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Empirical Research

Examining the Role of Spatial and Mathematical Processes and Gender in Postsecondary Precalculus

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Supplementary Materials: Code, Data [see Index of Supplementary Materials]

Abstract

Passing the introductory calculus sequence is critical to undergraduate students' retention in STEM programs. This study examines the relations between three interrelated processes found to influence mathematics learning and achievement: spatial skills, spatial anxiety, and math anxiety. Additionally, it examines the role of gender on these relations and if and how they help explain precalculus achievement. Findings revealed that spatial skills, spatial anxiety, and gender were linked to math anxiety. Furthermore, spatial anxiety and math anxiety were related to strong final exam performance, but spatial skills and gender were not related to achievement. The presented evidence is in accordance with prior research and corroborates the existence of these relational patterns in a postsecondary academic context in addition to the laboratory context. These findings have broad implications for the development and implementation of efforts aimed at improving postsecondary mathematics outcomes, and subsequent persistence, retention, and representation in STEM programs.

Keywords

spatial skills, mathematics, postsecondary, math anxiety, spatial anxiety

Non-Technical Summary

Background

This study investigates factors which influence precalculus achievement in college students, focusing on spatial skills, spatial anxiety, math anxiety, and gender differences. Spatial skills involve visualizing, understanding, and manipulating the relationships between different objects and our environment, while spatial and math anxiety refer to the stress experienced during respective tasks. Prior research shows that these factors affect mathematics performance, but their relationships in postsecondary settings are less understood.

Why was this study done?
Improving retention in STEM (Science, Technology, Engineering, and Mathematics) fields is crucial, particularly for underrepresented groups such as women. Many students leave STEM programs during early college years, where mathematics courses like precalculus serve as critical gateways. This study aimed to understand how spatial skills, spatial anxiety, math anxiety, and gender might influence success in these courses to help address achievement gaps and improve STEM retention.

What did the researchers do and find?
We collected and analyzed data from 820 undergraduate students enrolled in precalculus at a four-year university. We measured students' spatial skills, spatial anxiety, math anxiety, and precalculus achievement. Results showed significant differences between genders, with female students reporting higher math and spatial anxiety and lower spatial skills and final exam scores. Furthermore, spatial anxiety partially mediated the relationship between gender and math anxiety, while higher math anxiety was linked to lower precalculus performance.

What do these findings mean?
Our findings suggest that gender differences in spatial skills and math and spatial anxiety may contribute to disparities in math performance. Targeted interventions such as training programs to reduce anxiety and improve spatial skills may help address these gender differences and close the gender gap in STEM fields. Improving students' outcomes in foundational courses like precalculus could enhance persistence in STEM, leading to better representation in these fields.

Highlights

- *Spatial, affective, and mathematical processes are linked to gender and precalculus achievement:* This study investigates the relations between spatial skills, spatial anxiety, math anxiety, and the role of gender on precalculus achievement in 820 postsecondary students enrolled in an introductory precalculus course sequence at a four-year university. Analyses reveal direct and indirect relations between all factors.
- *Math and spatial anxieties, spatial skills, and mathematics achievement vary by gender:* Students who self-identified as female showed significantly higher levels of spatial anxiety and math anxiety alongside lower levels of spatial skills, which trended with lower mathematical task performance.
- *Spatial and affective processes mediate the relation between gender and math anxiety:* Small-scale spatial skills, mental manipulation anxiety, and navigation anxiety partially and uniquely mediated the relation between gender and math anxiety.
- *Math anxiety is related to precalculus achievement:* Mediation analysis also indicated that math anxiety partially and uniquely mediated the relation between gender and precalculus achievement.

Achievement and Persistence in Undergraduate Precalculus

A close examination of the demographics of students leaving the STEM disciplines reveals that female students leave in much greater proportions than their male counterparts (Seymour et al., 2019), continuing the persistent underrepresentation of females in STEM domains. Efforts aimed at understanding the drivers of low retention rates of female students in undergraduate STEM programs have revealed a range of contributing factors, such as the competitive culture of STEM courses (e.g., Seymour & Hewitt, 1997), or a loss of motivation and subsequent loss of interest in the major (Seymour et al., 2019). Most dropouts from STEM majors occur in the first two years of undergraduate study (e.g., Seymour et al., 2019), during which students are enrolled in introductory content courses in their major as well as a calculus sequence. Thus, efforts aimed at increasing the retention of students within STEM programs might best be targeted at students enrolled in gateway courses completed in these first two years. Here we focus on student achievement in an undergraduate precalculus course which prepares students for the calculus sequence required for most STEM major programs.

