All mediation analyses use Model 4, except the final sequential mediation analysis which uses Model 6. The strength and significance of the mediation models were tested using the bootstrapping method with 10,000 iterations (Preacher, Rucker, & Hayes, 2007). For all mediation analyses, the confidence interval of the total (combined direct and indirect) effect of sex on math anxiety was significant (Table 3, all analyses section). This indicates that sex is a

Table 3
Mathematical processes as mediators of the relation between sex and math anxiety.

Analysis	Model	Estimate	SE/SE†	P	%C	95% CI	99% CI
All Analyses	*Model without Mediator*						
	Intercept	−0.21	0.11	0.06		[−0.43, 0.01]	[−0.50, 0.08]
	Sex → sMARS (c)	0.36*	0.15	0.01		[0.07, 0.65]	[−0.018, 0.74]
	$R^2_{Sex \rightarrow sMARS}$	0.28					
A (Fig. 3A)	*Model with MATH as Mediator*						
	Intercept	−0.16	0.1	0.13		[−0.37, 0.05]	[−0.43, 0.11]
	Sex → MATH (a)	−0.25	0.17	0.14		[−0.58, 0.08]	[−0.68, 0.19]
	MATH → sMARS (b)	−0.33**	0.06	< 0.0001		[−0.45, 0.20]	[−0.49, −0.16]
	Sex → sMARS'(c′)	0.28*	0.14	0.04		[0.01, 0.55]	[−0.07, 0.64]
	Indirect Effect (a*b)	**0.08**	**0.06†**		**0.22**	**[−0.02, 0.20]**	**[−0.05, 0.25]**
	$R^2_{Sex \rightarrow MATH \rightarrow sMARS}$	0.38					
B (Fig. 3B)	*Model with PMATH as Mediator*						
	Intercept	−0.14	0.08	0.11		[−0.31, 0.03]	[−0.37, 0.09]
	Sex → PMATH (a)	−0.15	0.15	0.31		[−0.45, 0.14]	[−0.54, 0.24]
	PMATH → sMARS (b)	−0.61**	0.06	< 0.0001		[−0.73, −0.50]	[−0.77, −0.47]
	Sex → sMARS'(c')	0.27*	0.11	0.02		[0.04, 0.49]	[−0.03, 0.57]
	Indirect Effect (a*b)	**0.09**	**0.09†**		**0.25**	**[−0.08, 0.30]**	**[−0.14, 0.34]**
	$R^2_{Sex \rightarrow PMATH \rightarrow sMARS}$	0.56					

Note: Regression results for mathematical ability mediation analyses. The mediation of the effect of sex on math anxiety by each of (A) actual math ability (MATH) (B) perceived math ability (PMATH).

- SE refers to standard error within the normal linear regression for all direct effects. SE† refers to bootstrapped standard error and is reported for all indirect effects. All values that are SE† are denoted with a † symbol.
- P refers to the significance of the linear regression of the indirect effects.
- %C refers to the percent of the total effect (c) that is accounted for by the indirect effect (a*b).
- R^2 refers to the total variance of the outcome variable explained by the predictors and all covariates.
- The 95% and 99% confidence intervals (CI) are obtained by the bias-corrected bootstrap with 10,000 resamples. CIs for R^2 indices are obtained analytically. For the CIs the first number reported in the bracket is the lower bound and the second number reported is the upper bound of the CI. CIs are considered statistically significant if the lower bound to the upper bound do not cross zero (e.g. [0.0142, 0.2999]).
- $^{*}p < .05$, $^{**}p < .01$.
- The data in this table are depicted in Fig. 3.

unique and significant predictor of math anxiety (this is depicted in Fig. 1B as the direct path from sex to the dark- coloured square). In what follows, we test each of the five paths (depicted in Fig. 1B) connecting sex and math anxiety using single-mediator mediation analyses to determine which, if any, of the candidate mediators explain the relation between sex and math anxiety.

3.3.1. Single mediators: Mathematical domain

In this set of analyses, we examined if the relation between sex and math anxiety is mediated by each of two other aspects of processing within the mathematical domain: math ability and perceived math ability (depicted as white squares in Fig. 1B).

3.3.1.1. Math ability as a mediator. The relation between sex and math anxiety was not significantly mediated by math ability (Table 3A, Fig. 3A). Although math ability does significantly predict math anxiety at a 99 percent confidence interval, sex does not predict math ability at a 95 or a 99 percent confidence interval. Thus, we find no evidence supporting the path depicted in Fig. 1B from sex to math anxiety (black square) via math ability (top white square).

3.3.1.2. Perceived math ability as a mediator. The relation between sex and math anxiety was not significantly mediated by perceived math ability (Table 3B, Fig. 3B). Although perceived math ability did significantly predict math anxiety at a 99 percent confidence interval, sex did not predict perceived math ability at a 95 or a 99 percent confidence interval. Thus, we find no evidence supporting the path depicted in Fig. 1B from sex to math anxiety (black square) via perceived math ability (bottom white square).

Together, these findings suggest that processing within the math domain (represented in Fig. 1B as white squares) does not explain the relation between sex and math anxiety.

3.3.2. Single mediators: Spatial domain

In this set of analyses, we examined if the relation between sex and math anxiety is mediated by each of three aspects of processing within the spatial domain: spatial ability, perceived spatial ability, and spatial anxiety (depicted as circles in Fig. 1B).

3.3.2.1. Spatial manipulation ability as a mediator. The relation between sex and math anxiety was mediated by spatial manipulation ability using a 99 percent confidence interval (Table 4, Fig. 4A). This mediation model accounted for 30% of the variance in math anxiety. The indirect effect accounted for 34% of the total effect (%C = 0.34). Sex significantly predicted spatial manipulation ability at 99 percent confidence interval, and spatial manipulation ability significantly predicted math anxiety at a 95 percent confidence interval. Evidence thus supports the presence of a significant pathway, depicted in Fig. 1B, connecting sex to math anxiety (black square) via spatial ability (top circle).

3.3.2.2. Perceived spatial ability as a mediator. The relation between sex and math anxiety was mediated by perceived spatial manipulation ability using a 99 percent confidence interval (Table 4, Fig. 4B). This mediation model accounted for 31% of the variance in math anxiety. The indirect effect accounted for 23% of the total effect (%C = 0.23). Sex significantly predicted perceived spatial manipulation ability at 95 percent confidence interval, and perceived spatial manipulation ability significantly predicted math anxiety at a 99 percent confidence interval. Evidence thus supports the presence of a significant pathway, depicted in Fig. 1B, connecting sex to math anxiety (black square) via perceived spatial ability (bottom circle).

3.3.2.3. Spatial manipulation anxiety as a mediator. The relation between sex and math anxiety was mediated by spatial manipulation

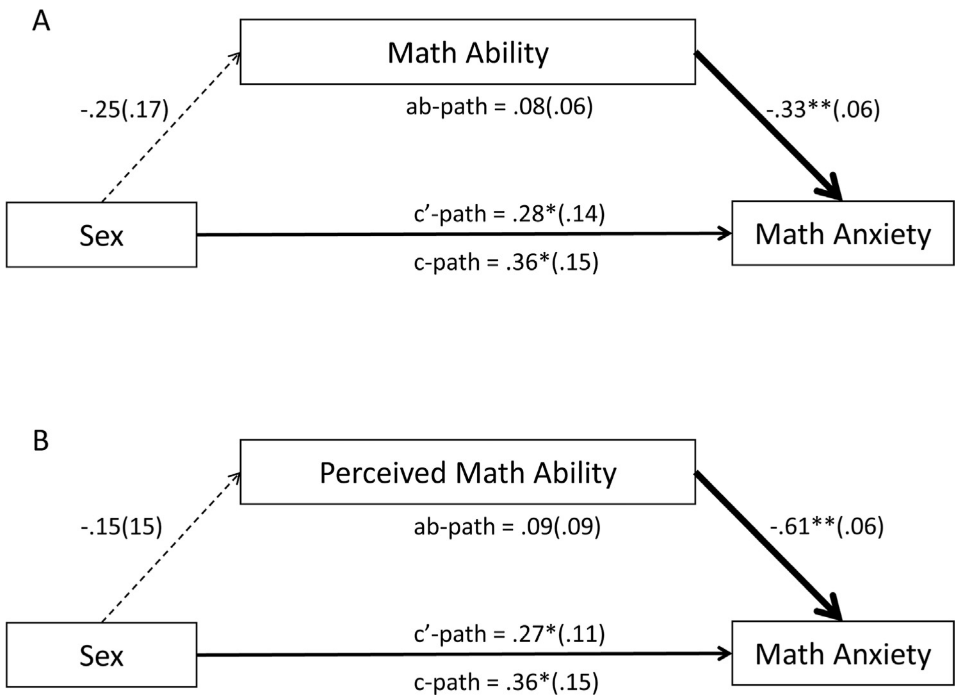

Fig. 3. This figure shows that the relation between sex and math anxiety is not mediated through (A) actual math ability or (B) perceived math ability. Statistics supporting this figure are reported in Table 3 in the following way: Asterisks indicate the significance of the coefficients (* indicates a significant 95% confidence interval, ** indicates significant 99% confidence interval).

anxiety using a 99 percent confidence interval (Table 4C, Fig. 4C). This mediation model accounted for 35% of the variance in math anxiety. The indirect effect accounted for 36% of the total effect (%C = 0.36). Sex significantly predicted spatial manipulation anxiety at 99 percent confidence interval, and spatial manipulation anxiety significantly predicted math anxiety at a 99 percent confidence interval. Evidence thus supports the presence of a significant pathway, depicted in Fig. 1B, connecting sex to math anxiety (black square) via spatial manipulation anxiety (middle circle).

Together, these findings suggest that all aspects of processing within the spatial domain (represented in Fig. 1B as circles) explain the relation between sex and math anxiety. Specifically, the results of the five single mediator mediation analyses reveal that all aspects of spatial processing including, spatial manipulation ability, perceived spatial manipulation ability, and spatial manipulation anxiety (represented as circles in Fig. 1B) mediate the relation between sex and math anxiety. However, potential mediators within the mathematical domain (i.e. math ability and perceived math ability; represented as white squares in

Table 4
Spatial processes as mediators of the relation between sex and math anxiety.