Research indicates that both cognitive and affective processes influence student learning and achievement in a domain. Moreover, recent studies illuminate the interrelated nature of these processes (e.g., Brosch et al., 2013), and their complex interactions with gender to influence learning and achievement (Atit et al., 2020). Three such processes, found predominantly through laboratory studies to interact with gender to influence mathematics achievement are spatial skills, spatial anxiety, and math anxiety (e.g., Daker et al., 2022). However, the nature of their relations in students enrolled in an undergraduate mathematics course is unknown. Here we investigate the relations between spatial skills, spatial anxiety, math anxiety, and gender in postsecondary precalculus students and examine how these relations trend with achievement in the course.

Spatial Skills and Mathematics Achievement

Spatial skills enable us to mentally manipulate, organize, and reason about spatial relationships in real and imagined spaces (e.g., Uttal et al., 2013). These skills allow for completion of common tasks such as assembling furniture or navigating from one location to another. Within mathematics, spatial skills and student outcomes are fundamentally linked across all educational levels (e.g., Atit et al., 2022). A meta-analysis synthesizing the findings from 29 studies found that training spatial skills leads to improvements in students' mathematical understanding and performance, with the strength of the effect increasing as participant age increased from three years to twenty years (Hawes et al., 2022).

Prior research supports both domain-general and domain-specific hypotheses that seek to explain the relation between spatial skills and mathematical performance. Domain-general theory proposes that spatial skills influence and apply to a broad range of mathematical tasks such as visualization to support mathematical problem-solving and numerical reasoning and are not exclusive to specific mathematical subjects or domains. This hypothesis is supported by evidence of shared cognitive processes (Gundersen et al., 2015; Mix & Cheng, 2012), neural activation overlap (see Hawes & Ansari, 2020; Hubbard et al., 2005), and the success of interventions that involve translating mathematical problems and symbols into spatial representations (Novack et al., 2014; Valenzeno et al., 2003).

Domain-specific theory argues that spatial skills may be task-specific and tailored to particular types of mathematical reasoning such as geometry and graphing, but not necessarily arithmetic or algebraic reasoning. This hypothesis is supported by evidence which suggests that specific spatial skills are uniquely related to specific mathematical tasks or domains. For example, a recent analysis by Delage and colleagues (2024) demonstrated that a geometry and spatial sense task presented significant cross-domain factor loadings and unique cognitive links with mathematical tasks (i.e., measurement, data management) and spatial tasks (i.e., perspective-taking, dot localization). A recent meta-analysis by Hawes and colleagues (2022) found the average effect size of spatial training on mathematics relative to control conditions to be 0.28, with significant variability however, suggesting that the distinct benefits of such training may depend on spatial and mathematical task type.

One widely accepted distinction in the different kinds of spatial skills is the division between small-scale and large-scale spatial skills (Hegarty & Waller, 2004). Small-scale spatial skills, such as mental rotation or spatial visualization, involve skills for completing tasks requiring the visualization and manipulation of 2D and 3D forms and have been linked to students' mathematics learning and achievement at all educational levels (e.g., Geer et al., 2019). Research in K-12 students suggests that small-scale spatial skills and mathematics outcomes are reciprocally related (e.g., Geer et al., 2019; Lombardi et al., 2019). In elementary students, mental rotation skills predict future mathematics outcomes, and positive mathematics outcomes predict greater mental rotation skills in subsequent years (Geer et al., 2019). In middle school students, fifth grade mathematics performance predicts sixth grade mental rotation skills, and seventh grade mental rotation skills predict seventh grade mathematics achievement (Lombardi et al., 2019). In high school students, spatial visualization skills are correlated to mathematics outcomes across tenth to twelfth grades (Tartre & Fennema, 1995).