Analysis	Model	Estimate	SE/SE†	P	%C	95% CI	99% CI
All Analyses	*Model without Mediator*						
	Intercept	−0.21	0.11	0.06		[−0.43, 0.01]	[−0.50, 0.08]
	Sex → sMARS (c)	0.36^{*}	0.15	0.01		[0.07, 0.65]	[−0.018, 0.74]
	$R^2_{Sex \rightarrow sMARS}$	0.28					
A	*Model with MRT as Mediator*						
(Fig. 4A)	Intercept	−0.13	0.12	0.24		[−0.36, 0.09]	[−0.43, 0.16]
	Sex → MRT (a)	-0.69^{**}	0.16	< 0.0001		[− 0.10, − 0.38]	[−1.09, −0.28,]
	MRT → sMARS (b)	-0.18^{*}	0.07	0.01		[−0.32, −0.04,]	[− 0.36, 0.01]
	Sex → sMARS (c′)	0.24	0.15	0.11		[−0.06, 0.54]	[−0.16, 0.64]
	Indirect Effect (a*b)	**0.12^{**}**	**$0.06^{\dagger}$**		**0.34**	**[0.03, 0.26]**	**[0.003, 0.30]**
	$R^2_{Sex \rightarrow MRT \rightarrow sMARS}$	0.3					
B	*Model with SIQ as Mediator*						
(Fig. 4B)	Intercept	−0.16	0.11	0.16		[−0.38, 0.06]	[−0.45, 0.13]
	Sex → SIQ (a)	-0.41^{*}	0.16	0.01		[−0.72, −0.09]	[−0.82, 0.01]
	SIQ → sMARS (b)	-0.21^{**}	0.07	0.003		[−0.34, −0.07]	[−0.39, −0.03]
	Sex → sMARS (c′)	0.28	0.14	0.06		[−0.009, 0.57]	[−0.10, 0.66]
	Indirect Effect (a*b)	**0.08^{**}**	**$0.04^{\dagger}$**		**0.23**	**[0.02, 0.20]**	**[0.005, 0.24]**
	R^2 $_{Sex \rightarrow SIQ \rightarrow sMARS}$	0.31					
C	*Model with SAM as Mediator*						
(Fig. 4C)	Intercept	−13	0.11	0.22		[−0.35, 0.08]	[−0.41, 0.15]
	Sex → SAM (a)	0.42^{**}	0.16	0.01		[0.11, 0.74]	[0.01, 0.83]
	SAM → sMARS (b)	0.30^{**}	0.07	< 0.0001		[0.16, 0.43]	[0.12, 0.47]
	Sex → sMARS (c′)	0.24	0.14	0.1		[−0.04, 0.52]	[−0.13, 0.61]
	Indirect Effect (a*b)	**0.13^{**}**	**$0.06^{\dagger}$**		**0.36**	**[0.04, 0.29]**	**[0.02, 0.32]**
	R^2 $_{Sex \rightarrow SAM \rightarrow sMARS}$	0.35					

Note: Regression results for spatial manipulation mediation analyses. The mediation of the effect of sex on math anxiety by each of (A) actual spatial manipulation ability (MRT), (B) perceived spatial manipulation ability (SIQ), and (C) spatial manipulation anxiety (SAM). See notes from Table 3. The data in this table are depicted in Fig. 4.

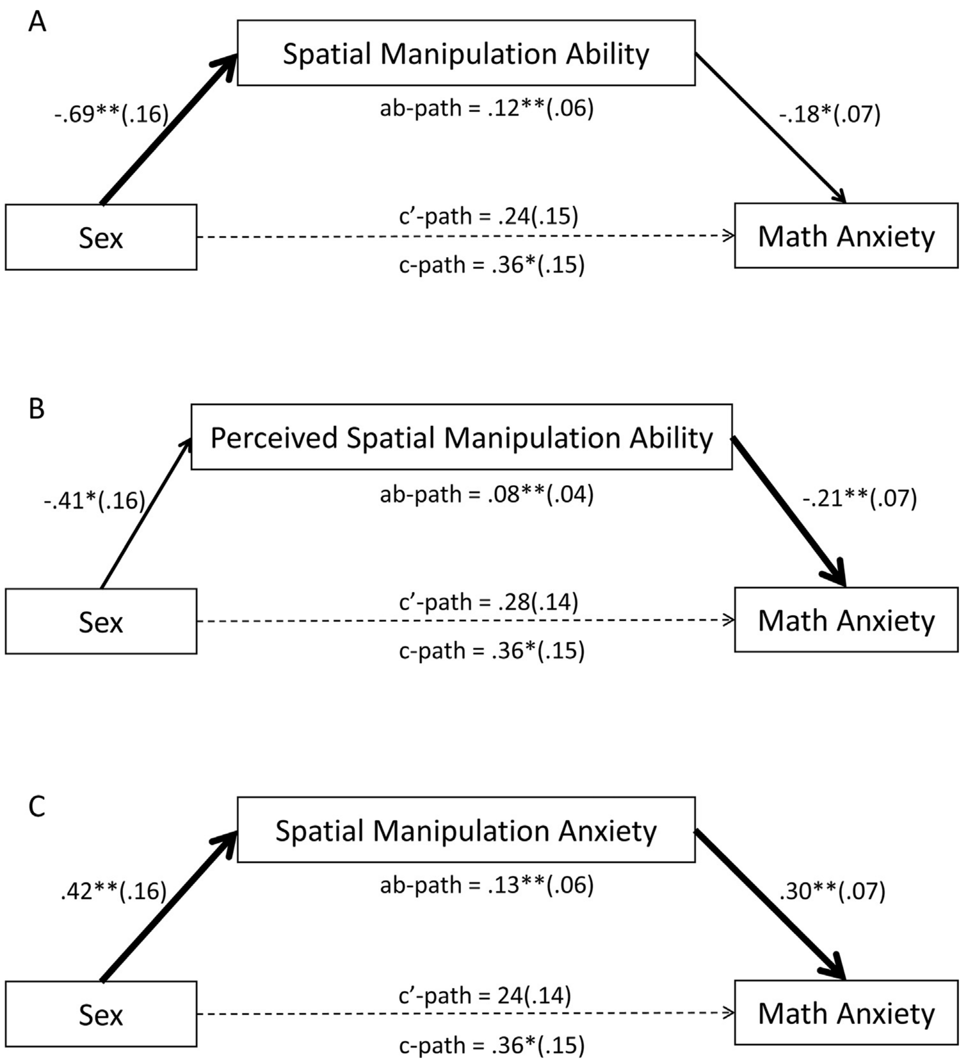

Fig. 4. This figure shows mediation of the effect of sex on math anxiety through (A) spatial manipulation ability, (B) perceived spatial manipulation ability, and (C) spatial manipulation anxiety. Asterisks indicate the significance of the coefficients (* indicates a significant 95% confidence interval, ** indicates significant 99% confidence interval).

Table 5
Competing spatial processes as meditors of the relation between sex and math anxiety.

Model	Estimate	SE/SE†	P	%C	95% CI	99% CI
Model without any Mediators						
Intercept	−0.21	0.11	0.06		[−0.43, 0.01]	[−0.50, 0.08]
Sex → sMARS (c)	0.36*	0.15	0.01		[0.07, 0.65]	[−0.018, 0.74]
$R^2_{Sex \rightarrow sMARS}$	0.28					
Model with MRT, SIQ and SAM as Mediators						
Intercept	−0.08	0.11	0.46		[−0.22, 0.12]	[−0.72, −0.09]
Sex → MRT (a)	−0.68**	0.16	< 0.0001		[−0.96, −0.34]	[−1.06, −0.25]
Sex → SIQ (a)	−0.41*	0.16	0.01		[−0.70, −0.08]	[−0.80, 0.02]
Sex → SAM (a)	0.42**	0.16	0.008		[0.11, 0.73]	[0.01, 0.83]
MRT → sMARS (b)	−0.10	0.07	0.15		[−0.24, 0.04]	[−0.28, 0.08]
SIQ → sMARS (b)	−0.09	0.07	0.2		[−0.23, 0.05]	[−0.28, 0.10]
SAM → sMARS (b)	0.23**	0.07	0.002		[0.10, 0.33]	[0.07, 0.37]
Sex → sMARS (c′)	0.15	0.15	0.3		[−0.14, 0.44]	[−0.37, 0.21]
*Indirect Effects (a*b)*						
Sex → MRT → sMARS	**0.07**	**0.05†**		**0.19**	[−0.04, 0.10]	[−0.07, 0.14]
Sex → SIQ → sMARS	**0.04**	**0.04†**		**0.11**	[−0.04, 0.06]	[−0.06, 0.08]
Sex → SAM → sMARS	**0.10****	**0.05†**		**0.27**	[0.02, 0.20]	[0.01, 0.24]
Sex → Total → sMARS	**0.20***	**0.07†**		**0.55**	[0.07, 0.36]	[0.03, 0.42]
$R^2_{Sex \rightarrow MRT,\ SIQ,\ SAM \rightarrow sMARS}$	0.62					

Note: Regression results for the unique mediation effects for actual spatial manipulation ability (MRT), perceived spatial manipulation ability (SIQ), and spatial manipulation anxiety (SAM). See notes for Table 3. The data in this table are depicted in Fig. 5.

Fig. 1B) did not mediate the relation between sex and math anxiety. Together, these results suggest that spatial processing, but not mathematical processing mediates the relation between sex and math anxiety.

3.4. Competing mediators

In view of results from the single mediator analyses (i.e. all aspects of processing in the spatial domain mediated the relationship between sex and math anxiety), it is important to examine the unique contributions of each of these aspects of spatial processing (ability, perceived ability and anxiety). Therefore, we ran a mediation analysis that included actual spatial manipulation ability, perceived spatial manipulation ability, and spatial manipulation anxiety as simultaneous, competing mediators. This analysis was used to determine the *unique* contribution of each mediator to explaining the relation between sex and math anxiety. In this mediation analyses, math ability and perceived math ability were included as covariates in addition to controlling for working memory, trait anxiety, and perceived spatial recognition ability. We adopted this more conservative approach to ensure that the variance explained by the three competing spatial mediators was unique to different aspects of spatial processing and were not a proxy for mathematical processing.

The relation between sex and math anxiety was mediated by the combined effect of three spatial domain mediators (spatial manipulation ability, perceived spatial manipulation ability, and spatial manipulation anxiety) using a 95 percent confidence interval, and a 99 percent confidence interval (Table 5, Fig. 5). This mediation model accounted for 62% of the variance in math anxiety. The total indirect effect accounted for 55% of the total effect (%C = 0.55). Spatial manipulation anxiety was a significant unique mediator using a 99 percent confidence interval and accounted for 27% of the total effect (%C = .27). In this model, Sex significantly predicted spatial manipulation anxiety at a 99 percent confidence interval, and spatial manipulation anxiety significantly predicted math anxiety at a 99 percent confidence interval. Perceived spatial manipulation ability and actual spatial manipulation ability were not significant unique mediators of the relation between sex and math anxiety. Indeed, although sex predicted spatial manipulation ability at a 99 percent confidence interval, spatial manipulation ability did not significantly predict math anxiety. Similarly, sex predicted perceived spatial manipulation ability at a 95 percent confidence interval, but perceived spatial manipulation ability did not significantly predict math anxiety. Therefore, spatial manipulation anxiety (represented in Fig. 1B as the middle circle), but not actual or perceived spatial manipulation ability (represented in Fig. 1B and the top and bottom circles) uniquely mediated the relation between sex and math anxiety. In sum, despite the finding that all aspects of processing within the spatial domain *individually* mediated the relation between sex and math anxiety, only spatial manipulation anxiety contributed *unique* explanatory power over and above the other two spatial factors.