Unlike the corpus of research in K-12 students, only a few studies have examined the relations between small-scale spatial skills and mathematics outcomes in postsecondary students. Wei and colleagues (2012) examined the role of small-scale spatial skills in understanding college-level mathematics concepts (e.g., algebra, statistics, logic) in undergraduate students who were not majoring in mathematics-intensive STEM disciplines. Results showed that small-scale spatial skills were significantly correlated with mathematics performance while controlling for students' general reasoning, language, and basic numerical reasoning skills. Sorby and colleagues (2013) found causal evidence that training small-scale spatial skills in first-year engineering students improved their calculus grades. These findings indicate that small-scale spatial skills are critical to mathematics achievement in postsecondary mathematics education.

Distinguishable from small-scale spatial skills are large-scale spatial skills, which are used when navigating or learning the layout of an environment such as a building or city (Hegarty & Waller, 2004). One large-scale spatial skill that is often examined in studies of STEM teaching and learning is spatial orientation, or perspective-taking (e.g., Lowrie & Logan, 2018), which involves imagining how an object or a stimulus array will appear from another perspective. However, few studies have examined the link between perspective-taking and mathematics achievement. Lowrie and colleagues (2016) found that primary and secondary students' perspective-taking skills correlated strongly with their performance on spatial (e.g., geometric) and non-spatial (e.g., algorithmic) mathematics problems. Additionally, bolstering primary students' perspective-taking, spatial visualization, and mental rotation skills improved their performance on both spatial and non-spatial mathematics problems (Lowrie et al., 2019). Moreover, Ventura and colleagues (2013) found that perspective-taking skills were significantly correlated with postsecondary students' high school SAT mathematics (SAT-M) scores.

In sum, both small and large-scale spatial skills have been found to contribute to students' mathematics achievement (e.g., Lowrie et al., 2016). However, the distinct contribution of each one to students' mathematics achievement is unknown. Moreover, no studies, to our knowledge, have explored the role of large-scale spatial skills on postsecondary students' mathematics achievement. Since spatial skills are malleable and can be improved with training and practice (Uttal et al., 2013), identifying how small and large-scale spatial skills relate and potentially contribute to undergraduate mathematics achievement is critical for improving postsecondary students' mathematics outcomes.

Gender, Spatial Skills, and Mathematics Achievement

Just as unclear as the relations of small versus large-scale spatial skills to students' mathematics achievement is how these relations vary by gender. Females are underrepresented at the highest levels of STEM occupations (Halpern et al., 2007), especially in mathematics-intensive STEM domains (see Wang & Degol, 2017). Moreover, males outperform females on tests of mathematical aptitude (e.g., SAT-M; Halpern et al., 2007), especially on the most complex problems (Hyde et al., 1990). Underlying the gender differences in mathematics outcomes are reported gender differences in spatial skills (Casey et al., 1995), as well as differences in the relations between spatial and mathematical skills (e.g., Tartre & Fennema, 1995). For instance, Casey and colleagues (1995) found that gender differences on the SAT-M were related to gender differences on a spatial skills measure in high-achieving students. Males performed better than females on both mental rotation and the SAT-M.

Contrary to the findings suggesting that gender differences in spatial skills underlie gender disparities in mathematics outcomes, a meta-analysis revealed that gender is not an influential factor. Findings from 45 studies were synthesized to identify if the association between spatial skills and mathematical skills varied by participants' grade or gender, neither of which were found to be significant moderators (Atit et al., 2022). One limitation of this analysis is that it did not examine if the role of gender in the association differed depending on the type of spatial skill. Thus, how gender differentially influences the relation between small versus large-scale spatial skills and mathematics achievement is unknown. As spatial skills are fundamental to mathematics learning and achievement (e.g., Atit et al., 2022), identifying how these relations vary by gender could have broad implications for improving diversity in STEM domains.

Math Anxiety and Mathematics Achievement

Math anxiety, "feelings of tension and anxiety that interfere with the manipulation of numbers and the solving of mathematical problems" (Richardson & Suinn, 1972, p. 551), hinders mathematics achievement in both children and adults (e.g., Hembree, 1990). Individuals with high math anxiety perform less well on simple numerical tasks such as magnitude comparison (e.g., Maloney et al., 2011), and simple addition and multiplication problems (Ashcraft & Faust, 1994). These individuals also exhibit weaker performance on more complex mathematical tasks, including complex addition and challenging word problems (e.g., Ashcraft & Faust, 1994). Importantly, math anxiety is not simply a proxy for poor mathematics skills. Rather, math anxiety is believed to cause negative thoughts that deplete working memory resources necessary for optimal performance in mathematics (Ashcraft & Kirk, 2001), resulting in individuals with high math anxiety underperforming compared to their low-anxiety counterparts on mathematical tasks. Studies examining the influence of math anxiety on postsecondary students' mathematics performance have predominantly been conducted in a laboratory setting (e.g., Daker et al., 2022; Delage et al., 2022). No research, to our knowledge, has examined the relations between math anxiety and mathematical performance of postsecondary precalculus students who are currently enrolled in a postsecondary precalculus course.

Gender and Math Anxiety

Many studies have reported higher levels of math anxiety for females than for males (e.g., Ashcraft & Faust, 1994), and research reveals that this gender gap manifests internationally. Stoet and colleagues (2016) measured math anxiety among 761,655 high school students across 68 nations, including the United States, who participated in the Programme for International Student Assessment. Results revealed that females reported more math anxiety than males overall, and this gender gap was wider in countries with greater economic development.

Laboratory studies conducted with undergraduate students in the last decade reveal that differences in spatial skills and spatial anxiety may underlie the gender differences in math anxiety (Delage et al., 2022; Maloney et al., 2011; Sokolowski et al., 2019). For instance, Maloney and colleagues (2011) examined the relations between participants' perceived level of spatial skills, mental rotation skills, and math anxiety, and found that perceived spatial skills significantly mediated the gender difference in math anxiety. However, mental rotation skills were not a significant mediator. Building on this research, Sokolowski and colleagues (2019) examined the relations between math anxiety, spatial anxiety, and perceived versus actual spatial skills and mathematical skills. Their results revealed that spatial processes, but not mathematical processes, mediated the relation between gender and math anxiety, after controlling for participants' general anxiety and general reasoning skills. Moreover, spatial anxiety was the strongest mediator between gender and math anxiety, over actual and perceived spatial skills (Sokolowski et al., 2019). More recently, Delage and colleagues (2022) further investigated these relations by examining the role of small versus large-scale spatial processes and mathematics performance in the relation between gender and math anxiety. Small-scale spatial skills, small-scale spatial anxiety, large-scale spatial anxiety, and mathematics performance explained the gender difference in math anxiety, with small-scale spatial anxiety being the strongest mediator of this relation (Delage et al., 2022).

The Current Study

First, we examined the links between spatial processing factors (i.e., spatial skills and spatial anxiety), math anxiety, and precalculus achievement in postsecondary precalculus students. Research indicates that small-scale spatial skills and spatial anxiety play a role in explaining math anxiety (Delage et al., 2022; Sokolowski et al., 2019). Additionally, spatial skills are positively associated with mathematics achievement (Atit et al., 2022) whereas math anxiety hinders mathematics performance (e.g., Hembree, 1990). Thus, we expect a significant association between spatial processing factors and math anxiety. Furthermore, we expect small-scale spatial skills, spatial anxiety, and math anxiety to be significantly associated with students' precalculus achievement.

Second, we examined the differences between genders in spatial processing factors, math anxiety, and precalculus achievement. Prior research has detected differences between genders in spatial processing factors (Casey et al., 1995), math anxiety (e.g., Ashcraft & Faust, 1994; Delage et al., 2022), and mathematics achievement (Casey et al., 1995). Therefore, we expect significant gender differences in these factors.

Third, we examined if spatial processing factors mediate the relation between gender, math anxiety, and precalculus achievement. Informed by prior findings illustrating that spatial anxiety for small-scale (i.e., manipulation) and large-scale (i.e., navigation) spatial tasks are significant mediators between gender and math anxiety (Delage et al., 2022; Sokolowski et al., 2019), we hypothesized that spatial anxiety would mediate the relation between students' gender and math anxiety, but we did not expect spatial skills to mediate the relation. Moreover, based on findings indicating that math anxiety hinders mathematics achievement (Hembree, 1990) and that females experience greater math anxiety than males (Ashcraft & Faust, 1994), we expect math anxiety to mediate the relation between gender and postsecondary precalculus achievement.

Method

This study examined longitudinal data from a larger project evaluating the efficacy of an undergraduate calculus course sequence. This study was approved by the Institutional Review Board at the University of California, Riverside (Protocol Number HS-21-114; Title of Study: A New Mathematics Gateway). See Supplementary Materials for data (Wilbur et al., 2024S-a).