3.5. Post-hoc analyses

The previous series of analyses revealed that spatial anxiety was the strongest mediator of the relation between sex and math anxiety. This means that spatial anxiety may be key to understanding sex differences in math anxiety. In what follows, we present post-hoc mediation analyses to (a) perform quality checks on the data, (b) examine the specificity of spatial manipulation anxiety as a mediator, and (c) examine whether multiple mediators sequentially mediate the relation between sex and math anxiety.

3.5.1. Quality checks

Before concluding that spatial anxiety explains math anxiety, it is critical to perform several quality checks. The previous analyses that revealed that spatial manipulation anxiety mediated the relation between sex and math anxiety, included covariates that controlled for working memory, trait anxiety, and perceived spatial recognition ability. However, these analyses did not control for mathematical processing. Therefore, the first post-hoc analysis examined whether spatial manipulation anxiety mediates the relation between sex and math anxiety while controlling for working memory, trait anxiety, perceived spatial recognition ability, math ability, and perceived math ability. Second, while our primary theoretical question of interest concerned sex differences in math anxiety (the c-path in all models up to this point), for purposes of interpretation, it is important to test for the reverse mediation. Therefore, we examined whether math anxiety mediates the relation between sex and spatial manipulation anxiety.

Additional post-hoc mediation analyses are also included to assess whether other types of spatial anxiety might mediate relation between sex and math anxiety. Specifically, we examined whether spatial recognition anxiety (SAR) and spatial navigation anxiety (SAN) mediate the relation between sex and math anxiety. A final post-hoc analysis was included to examine the whether spatial manipulation ability and spatial manipulation anxiety sequentially mediate the relation between sex and math anxiety (i.e. test the model: sex → spatial manipulation ability → spatial manipulation anxiety → math anxiety).

3.5.1.1. Spatial manipulation anxiety as a mediator while controlling for mathematical processing. The relation between sex and math anxiety was mediated by spatial manipulation anxiety at the 99 percent confidence level (Table 6A, Fig. 6A). This mediation model accounted for 62% of the variance in math anxiety. The total indirect effect accounted for 38% of the total effect (%C = 0.38). Sex significantly predicted spatial manipulation anxiety at a 95 percent confidence interval, and spatial manipulation anxiety significantly predicted

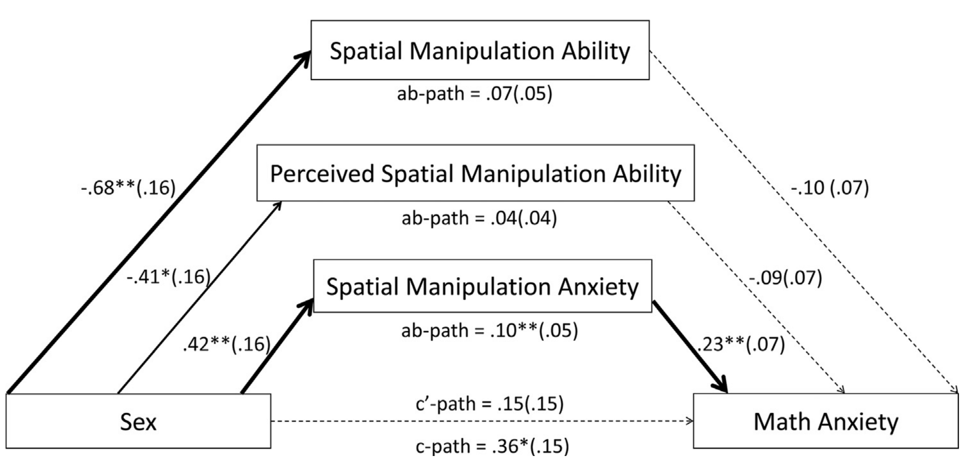

Fig. 5. This figure shows mediation of the effect of sex on math anxiety through spatial manipulation ability, perceived spatial manipulation ability, and spatial manipulation anxiety within one mediation analysis. Statistics supporting this figure are reported in Table 5. Asterisks indicate the significance of the coefficients (* indicates a significant 95% confidence interval, ** indicates significant 99% confidence interval).

Table 6
Post-hoc quality checks of key mediation findings.

Analysis	Model	Estimate	SE/SE†	P	%C	95% CI	99% CI
All Analyses	*Model without Mediator*						
	Intercept	−0.13	0.09	0.15		[−0.30, 0.05]	[−0.35, 0.10]
	Sex → sMARS (c)	0.24^{*}	0.11	< 0.0001		[0.02, 0.47]	[−0.05, 0.54]
	$R^2_{Sex \rightarrow sMARS}$	0.58					
A	*Model with SAM as Mediator*						
(Fig. 6A)	Intercept	−0.07	0.08	0.41		[−0.23, 0.10]	[−0.29, 0.15]
	Sex → SAM (a)	0.41^{*}	0.16	0.01		[0.10, 0.72]	[−0.0002, 0.82]
	SAM → sMARS (b)	0.23^{**}	0.05	< 0.0001		[0.13, 0.33]	[0.09, 0.37]
	Sex → sMARS (c′)	0.15	0.11	0.17		[−0.07, 0.37]	[−0.14, 0.44]
	Indirect Effect (a*b)	$\mathbf{0.09^{**}}$	$\mathbf{0.04^{\dagger}}$		**0.38**	[0.03, 0.20]	[0.007, 0.23]
	$R^2_{Sex \rightarrow SAM \rightarrow sMARS}$	0.62					
All Analyses	*Model without Mediator*						
	Intercept	-0.25^{*}	0.12	0.03		[−0.49, −0.01]	[−0.57, 0.06]
	Sex → SAM (c)	0.41	0.16	0.01		[0.09, 0.72]	[−0.0002, 0.82]
	$R^2_{Sex \rightarrow SAM}$	0.16					
B	*Model with sMARS as Mediator*						
(Fig. 6B)	Intercept	−0.20	0.12	0.09		[−0.42, 0.03]	[−0.50, 0.11]
	Sex → sMARS (a)	0.24^{*}	0.11	0.03		[0.02, 0.48]	[−0.05, 0.54]
	sMARS → SAM (b)	0.45^{**}	0.1	< 0.0001		[0.24, 0.65]	[0.18, 0.71]
	Sex → SAM (c′)	0.3	0.15	0.049		[0.002, 0.60]	[−0.09, 0.70]
	Indirect Effect (a*b)	$\mathbf{0.11^{*}}$	$\mathbf{0.06^{\dagger}}$		**0.27**	[0.01, 0.24]	[−0.02, 0.30]
	$R^2_{Sex \rightarrow sMARS \rightarrow SAM}$	0.25					

Note: Regression results for post-hoc quality checks. (A) The mediation of the relation between sex and math anxiety by (sMARS) spatial manipulation anxiety (SAM), (B) The mediation of the relation between sex and spatial anxiety (SAM) by math anxiety (sMARS). See notes for Table 3. The data in this table are depicted in Fig. 6.

math anxiety at a 99 percent confidence interval. Note that this analysis is akin to the mediation analysis reported in Table 4A and Fig. 4A, with the exception that the current analysis included math ability and perceived math ability as covariates.

3.5.1.2. Reverse mediation analysis.. The relation between sex and spatial manipulation anxiety was not mediated by math anxiety at the 99% level. Math anxiety did mediate this relation at the 95% level (Table 6B, Fig. 6B). Notably, the direct effect of sex on perceived math ability remained significant in addition to this significant indirect effect. This mediation model accounted for 25% of the variance in spatial manipulation anxiety. The total indirect effect accounted for 27% of the total effect (%C = 0.27).

In sum, the model of primary theoretical interest (Section 3.5.1.1) was a better overall fit of the data than when we reverse the positions of math anxiety and spatial manipulation anxiety (%C = 0.38 vs 0.27). Specifically, spatial manipulation anxiety accounted for a greater proportion of the sex → math-anxiety relation than did math anxiety of the sex → manipulation-anxiety relation. This was driven by the fact that the indirect effect passing through spatial manipulation anxiety passed the more stringent 99% confidence level. In contrast, the indirect effect passing through math anxiety passed only the more liberal 95% confidence level. Additionally, when spatial anxiety was included as a mediator of the relation of primary theoretical interest (sex → math-anxiety), the direct path between sex and math anxiety was no longer significant. Conversely, when math anxiety was included as a mediator of the relation between sex and spatial anxiety, the direct path (sex → spatial anxiety) remained significant. In sum, though the data cannot rule out the possibility of a reciprocal relation between math and spatial anxiety, they do lend greater support to the interpretation that spatial manipulation anxiety is better positioned to stand in an explanatory role with respect to sex differences in math anxiety.

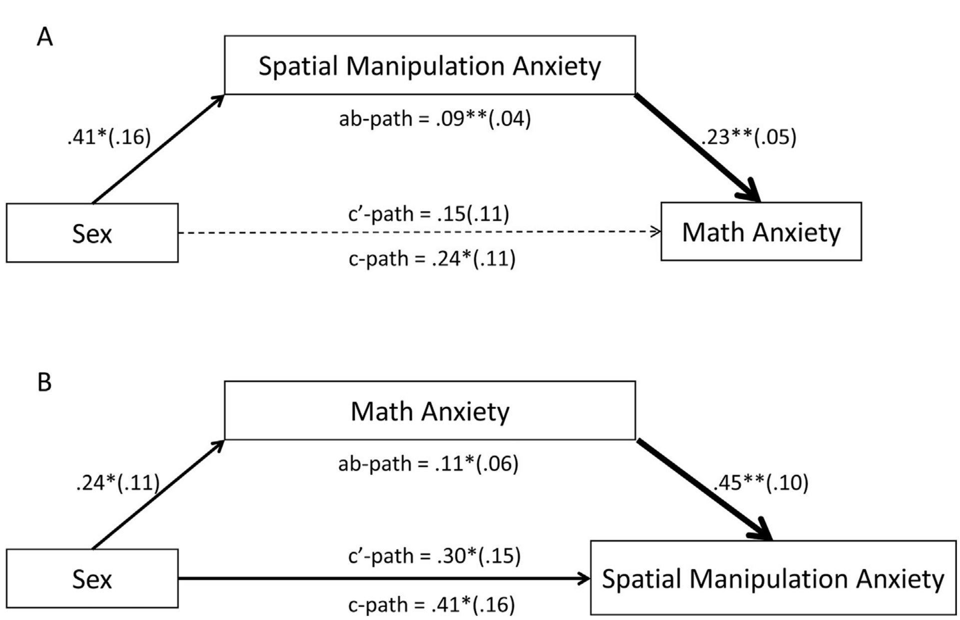

Fig. 6. The effect of sex on math anxiety is mediated by (A) spatial manipulation anxiety. (B) Testing the reverse mediation revealed that the effect of sex on spatial manipulation anxiety was mediated by math anxiety, but the direct path between sex and math anxiety remained significant. Statistics supporting this figure are reported in Table 6. Asterisks indicate the significance of the coefficients (* indicates a significant 95% confidence interval, ** indicates significant 99% confidence interval).