Participants

We analyzed data from 820 undergraduate students (423 males, 380 females, 17 students self-identified as neither male or female or did not respond) enrolled in a precalculus course at a four-year university during the 2021-2022 and 2022-2023 academic years. Students predominantly self-identified as Asian/Asian American (53.4%) or Chicano/Latino (25.1%) in origin, as shown in Appendix A.

Spatial Skills Measures

Mental Rotations Test (MRT)

Students completed a researcher-created online version of the Mental Rotations Test to assess small-scale spatial skills. The test consists of 24 problems where students identified two rotated versions of a given figure among four options. Each correct pair earned one point, with total scores ranging from 0 to 24. The test was divided into two halves of 12 problems each, with students given three minutes to complete each half. Internal reliability, assessed by Cronbach's α, was very good (α = 0.88).

Guay's Visualization of Views Test (VOV)

Students completed an online version of Guay's Visualization of Views Test (VOV; Eliot & Smith, 1983) to assess perspective-taking, a large-scale spatial skill. The test comprises 24 items, each presenting a line drawing of a 3D figure within a transparent cube, alongside an alternative view of the figure. Students had eight minutes to identify the corner of the cube from which alternative views would be visible. Scoring followed Hegarty and colleagues' (2009) method, with scores adjusted for guessing. The maximum score was 24. Internal reliability, assessed by Cronbach's α, was excellent (α = 0.91).

Anxiety Measures

General Anxiety Measure (TAI)

The Trait Anxiety Inventory (TAI; Spielberger et al., 1970) comprises 20 items measuring general anxiety in adults. Students rated the frequency of experiencing anxiety-related feelings on a scale from 0 to 3. Total scores ranged from 0 to 60, with higher scores indicating greater anxiety. Internal reliability, assessed by Cronbach's α, was excellent (α = 0.93).

Math Anxiety Measure (sMARS)

The short Math Anxiety Rating Scale (sMARS; Alexander & Martray, 1989) comprises 25 items assessing math anxiety. Students rated their anxiety levels on a 1 to 5 Likert scale. Total scores ranged from 25 to 125, with higher scores indicating greater math anxiety. Internal reliability, assessed by Cronbach's α, was excellent (α = 0.95).

Spatial Anxiety Scale (SAS)

The Spatial Anxiety Scale (SAS; Lyons et al., 2018) consists of 24 items measuring participants' anxiety when completing spatial tasks. The full scale can be divided into three subscales (8 items in each subscale) with two subscales, Imagery and Mental Manipulations, focusing on small-scale spatial tasks, while a Navigation subscale focuses on large-scale spatial tasks. For each item, participants were asked to indicate how anxious they would feel about a given task. Responses ranged from "not at all" to "very much". Total score for each subscale ranged from 0 to 32. The internal reliability for each subscale was very good or excellent: α = 0.88 for Imagery, α = 0.87 for Mental Manipulation, and α = 0.92 for Navigation.

Mathematics Achievement Measure (FE)

The mathematics achievement measure was the final exam (FE) in the precalculus course, comprising 10 questions worth a total of 100 points. Exams were scored anonymously based on accuracy and completeness. Questions tested various skills, including recalling basic facts, applying principles directly, modeling real-world scenarios, synthesizing principles, and performing multi-part calculations. Sample items can be found in Appendix B.

Course Entry Survey

The Course Entry Survey, shown in Appendix C, included items asking about participant demographics, undergraduate major, their reason for enrolling in introductory precalculus, and concurrent STEM enrollment. For analysis purposes, gender was coded such that males = 0 and females = 1.

Procedure

All surveys and instruments described here, except for the final exam, were administered online via *Canvas*, a learning management system, at the beginning of the course. All measures were completed as part of normal course requirements and had similar point values, graded for completion and not performance. Students were not compensated for their participation. The final exam was administered to all students at the completion of the 10-week quarter. As Canvas was unable to present measures in a random order to each student to reduce bias and order effects, measures were administered in the order presented above so that the cognitive activation of stereotypes that may result from the collection of demographic information (e.g., Steele & Aronson, 1995) in the Course Entry Survey would not occur prior to other measures.