Table 7
Types of spatial anxiety as mediators of the relation between sex and math anxiety.

Analysis	Model	Estimate	SE/SE†	P	%C	95% CI	99% CI
All Analyses	*Model without Mediator*						
	Intercept	−0.13	0.09	0.15		[−0.30, 0.05]	[−0.35, 0.10]
	Sex → sMARS (c)	0.24*	0.11	< 0.0001		[0.02, 0.47]	[−0.05, 0.54]
	$R^2_{Sex \rightarrow sMARS}$	0.58					
A	*Model with SAR as Mediator*						
(Fig. 7A)	Intercept	−1.09	0.09	0.2		[−0.28, 0.06]	[−0.33, 0.11]
	Sex → SAR (a)	0.14	0.15	0.33		[−0.14, 0.43]	[−0.24, 0.52]
	SAR → sMARS (b)	0.19**	0.06	0.001		[0.07, 0.31]	[0.04, 0.34]
	Sex → sMARS (c′)	0.22	0.11	0.05		[−0.0005, 0.44]	[−0.07, 0.50]
	Indirect Effect (a*b)	**0.03**	**0.03**†		**0.11**	[−0.02, 0.11]	[−0.04, 0.14]
	$R^2_{Sex \rightarrow SAR \rightarrow sMARS}$	0.6					
B	*Model with SAN as Mediator*						
(Fig. 7B)	Intercept	−0.03	0.08	0.68		[−0.20, 0.13]	[−0.25, 0.18]
	Sex → SAN (a)	0.55**	0.15	5E−04		[0.24, 0.85]	[0.15, 0.95]
	SAN → sMARS (b)	0.27**	0.05	< 0.0001		[0.17, 0.38]	[0.14, 0.41]
	Sex → sMARS (c′)	0.1	0.11	0.39		[−0.12, 0.31]	[−0.19, 0.38]
	Indirect Effect (a*b)	**0.15****	**0.05**†		**0.62**	[0.07, 0.27]	[0.05, 0.33]
	$R^2_{Sex \rightarrow SAN \rightarrow sMARS}$	0.64					

Note: Regression results for post-hoc mediation analyses. The mediation of the relation between sex and math anxiety by (A) spatial recognition anxiety (SAR), and (B) spatial navigation anxiety (SAN). See notes for Table 3. The data in this table are depicted in Fig. 7.

3.5.2. *Other types of spatial anxiety as mediators*

The post-hoc quality checks highlight the robustness of the finding that spatial manipulation anxiety mediates the relation between sex and math anxiety. Given the variegated nature of spatial processing, in this section we assess whether other types of spatial anxiety, namely, spatial navigation anxiety (SAN) and spatial recognition anxiety (SAR), might contribute overlapping or even unique variance in explaining the relation between sex and math anxiety. The following set of analyses proceed in a manner similar to the main mediation analyses above, starting with single mediators and then progressing to multiple mediators. All post-hoc analyses include working memory, trait anxiety, perceived spatial recognition ability, math ability, and perceived math ability as covariates.

3.5.2.1. Spatial recognition anxiety as a mediator. The relation between sex and math anxiety was not mediated by spatial recognition anxiety (Table 7A, Fig. 7A), indicating that *not all types of spatial anxiety* significantly mediate the relation between sex and math anxiety.

3.5.2.2. Spatial navigation anxiety as a mediator. The relation between sex and math anxiety was mediated by spatial navigation anxiety using a 99 percent confidence interval (Table 7B, Fig. 7B). This mediation model accounted for 64% of the variance in math anxiety. The total indirect effect accounted for 62% of the total effect (%C = 0.62). Hence, *it is not only spatial manipulation anxiety* that mediates the relation between sex and math anxiety.

3.5.2.3. Competing mediators. The post-hoc single mediator analyses above indicated that spatial navigation anxiety, like spatial manipulation anxiety, mediates the relation between sex and math,

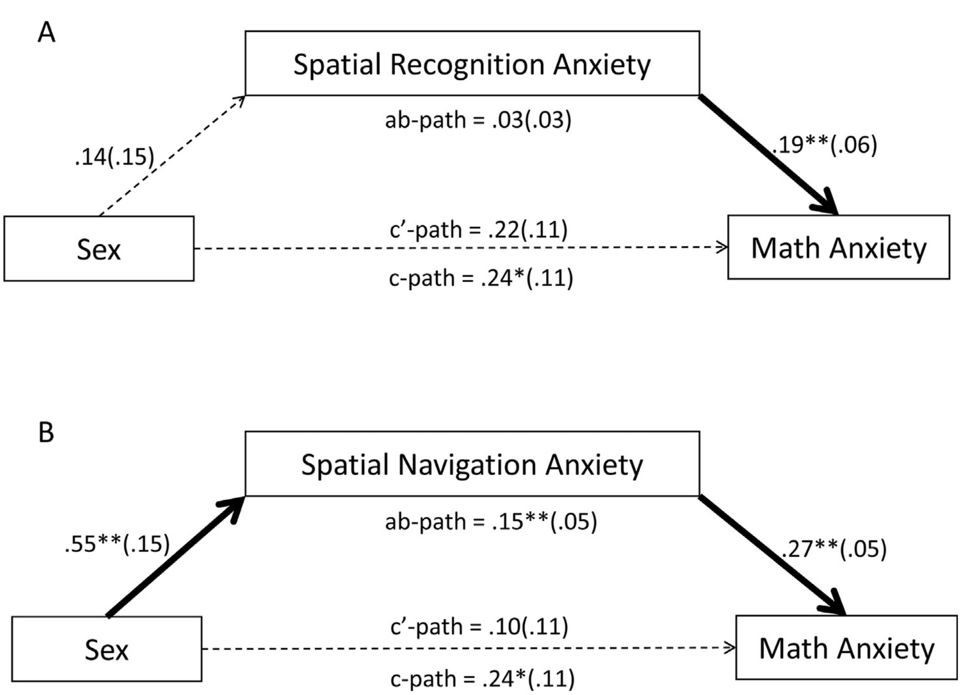

Fig. 7. The effect of sex on math anxiety is mediated by (B) spatial navigation anxiety but not (A) spatial recognition anxiety. Statistics supporting this figure are reported in Table 7. Asterisks indicate the significance of the coefficients (* indicates a significant 95% confidence interval, ** indicates significant 99% confidence interval).

Table 8
Competing spatial manipulation processes and spatial navigation anxiety as mediators of the relation between sex and math anxiety.

Model	Estimate	SE/SE†	P	%C	95% CI	99% CI
Model without Mediator						
Intercept	−0.13	0.09	0.15		[−0.30, 0.05]	[−0.35, 0.10]
Sex → sMARS (c)	0.24*	0.11	< 0.0001		[0.02, 0.47]	[−0.05, 0.54]
$R^2_{Sex\ \rightarrow\ sMARS}$	0.58					
Model with MRT, SIQ, SAM and SAN as Mediators						
Intercept	−0.01	0.08	0.91		[−0.17, 0.16]	[−0.23, 0.21]
Sex → MRT (a)	0.65**	0.15	< 0.0001		[0.35, 0.96]	[0.25, 1.06]
Sex → SIQ (a)	−0.39*	0.16	0.01		[−0.70, −0.08]	[−0.80, 0.02]
Sex → SAM (a)	0.41*	0.16	0.01		[0.10, 0.72]	[−0.0002, 0.82]
Sex → SAN (a)	**0.55****	**0.15**	**0.001**		[0.24, 0.85]	[0.15, 0.95]
MRT → sMARS (b)	0.01	0.05	0.85		[−0.10, 0.12]	[−0.13, 0.15]
SIQ → sMARS (b)	0.002	0.06	0.97		[−0.11, 0.11]	[−0.14, 0.15]
SAM → sMARS (b)	0.16**	0.06	0.01		[0.04, 0.27]	[0.007, 0.31]
SAN → sMARS (b)	**0.22****	**0.06**	**2E−04**		[0.11, 0.33]	[0.07, 0.36]
Sex → sMARS (c')	0.06	0.11	0.62		[−0.16, 0.28]	[−0.24, 0.35]
*Indirect Effects (a*b)*						
Sex → MRT → sMARS	0.007	0.03†		0.03	[−0.07, 0.07]	[−0.09, 0.10]
Sex → SIQ → sMARS	−0.001	0.02†		−0.003	[−0.05, 0.04]	[−0.07, 0.06]
Sex → SAM → sMARS	0.06*	0.04†		0.26	[0.01, 0.16]	[−0.002, 0.20]
Sex → SAN → sMARS	0.12**	0.05†		0.49	[0.04, 0.23]	[0.03, 0.28]
Sex → Total → sMARS	0.19**	0.07†		0.77	[0.07, 0.34]	[0.04, 0.39]
$R^2_{Sex\ \rightarrow MRT,\ SIQ,\ SAM,\ SAN\ \rightarrow\ sMARS}$	0.65					

Note: Regression results for post-hoc mediation analyses for the unique mediation effects actual spatial manipulation ability (MRT), perceived spatial manipulation ability (SIQ), spatial manipulation anxiety (SAM), and spatial navigation anxiety (SAN). See notes for Table 3. The data in this table are depicted in Fig. 8.

even when controlling for working memory, trait anxiety, perceived spatial recognition ability, math ability, and perceived math ability as covariates. However, that analysis does not reveal whether the mediating effects of spatial manipulation anxiety and spatial navigation anxiety account for the same or unique variance. Therefore, we ran a post-hoc competing mediator analysis to determine whether spatial navigation added unique variance to the mediation between sex and math anxiety, over and above all other aspects of small-scale spatial processing. Specifically, spatial navigation anxiety was added as a competing mediator to the mediation analyses reported in Table 5, Fig. 5, that examined the effect of actual spatial manipulation ability, perceived spatial manipulation ability and spatial manipulation anxiety as mediators between sex and math anxiety.

This post-hoc analysis revealed that the relation between sex and math anxiety was mediated by the combined effect of spatial manipulation ability, perceived spatial manipulation ability, spatial manipulation anxiety, and spatial navigation anxiety using a 99 percent confidence interval (Table 8, Fig. 8). This mediation model accounted for 65% of the variance in math anxiety. The total indirect effect accounted for 77% of the total effect (%C = 0.77). In this model, spatial navigation anxiety was a significant mediator using a 99 percent confidence interval. The indirect effect of spatial navigation anxiety accounted for 49% of the total effect (%C = 0.49C). Spatial manipulation anxiety was a significant mediator using a 95 percent confidence interval, but not a 99 percent confidence interval. The indirect effect of spatial manipulation anxiety accounted for 26% of the total effect (% = 0.26). Consistent with the analysis in Table 5/Fig. 5, perceived and actual spatial manipulation ability were not significant mediators of the relation between sex and math anxiety within the context of this model. In this model, sex predicted spatial manipulation ability and spatial navigation anxiety at a confidence interval of 99 percent, and sex predicted perceived spatial manipulation ability and spatial manipulation anxiety at a confidence interval of 95 percent. However, math anxiety was only predicted by spatial manipulation anxiety and spatial navigation anxiety (both at a 99 percent confidence interval). Actual and perceived spatial manipulation ability did not significantly predict math anxiety. These findings, that both spatial manipulation and spatial navigation anxiety were significant unique mediators, indicates that multiple sub-domains of spatial anxiety (but not all domains, as spatial recognition anxiety was not a significant mediator), contribute to explaining the relation between sex and math anxiety.

3.5.3. Sequential mediator pathway analysis

A post-hoc exploratory analyses was included to further unpack *how* spatial manipulation anxiety can explain the relation between sex and math anxiety. Specifically, this analysis examined whether the serial indirect path in the model sex → spatial ability → spatial manipulation anxiety → math anxiety was significant in the current data (controlling for all covariates in the post-hoc analyses – working memory, trait anxiety, perceived spatial recognition ability, math ability, and perceived math ability). Results revealed that the relation between sex and math anxiety was mediated by spatial manipulation ability → spatial manipulation anxiety at the 99% confidence level (Table 9, Fig. 9). This mediation model accounted for 62% of the variance in math anxiety. The total indirect effect of this model accounted for 50% of the total effect (%C = 0.62). The specific indirect effects are reported in Table 9. Sex significantly predicted spatial manipulation ability at a 99 percent confidence interval, spatial manipulation ability significantly predicted spatial manipulation anxiety at a 99 percent confidence interval, and spatial manipulation anxiety significantly predicted math anxiety at a 99 percent confidence interval. Additional indirect effects indicate that the path eliding spatial anxiety (sex → spatial ability → math anxiety) and the path eliding spatial ability (sex → spatial anxiety → math anxiety) were both not significant.

4. Discussion

What explains sex differences in math anxiety? The current study aimed to address this question by testing various cognitive and emotional factors previously shown or believed to contribute to sex differences in math anxiety. More specifically, we used a novel theoretical framework (Fig. 1) to examine how cognitive and emotional factors involved in spatial and mathematical processing may contribute to higher reported levels of math anxiety in women than men. Our analyses produced two central findings. First, within the spatial domain, actual ability, perceived ability, and anxiety all significantly mediated the relation between sex and math anxiety when the mediators were considered separately (circles in Fig. 1B); but within the mathematical

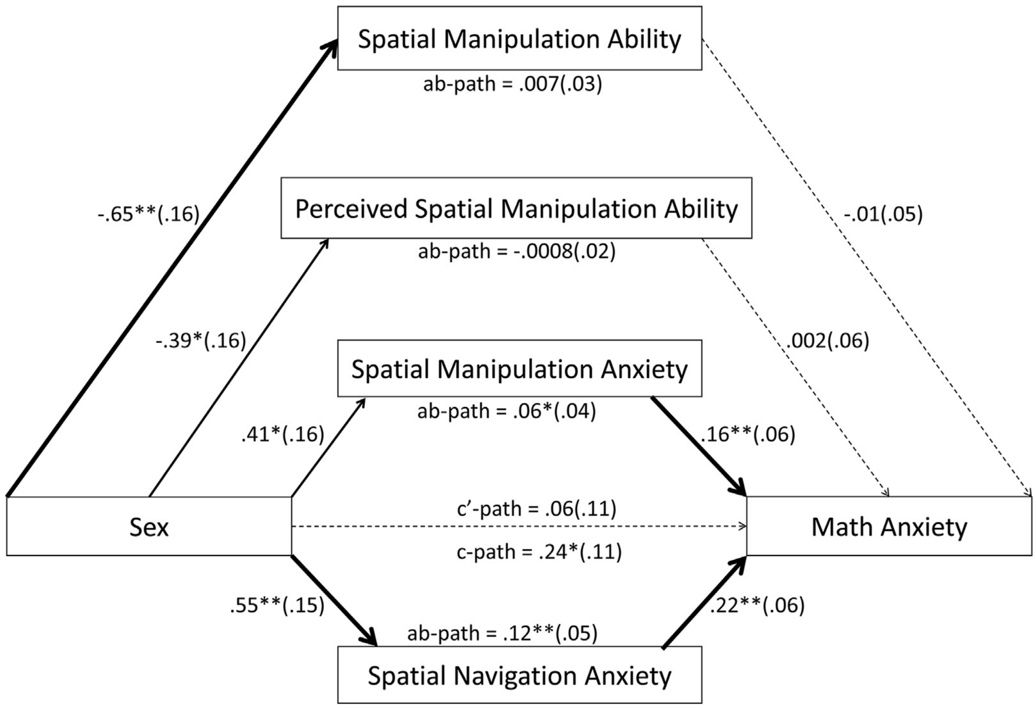

Fig. 8. The unique mediation effects for the combined post-hoc mediation analysis. Statistics supporting this figure are reported in Table 8. Asterisks indicate the significance of the coefficients (* indicates a significant 95% confidence interval, ** indicates significant 99% confidence interval).

domain, neither ability nor perceived ability were significant mediators of this relation (squares in Fig. 1B). There was a significant sex difference in perceived math ability (males reported higher levels of perceived math ability), but not actual math ability. This surprising finding suggests that sex differences in math anxiety are better explained by processes in the spatial domain compared to the mathematical domain. Second, when we assessed the three aspects of spatial processing (ability, perceived ability and anxiety) within a single model, results showed that sex differences in math anxiety were better explained by spatial anxiety than actual or perceived spatial ability. One possibility is that these results simply reflect a strong relation between anxiety measures. However, all models included a measure of general anxiety as a covariate, which argues against this interpretation. Instead, our results are more consistent with the interpretation that the sex differences in spatial and math anxiety may actually be a consequence of sex-differences in the degree to which individuals are anxious specifically about spatial processing. Finally, post-hoc analyses revealed that the central role of spatial anxiety in explaining sex differences in math anxiety is not limited just to contexts concerning spatial mental manipulation. Specifically, anxiety about spatial navigation contributed additional, unique variance in explaining the relation between sex and math anxiety. On the other hand, spatial recognition anxiety did not mediate the relation between sex and math anxiety, which indicates the mediating role of spatial anxiety does not hold for anxiety about *any* type of spatial processing. In sum, here we present the first systematic test of mathematical and spatial factors that have been suggested to play a role in explaining sex differences in math anxiety.

Table 9
Spatial manipulation ability and spatial manipulation anxiety as serial mediators of the relation between sex and math anxiety.

Model	Estimate	SE/SE†	P	%C	95% CI	99% CI
Model without Mediator						
Intercept	−0.13	0.09	0.15		[−0.30, 0.05]	[−0.35, 0.10]
Sex → sMARS (c)	0.24*	0.11	< 0.0001		[0.02, 0.47]	[−0.05, 0.54]
$R^2_{Sex \rightarrow sMARS}$	0.58					
Model with MRT and SAM as sequential mediators						
Intercept	−0.05	0.09	0.53		[−0.22, 0.11]	[−0.28, 0.17]
Sex → MRT (a_1)	0.65**	0.15	< 0.0001		[0.34, 0.96]	[0.25, 1.06]
Sex → SAM (a_2)	−0.27	0.16	0.10		[−0.05, 0.59]	[−0.15, 0.69]
MRT → SAM (d_{21})	0.22**	0.07	0.005		[0.07, 0.37]	[0.02, 0.42]
MRT → sMARS(b_1)	0.04	0.05	0.47		[−0.07, 0.15]	[−0.10, 0.18]
SAM → sMARS (b_2)	0.22**	0.05	0.0001		[0.11, 0.33]	[0.08, 0.36]
*Indirect Effects (a*b)*						
Sex → MRT → sMARS(ab_1)	0.03	0.04†		0.13	[−0.04, 0.10]	[−0.06, 0.13]
Sex → SAM → sMARS(ab_2)	0.06	0.04†		0.25	[−0.01, 0.15]	[−0.03, 0.17]
Sex → MRT → SAM → sMARS(ab_3)	0.03**	0.02†		0.13	[0.007, 0.07]	[0.002, 0.08]
Sex → Total → sMARS	0.12**	0.05†		0.50	[0.02, 0.23]	[−0.006, 0.28]
R^2	0.62					

Note: Regression results for post-hoc mediation analyses for the serial indirect path sex → spatial manipulation ability → spatial manipulation anxiety → math anxiety. See notes for Table 3. The data in this table are depicted in Fig. 9.

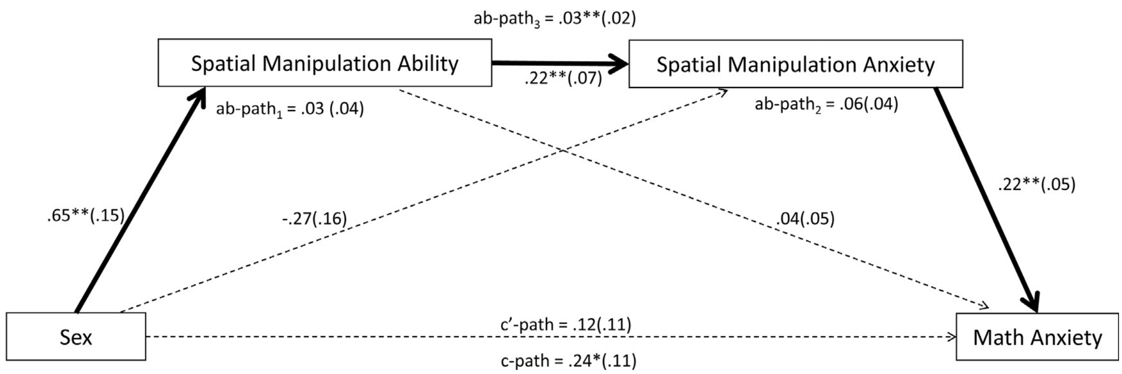

Fig. 9. The effect of sex on math anxiety is mediated by the sequential path MRT → SAM. Statistics supporting this Figure are reported in Table 9. Asterisks indicate the significance of the coefficients (* indicates a significant 95% confidence interval, ** indicates significant 99% confidence interval).

4.1. Spatial domain vs. mathematical domain

A key question addressed by the current study is whether the mathematical domain or spatial domain (or both) mediate the relation between sex and math anxiety. The results revealed that all aspects of spatial processing outlined in our framework (Fig. 1; circles) mediated the relation between sex and math anxiety. By contrast, neither our measure of actual math ability nor perceived math ability (white squares in Fig. 1), significantly mediated the relation between sex and math anxiety.

Mathematical ability is an intuitive explanation for the sex differences in math anxiety. The robust correlation between math anxiety and math ability, coupled with the oft-hypothesized negative feedback loop between math ability and math anxiety (e.g. Cargnelutti, Tomasetto, & Passolunghi, 2016; Krinzinger, Kaufmann, & Willmes, 2009) sets math ability as a potentially promising candidate for mediating the relation between sex and math anxiety. In other words, an intuitive prediction for why there are sex differences in math anxiety is that women who are bad at math consequently become anxious about math. However, our results are not consistent with this view. Instead, we found that no aspect of processing within the mathematical domain explained the relation between sex and math anxiety (squares in Fig. 1B; for relevant results, see Fig. 3). Broadly, this is consistent with mounting evidence suggesting minimal sex differences in actual math ability (Else-Quest et al., 2010; Halpern et al., 2007; Hutchison et al., 2018) but large sex difference in math *anxiety* (Ferguson et al., 2015; Hembree, 1990; Maloney et al., 2012). Our results extend these group-level results by showing that even at the individual level, math ability was not a significant mediator and therefore cannot be used to explain the gender-gap in anxiety about mathematics. It is worth noting that sex differences in math ability have been found in a limited set of circumstances (Bull et al., 2013; Willingham & Cole, 1997); hence, the explanatory role of math ability for sex differences in math anxiety in those contexts cannot be ruled out, However, as noted above and in the introduction, we should emphasize that the clear bulk of the literature suggests such contexts likely to be the exception, not the rule (Else-Quest et al., 2010; Halpern et al., 2007; Hutchison et al., 2018). This in turn suggests that the results presented here are more reflective of the broader pattern of results in the literature.

Unlike actual math ability, a large body of research has reported sex differences in attitudes about mathematics, such as math self-concept, which are highly related to perceived math ability (e.g. Eccles & Harold, 1992; Nagy et al., 2010; Sáinz & Eccles, 2012). However, by using an individual differences approach, we revealed that, like actual math ability, perceptions about one's math ability did not significantly mediate the relation between sex and math anxiety. One may object by pointing out that this conclusion is based on the use of a single-item measure. However, the correlation coefficient between perceived math ability and actual math ability in the current data of ($r = 0.37$) is slightly higher than that which is typically reported in the literature. Indeed, the average correlation observed between perceived and actual ability is 0.33 (Freund & Kasten, 2012). Consequently, we conclude that this limitation of measurement has not compromised the current results. We thus find no evidence that the relation between sex and math anxiety is driven by actual or perceived ability within the mathematical domain. As outlined in the introduction, we turned to spatial processing as another potential explanation of why women on average tend to be more math-anxious than men.

Unlike mathematical processing, a large body of research has reported group-level sex differences in spatial ability (Masters & Sanders, 1993; Nordvik & Amponsah, 1998; Silverman et al., 2007; Voyer et al., 1995). These robust sex differences in spatial ability, coupled with the well documented link between spatial and mathematical processing suggest that spatial processing may prove central to explaining the link between sex and math anxiety. Consistent with this intuition, we found strong evidence indicating that individual differences in spatial processing explain sex differences in math anxiety. Indeed, we found that all three aspects of spatial processing (actual ability, perceived ability and anxiety) mediated the relation between sex and math anxiety (circles in Fig. 1B; see Fig. 4 for relevant results). Broadly, these results align with previous research (Ferguson et al., 2015; Maloney et al., 2012). Moreover, by assessing all three aspects of spatial processing within a single study, and by aligning these aspects along a single subdomain of spatial skills (i.e. mental manipulation), we provide strong converging evidence demonstrating that spatial processing plays a pivotal role in understanding sex differences in math anxiety. On the other hand, the results from the separate mediation analyses in Fig. 4 beg the question: What drives these convergent results? Do the three aspects of spatial processing mediate the relation between sex and math anxiety via common or separate pathways? If the three aspects of spatial processing mediate via a common pathway, is this more attributable to one aspect of spatial processing over and above the others? We address these questions in the next section.

4.2. Cognitive and emotional factors in spatial processing

Single-mediator analyses (Fig. 4) showed that all three aspects of spatial processing (actual ability, perceived ability and anxiety) mediated the relation between sex and math anxiety. To assess whether these convergent results were driven by common or separate pathways, we treated the three spatial processing measures as competing mediators within a single model. Results indicated that spatial anxiety was the strongest unique mediator. This points to spatial anxiety as the central route by which spatial processing links sex differences and math anxiety (Fig. 5). Hence, our results are more consistent with the notion that affective as opposed to cognitive factors in the spatial domain are what explain sex differences in math anxiety. Moreover, the link between spatial processing and math anxiety cannot be attributed to common variation in overall anxiety, as the model included general trait anxiety as a control measure. Finally, it is worth noting that the combined model included perceived and actual math ability. This means that spatial anxiety is not simply a proxy for math ability.

The finding that spatial anxiety explains sex differences in math anxiety over and above actual or perceived spatial ability has important ramifications for helping illuminate why women are underrepresented in STEM disciplines (Hango, 2013). For instance, given increasing evidence that there is a small gender-gap in math processing (Else-Quest et al., 2010; Halpern et al., 2007; Hutchison et al., 2018), coupled with evidence of a more robust gap in spatial processing (Masters & Sanders, 1993; Nordvik & Amponsah, 1998; Silverman et al., 2007; Voyer et al., 1995), it may be tempting to shift the interpretation from 'women are bad at math' to 'women are bad at space', and then assume the problem is somehow 'solved'. However, we believe this would be a mistake. Indeed, these data reveal a robust male advantage in spatial ability (Fig. 2), and that spatial ability mediates the relation between sex and math anxiety (Fig. 4A; results that are highly consistent with prior work; Bull et al., 2013; Ferguson et al., 2015; Silverman et al., 2007; Voyer et al., 1995; Maloney et al., 2012; Ferguson et al., 2015). However, although it is tempting to conclude that women experience math anxiety more than men simply because women have poorer spatial abilities, further analyses showed that this conclusion may be premature, and certainly incomplete. By assessing multiple aspects of spatial processing in a single study we could pit an ability-based explanation against an explanation that emphasizes affective factors (i.e., spatial anxiety). The results of the current study favored the affect-based explanation (Fig. 5). In other words, it appears to be spatial anxiety, not actual or perceived spatial ability, that uniquely explains sex-differences in math anxiety. Critically, as the goal of the current study was to replicate the findings from Maloney et al. (2012) and extend them to compare different aspects of spatial processing, we only examined and compared single mediators within the cognitive domains of mathematical and spatial processing. The findings of the current study indicate that women are nervous about math because they are nervous about spatial processing, which is not 'merely' a proxy for poor spatial ability – perceived or actual.

In sum, our results indicate that affective processing, specifically within the spatial domain, plays a particularly prominent role in explaining the gender-gap in math anxiety. By extension, this affective processing may prove key to both understanding and closing the gender-gap in STEM representation. Moreover, the current study highlights that, despite the presence of large sex-differences in spatial ability, it is critical to examine emotional factors in addition to cognitive factors to understand why women experience more math anxiety than men. More broadly, it is plausible that affective factors, such as spatial anxiety, may play a critical role in the female under-representation in STEM more generally (e.g. Ortner & Sieverding, 2008; Tarampi et al., 2016).

Consistent with this view, a growing body of research has demonstrated that spatial and mathematical performance can be influenced by subtle socio-emotional manipulations. For example, activating a male prime in women boosted performance of spatial skills in women but not men (Ortner & Sieverding, 2008). Similarly, reframing a spatial perspective-taking task as a socio-emotional perspective-taking task boosted female but not male performance (Tarampi et al., 2016). A complimentary line of research has revealed that females report greater trait (i.e. habitual) math anxiety, but not state (i.e. momentary) math anxiety (Goetz, Bieg, Ludtke, Pekrun, & Hall, 2013). These data bolster the idea the sex differences in math anxiety depend on situational factors, including potential variation in state-level affective responses. As we discuss in the next section, it is possible that situational (state) spatial anxiety may emerge as a function of the mathematics problem at hand, with sex differences more apparent for problems that are more inherently spatial in nature.

4.3. Spatial strategy use as a potential mechanism

The key finding in the current study is that spatial anxiety explains the link between sex and math anxiety. Here, we speculate a potential theoretical explanation for these unexpected findings. Maloney et al. (2012) posited a "pathway to math anxiety" wherein early sex differences in spatial ability (i.e. females have poorer spatial abilities) leads to differences in how males and females first experience learning mathematical content. In this view, poor spatial skills put female children at a disadvantage when developing math skills. These poorer math skills in female children increase the likelihood of negative emotional experiences in the context of mathematics, which increase the likelihood of female children developing higher levels of math anxiety. We propose a refined and extended version of the model proposed by Maloney et al. (2012).

First, it is critical to consider that research consistently reports sex differences in several key spatial abilities, such as spatial visualization, but rarely mathematics abilities (Casey et al., 1995; Else-Quest et al., 2010; Hyde et al., 2008). Yet, spatial skills, especially spatial visualization, have been suggested to play key roles in solving novel and complex math problems, perhaps even more so than familiar ones (Halpern et al., 2007; Mix et al., 2016). What leads to this divergence? One possibility, briefly outlined in the introduction, is that sex differences in spatial skills (or use of spatial strategies during math problem solving) result in increased spatial anxiety which in turn influences one's overall anxiety towards mathematics. Indeed, the final post-hoc analysis in the current study that examined the path sex → spatial manipulation ability → spatial manipulation anxiety → math anxiety (Fig. 9) supported this prediction. In view of this model, it follows that individuals with poorer spatial abilities also have heightened spatial anxiety. Moreover, it appears that this anxiety about spatial processing is indeed the key link between spatial ability and math anxiety. This is further supported by the finding that the secondary indirect pathways presented in this post-hoc analysis were not significant. Indeed, in the multi-step mediation analysis (Fig. 9), the sex → spatial manipulation ability → math anxiety, and the sex → spatial manipulation anxiety → math anxiety paths were not significant (whereas the sex → spatial manipulation ability → spatial manipulation anxiety → math anxiety path was significant).

If one is anxious about spatial reasoning, it seems likely that one might also begin to feel anxious more generally about mathematics given that many math problems are inherently spatial or lend themselves to spatial reasoning or spatial strategies. Indeed, various mathematical problems can be solved using a variety of approaches (e.g., visual-spatial vs. verbal-logical; Battista, 1990; Hegarty & Kozhevnikov, 1999). Moreover, spatial skills are related to the types of strategies used to solve mathematical problems (Casey, Lombardi, Pollock, Fineman, & Pezaris, 2017; Hegarty, & Kozhevnikov, 1999; Laski, Reeves, Ganley, & Mitchell, 2013). Accordingly, while there is little evidence of sex differences in actual math ability, there is evidence to suggest that males and females differ in their approaches to spatial and mathematical tasks (Battista, 1990; Gallagher et al., 2000; Heil & Jansen-Osmann, 2008; Pezaris & Casey, 1991). Thus, while males and females might appear similar in math ability, their underlying strategies may differ in the extent to which they recruit spatial processes.

Taken together, it is possible that sex differences in spatial anxiety, and in turn, math anxiety, may be rooted in sex-related differences in the use or avoidance of spatial strategies in solving mathematical tasks (which is supported by the combined model above as well as the final post-hoc analysis). For instance, if spatial strategies are the primary pedagogical means of conveying many mathematical concepts and procedures (e.g., through number lines), then females, perhaps relying more on verbal skills, may thus feel anxious because they perceive themselves as not doing math 'the right way'. Indeed, the final and arguably best model presented in the post-hoc analysis section (sex → spatial manipulation ability → spatial manipulation anxiety → math anxiety) provides compelling evidence for this – admittedly speculative – interpretation of what might explain sex differences in math anxiety. Future research efforts are needed to further test this possibility, paying particular attention to the role that visual-spatial strategy use might play in the development of potentially shared spatial and math anxieties.

It is also worth considering ways in which spatial anxiety may vary depending on the mathematics task at hand, with higher levels of spatial anxiety experienced for questions that are overtly spatial or more readily lend themselves to the adoption of spatial strategy use. Thus, a clear prediction we can make for future work is that the relation between spatial anxiety and math anxiety should itself be mediated by the extent to which a person believes math is fundamentally spatial in nature, and hence that spatial strategies are critical to achieving success in mathematics.

4.4. Small-scale vs. large-scale spatial anxiety as a mediator

Given the central role that spatial anxiety appears to play in explaining sex differences in math anxiety, a pertinent follow-up question is whether this applies to anxiety about *any* type of spatial processing, or whether the result is specific to anxiety about situations involving spatial mental manipulation. Notably, large-scale spatial skills (i.e. tasks that require physical or imagined movement through spatial environments) have also been shown to relate to sex differences in math anxiety (Ferguson et al., 2015). Intriguingly, our results showed that anxiety about both small-scale spatial processing (mental manipulation) and large-scale spatial processing (navigation) uniquely mediated the relation between sex and math anxiety (Figs. 7 and 8). Thus, our data indicate that the mediating effect of spatial anxiety on the relation between sex and math anxiety extends to anxiety about both small- and large-scale spatial situations. On the other hand, anxiety about spatial recognition did not significantly mediate sex-differences in math anxiety. This indicates that not all types of spatial anxiety play a role in explaining this relation. More generally, it is important to acknowledge that spatial processing is variegated (Uttal et al., 2013). Here we show that taking this fact into account may prove critical to fully unpacking the role that affective responses to spatial situations play in explaining sex differences in math anxiety.

5. Conclusion

The current paper aimed to illuminate the mechanisms underlying why women tend to be more math anxious than men. We used a novel theoretical framework (Fig. 1) to examine how cognitive and affective factors from spatial and mathematical domains contribute to higher ratings of math anxiety in women compared to men. Our findings revealed that processes within the spatial domain, but not the mathematical domain mediate the relation between sex and math anxiety. Therefore, sex differences in math anxiety are not simply due to sex differences in math ability. These results highlight the utility of looking across processing domains (columns in Fig. 1A). Within the spatial domain, it was spatial anxiety, more than perceived or actual spatial ability that contributed to explaining sex differences in math anxiety. Affective, rather than cognitive factors, may prove most influential in understanding why women tend to be more math anxious than men. Moreover, our results highlight the importance of evaluating many aspects of processing within as well as across domains (rows as well as columns in Fig. 1A). In sum, our approach illustrates the benefit of looking systematically across domains and at different aspects of processing within a single study. It was only by adopting this systematic framework that we were able to arrive at the surprising but robust result that affective and not cognitive processing, specifically within the spatial domain, best explains the link between sex and math anxiety. We speculate that the link between sex differences in spatial and math anxiety may be a consequence of sex-differences in the degree to which individuals use spatial versus non-spatial (e.g., verbal) strategies when solving mathematical tasks. Overall, our results may provide a significant advance in understanding why women are under-represented in STEM-related disciplines.

Supplementary data

Complete raw data can be found at: https://osf.io/hxsrd/.

Funding

This work was supported by the Banting Postdoctoral Fellowship to Lyons (National Sciences and Engineering Research Council, Canada); University of Western Ontario internal research award to Lyons (Western Research and Faculty of Social Science); Alexander Graham Bell Canada Graduate Scholarship to Sokolowski (National Sciences and Engineering Research Council, Canada) Social Sciences and Humanities Research Council of Canada (SSHRC) Doctoral Fellowship to Hawes.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2018.10.005.

References

Ahmed, W., Minnaert, A., Kuyper, H., & van der Werf, G. (2012). Reciprocal relationships between math self-concept and math anxiety. Retrieved from *Learning and Individual Differences, 11*, 385–389. http://www.academia.edu/16901714/Reciprocal_relationships_between_math_self-concept_and_math_anxiety.

Alexander, L., & Martray, C. R. (1989). The development of an abbreviated version of the Mathematics Anxiety Rating Scale. *Measurement and Evaluation in Counseling and Development, 22*(3), 143–150.

Ashcraft, M. H. (2002). Math anxiety: Personal, educational, and cognitive consequences. *Current Directions in Psychological Science, 11*(5), 181–185. https://doi.org/10.1111/1467-8721.00196.

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

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

Battista, M. T. (1990). Spatial visualization and gender differences in high school geometry. *Journal for Research in Mathematics Education, 21*(1), 1–47. https://doi.org/10.2307/749456.

Beilock, S. L., Gunderson, E. A., Ramirez, G., & Levine, S. C. (2010). Female teachers' math anxiety affects girls' math achievement. *Proceedings of the National Academy of Sciences, 107*(5), 1860–1863. https://doi.org/10.1073/pnas.0910967107.

Beilock, S. L., Rydell, R. J., & McConnell, A. R. (2007). Stereotype threat and working memory: Mechanisms, alleviation, and spillover. *Journal of Experimental Psychology. General, 136*(2), 256–276. https://doi.org/10.1037/0096-3445.136.2.256.

Bieg, M., Goetz, T., Wolter, I., & Hall, N. C. (2015). Gender stereotype endorsement differentially predicts girls' and boys' trait-state discrepancy in math anxiety. *Frontiers in Psychology, 6*, 1404. https://doi.org/10.3389/fpsyg.2015.01404.

Blajenkova, O., Kozhevnikov, M., & Motes, M. A. (2006). Object-spatial imagery: A new self-report imagery questionnaire. *Applied Cognitive Psychology, 20*(2), 239–263. https://doi.org/10.1002/acp.1182.

Brosch, T., Scherer, K., Grandjean, D., & Sander, D. (2013). The impact of emotion on perception, attention, memory, and decision-making. *Swiss Medical Weekly, 143*, w13786. https://doi.org/10.4414/smw.2013.13786.

Bull, R., Cleland, A. A., & Mitchell, T. (2013). Sex differences in the spatial representation of number. *Journal of Experimental Psychology: General, 142*(1), 181–192. https://doi.org/10.1037/a0028387.

Cargnelutti, E., Tomasetto, C., & Passolunghi, M. C. (2016). How is anxiety related to math performance in young students? A longitudinal study of Grade 2 to Grade 3 children. *Cognition and Emotion, 1–10*. https://doi.org/10.1080/02699931.2016.1147421.

Casey, B. M., Lombardi, C. M., Pollock, A., Fineman, B., & Pezaris, E. (2017). Girls' spatial skills and arithmetic strategies in first grade as predictors of fifth-grade analytical math reasoning. *Journal of Cognition and Development, 18*(5), 530–555. https://doi.org/10.1080/15248372.2017.1363044.

Casey, M. B., Nuttall, R., Pezaris, E., & Benbow, C. P. (1995). The influence of spatial ability on gender differences in mathematics college entrance test scores across diverse samples. *Developmental Psychology, 31*(4), 697–705. https://doi.org/10.1037/0012-1649.31.4.697.

Cheng, Y.-L., & Mix, K. S. (2014). Spatial training improves children's mathematics ability. *Journal of Cognition and Development, 15*(1), 2–11. https://doi.org/10.1080/15248372.2012.725186.

Chipman, S. F., Krantz, D. H., & Silver, R. (1992). Mathematics anxiety and science careers among able college women. *Psychological Science, 3*(5), 292–295. https://doi.org/10.1111/j.1467-9280.1992.tb00675.x.

Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review, 12*(5), 769–786. https://doi.org/10.3758/BF03196772.

Dasgupta, N., & Stout, J. G. (2014). Girls and women in science, technology, engineering, and mathematics: STEMing the tide and broadening participation in STEM careers. *Policy Insights from the Behavioral and Brain Sciences, 1*(1), 21–29. https://doi.org/10.1177/2372732214549471.

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 : BBF, 8*, 33. https://doi.org/10.1186/1744-9081-8-33.

Dolan, R. J. (2002). Emotion, cognition, and behavior. *Science, 298*(5596), 1191–1194. https://doi.org/10.1126/science.1076358.

Eccles, J. S., & Harold, R. D. (1992). Gender differences in educational and occupational patterns among the gifted. In N. Colangelo, S. G. Assouline, & D. L. Ambroson (Eds.). *Proceedings from the 1991 Henry B. and Jocelyn Wallace national research symposium on talent development* (pp. 3–29). Unionville, NY: Trillium Press.

Ekstrom, R. B., French, J. W., & Harman, H. H. (1976). Manual for kit of factor-referenced cognitive tests. New Jersey.

Else-Quest, N. M., Hyde, J. S., & Linn, M. C. (2010). Cross-national patterns of gender differences in mathematics: A meta-analysis. *Psychological Bulletin, 136*(1), 103–127. https://doi.org/10.1037/a0018053.

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

Flessati, S. L., & Jamieson, J. (1991). Gender differences in mathematics anxiety: An artifact of response bias? *Anxiety Research, 3*(4), 303–312. https://doi.org/10.1080/08917779108248759.

Flore, P. C., & Wicherts, J. M. (2015). Does stereotype threat influence performance of girls in stereotyped domains? A meta-analysis. *Journal of School Psychology, 53*(1), 25–44. https://doi.org/10.1016/J.JSP.2014.10.002.

Freund, P. A., & Kasten, N. (2012). How smart do you think you are? A meta-analysis on the validity of self-estimates of cognitive ability. *Psychological Bulletin, 138*(2), 296–321. https://doi.org/10.1037/a0026556.

Ganley, C. M., Mingle, L. A., Ryan, A. M., Ryan, K., Vasilyeva, M., & Perry, M. (2013). An examination of stereotype threat effects on girls' mathematics performance. *Developmental Psychology, 49*(10), 1886–1897. https://doi.org/10.1037/a0031412.

Gallagher, A. M., De Lisi, R., Holst, P. C., Mcgillicuddy-De Lisi, A. V., Morely, M., & Cahalan, C. (2000). Gender differences in advanced mathematical problem solving. *Journal of Experimental Child Psychology, 75*, 165–190. https://doi.org/10.1006/jecp.1999.2532.

Goetz, T., Bieg, M., Ludtke, O., Pekrun, R., & Hall, N. C. (2013). Do girls really experience more anxiety in mathematics? Retrieved from *Association for Psychological Science, 24*(10), 2079–2087. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1032.2227&rep=rep1&type=pdf.

Halpern, D. F., Benbow, C. P., Geary, D. C., Gur, R. C., Hyde, J. S., & Gernsbacher, M. A. (2007). The science of sex differences in science and mathematics. *Psychological Science in the Public Interest : A Journal of the American Psychological Society, 8*(1), 1–51. https://doi.org/10.1111/j.1529-1006.2007.00032.x.

Hango, D. (2013). Gender differences in science, technology, engineering, mathematics and computer science (STEM) programs at university Insights on Canadian Society. *Statistics Canada* (2291–849).

Hegarty, M., & Kozhevnikov, M. (1999). Types of visual-spatial representations and mathematical problem solving. *Journal of Educational Psychology, 91*(4), 684–689. https://doi.org/10.1037/0022-0663.91.4.684.

Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., & Lovelace, K. (2006). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence, 34*(2), 151–176. https://doi.org/10.1016/j.intell.2005.09.005.

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

Heil, M., & Jansen-Osmann, P. (2008). Sex differences in mental rotation with polygons of different complexity: Do men utilize holistic processes whereas women prefer piecemeal ones? *Quarterly Journal of Experimental Psychology, 61*(5), 683–689. https://doi.org/10.1080/17470210701822967.

Hill, C., Corbett, C., & Rose, A. St. (2010). Why so few? Women in science, technology, engineering, and mathematics. Washington.

Hutchison, J. E., Lyons, I. M., & Ansari, D. (2018). More similar than different: Gender differences in children's basic numerical skills are the exception not the rule. *Child Development*. https://doi.org/10.1111/cdev.13044.

Hyde, J. S., Lindberg, S. M., Linn, M. C., Ellis, A. B., & Williams, C. C. (2008). Gender similarities characterize math performance. *Science, 321*(5888), 494–495. https://doi.org/10.1126/science.1160364.

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. https://doi.org/10.1177/0734282908330583.

Lawton, C. A. (2010). Gender, spatial abilities, and wayfinding. *Handbook of gender research in psychology* (pp. 317–341). New York, NY: Springer, New York. http://doi.org/10.1007/978-1-4419-1465-1_16.

Laski, E. V., Reeves, T. D., Ganley, C. M., & Mitchell, R. (2013). Mathematics teacher educators' perceptions and use of cognitive research. *Mind, Brain, and Education, 7*(1), 63–74. https://doi.org/10.1111/mbe.12009.

Ledoux, J. E. (1989). Cognitive-emotional interactions in the brain. *Cognition & Emotion, 3*(4), 267–289. https://doi.org/10.1080/02699938908412709.

Levine, S. C., Foley, A., Lourenco, S., Ehrlich, S., & Ratliff, K. (2016). Sex differences in spatial cognition: Advancing the conversation. *Wiley Interdisciplinary Reviews. Cognitive Science, 7*(2), 127–155. https://doi.org/10.1002/wcs.1380.

Lohman, D. F. (1996). Spatial ability and G. In I. Dennis, & P. Tapsfield (Eds.). *Human abilities: Their nature and assessment* (pp. 97–116). Hillsdale, NJ: Erlbaum.

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

Lyons, I. M., Ramirez, G., Maloney, E. A., Rendina, D. N., Levine, S. C., & Beilock, S. L. (n.d.). Spatial Anxiety: A novel questionnaire with subscales for measuring three aspects of spatial anxiety. Journal of Numerical Cognition. Retrieved from http://mathbrainlab.com/sdm_downloads/spatial-anxiety-novel-questionnaire-subscales-measuring-three-aspects-spatial-anxiety/.

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

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

Maloney, E. A., Schaeffer, M. W., & Beilock, S. L. (2013). Mathematics anxiety and stereotype threat: Shared mechanisms, negative consequences and promising interventions. *Research in Mathematics Education, 15*(2), 115–128. https://doi.org/10.1080/14794802.2013.797744.

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. https://doi.org/10.1016/j.lindif.2012.01.001.

Masters, M. S., & Sanders, B. (1993). Is the gender difference in mental rotation disappearing? Retrieved from *Behavior Genetics, 23*(4), 337–341. http://www.ncbi.nlm.nih.gov/pubmed/8240213.

Mix, K. S., & Cheng, Y.-L. (2012). The relation between space and math: Developmental and educational implications. Retrieved from *Advances in Child Development and Behavior, 42*, 197–243. http://www.ncbi.nlm.nih.gov/pubmed/22675907.

Mix, K. S., Levine, S. C., Cheng, Y.-L., Young, C., Hambrick, D. Z., Ping, R., & Konstantopoulos, S. (2016). Separate but correlated: The latent structure of space and mathematics across development. *Journal of Experimental Psychology. General, 145*(9), 1206–1227. https://doi.org/10.1037/xge0000182.

Nagy, G., Watt, H. M. G., Eccles, J. S., Trautwein, U., Lüdtke, O., & Baumert, J. (2010). The development of students' mathematics self-concept in relation to gender: Different countries, different trajectories? *Journal of Research on Adolescence, 20*(2), 482–506. https://doi.org/10.1111/j.1532-7795.2010.00644.x.

Necka, E. A., Sokolowski, H. M., & Lyons, I. M. (2015). The role of self-math overlap in understanding math anxiety and the relation between math anxiety and performance. *Frontiers in Psychology, 6*(October), https://doi.org/10.3389/fpsyg.2015.01543.

Nordvik, H., & Amponsah, B. (1998). Gender differences in spatial abilities and spatial activity among university students in an egalitarian educational system. *Sex Roles, 38*(11/12), 1009–1023. https://doi.org/10.1023/A:1018878610405.

Ortner, T. M., & Sieverding, M. (2008). Where are the gender differences? Male priming boosts spatial skills in women. *Sex Roles, 59*(3–4), 274–281. https://doi.org/10.1007/s11199-008-9448-9.

Pessoa, L. (2010). Emergent processes in cognitive-emotional interactions. Retrieved from *Dialogues in Clinical Neuroscience, 12*(4), 433–448. http://www.ncbi.nlm.nih.gov/pubmed/21319489.

Pezaris, E., & Casey, M. B. (1991). Girls who use "masculine" problem-solving strategies on a spatial task: Proposed genetic and environmental factors. *Brain and Cognition, 17*(1), 1–22 Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1781977.

Preacher, K. J., Rucker, D. D., & Hayes, A. F. (2007). Addressing moderated mediation hypotheses: Theory, methods, and prescriptions. *Multivariate Behavioral Research, 42*(1), 185–227. https://doi.org/10.1080/00273170701341316.

Sáinz, M., & Eccles, J. (2012). Self-concept of computer and math ability: Gender implications across time and within ICT studies. *Journal of Vocational Behavior, 80*, 486–499. https://doi.org/10.1016/j.jvb.2011.08.005.

Shavelson, R. J., Hubner, J. J., & Stanton, G. C. (1976). Self-concept: Validation of construct interpretations. *Review of Educational Research, 46*(3), 407. https://doi.org/10.2307/1170010.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. Retrieved from *Science (New York, N.Y.), 171*(3972), 701–703. http://www.ncbi.nlm.nih.gov/pubmed/5540314.

Silverman, I., Choi, J., & Peters, M. (2007). The hunter-gatherer theory of sex differences in spatial abilities: Data from 40 countries. *Archives of Sexual Behavior, 36*(2), 261–268. https://doi.org/10.1007/s10508-006-9168-6.

Spielberger, C. D., Gorsuch, R. L., & Lushene, R. E. (1970). *Manual for the state-trait anxiety inventory*. Retrieved fromPalo Alto, CA: Consulting Psychologists Press. http://ubir.buffalo.edu/xmlui/handle/10477/2895.

Stoet, G., & Geary, D. C. (2013). Sex differences in mathematics and reading achievement are inversely related: Within- and across-nation assessment of 10 years of PISA data. *PloS One, 8*(3), e57988. https://doi.org/10.1371/journal.pone.0057988.

Storbeck, J., & Clore, G. L. (2007). On the interdependence of cognition and emotion. *Cognition & Emotion, 21*(6), 1212–1237. https://doi.org/10.1080/02699930701438020.

Tarampi, M. R., Heydari, N., & Hegarty, M. (2016). A tale of two types of perspective taking: Sex differences in spatial ability. *Psychological Science*. https://doi.org/10.1177/0956797616667459.

Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of

the operation span task. *Behavior Research Methods, 37*(3), 498–505. https://doi.org/10.3758/BF03192720.
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*(2), 352–402. https://doi.org/10.1037/a0028446.
Vandenberg, S., & Kuse, A. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills, 47*(2), 599–604. https://doi.org/10.2466/pms.1978.47.2.599.
Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. Retrieved from *Psychological Bulletin, 117*(2), 250–270. http://www.ncbi.nlm.nih.gov/pubmed/7724690.
Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology, 101*(4), 817–835. https://doi.org/10.1037/a0016127.
Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7*(11), 483–488. https://doi.org/10.1016/j.tics.2003.09.002.
Willingham, W. W., & Cole, N. S. (1997). *Gender and fair assessment.* Mahwah: Erlbaum.