Handling Missing Data

One hundred twenty-three students skipped one or more items, resulting in 274 missing item scores in the full data set (3.7% of total data). Analysis using Little's (1988) test statistic indicated missing data was missing completely at random, $\chi^2(73, n = 820) = 81.0, p = .24$ (Rubin, 1976). Missing scores were imputed by chained equations using predictive mean matching (van Buuren & Groothuis-Oudshoorn, 2011). Descriptive statistics for all measures (presented in Table 1) are consistent with those prior to imputation.

Table 1

Descriptive and Normality Statistics for All Measures

Measure	M (SD)[a]	γ[b]	κ[c]	W[d]
sMARS	67.26 (17.42)	0.15	2.93	1.00*
TAI	44.88 (10.28)	0.07	2.60	1.00*
Imagery[e]	13.52 (6.78)	0.18	2.68	0.99***
Mental Manipulation[e]	12.46 (6.81)	0.33	2.82	0.98***
Navigation[e]	15.49 (7.41)	0.05	2.36	0.99***
MRT	7.75 (4.74)	0.66	2.89	0.96***
VOV	10.08 (7.27)	0.03	2.01	0.97***
FE	81.52 (16.16)	-2.08	9.68	0.83***

[a]$n = 820$ for all measures. [b]Skewness. [c]Kurtosis. [d]Shapiro-Wilk test statistic. [e]Spatial Anxiety Subscales.
*$p < .05$. **$p < .01$. ***$p < .001$.

Results

All analyses were conducted using R version 3.5.3 (R Core Team, 2022). Preliminary analyses were conducted to assess the normality of the data examined for the study. Table 1 presents the descriptive statistics, skewness, kurtosis, and results for the Shapiro-Wilk test of normality for the sMARS, TAI, SAS subscales, MRT, VOV, and FE. Due to the limited representation of students who identified as non-binary, further analysis was narrowed to students who identified as male or female (n = 803).

As preliminary analyses indicated that data examined on all measures violated assumptions of normality, Spearman's correlations were conducted to examine the relations between all measures and students' gender (presented in Table 2). Following Cohen's (1988) conventions, results indicated that sMARS was moderately and positively correlated with all three SAS subscales (rs > 0.40) and TAI score (r = 0.46), but weakly and negatively correlated with MRT (r = -0.11), VOV (r = -0.08), and FE (r = -0.14). TAI was also moderately and positively correlated with all three SAS subscale scores (rs > 0.20), but weakly and negatively correlated with FE (r = -0.12). MRT was strongly and positively correlated with VOV score (r = 0.50). Gender was weakly and positively correlated with sMARS score (r = 0.19), and the Mental Manipulation (r = 0.10) and Navigation (r = 0.22) SAS subscales, but was weakly and negatively correlated with MRT (r = -0.19), VOV (r = -0.17), and FE (r = -0.08).

Table 2

Correlational Data Among All Examined Variables

Variable	1	2	3	4	5	6	7	8
1. sMARS[a]	–	–	–	–	–	–	–	–
2. TAI[b]	**0.46**	–	–	–	–	–	–	–
3. Imagery[c]	**0.42**	**0.26**	–	–	–	–	–	–
4. Manipulation[c]	**0.45**	**0.24**	**0.36**	–	–	–	–	–
5. Navigation[c]	**0.42**	**0.33**	**0.43**	**0.45**	–	–	–	–
6. MRT[d]	**-0.11**	0.04	-0.01	-0.04	0.00	–	–	–
7. VOV[e]	**-0.08**	0.01	0.03	**-0.10**	-0.04	**0.50**	–	–
8. Gender[f]	**0.19**	**0.16**	0.04	**0.10**	**0.22**	**-0.20**	**-0.17**	–
9. FE[g]	**-0.14**	**-0.12**	0.00	-0.06	0.00	0.03	**0.08**	**-0.08**

Note. Significant bivariate correlations at the p < .05 level appear in bold font.
[a]short Math Anxiety Rating Scale. [b]Trait Anxiety Inventory. [c]Subscales of the Spatial Anxiety Scale. [d]Mental Rotations Test. [e]Visualization of Views. [f]Gender was coded such that males = 0 and females = 1. [g]Final Exam.

These results indicate that precalculus students with higher math anxiety reported higher spatial anxiety and general anxiety, and demonstrated poorer mental rotation skills, perspective-taking skills, and mathematics achievement. Additionally, mathematics achievement, math anxiety, and spatial anxiety for manipulation and navigation tasks varied by students' gender with female students showing lower final exam scores, but higher math, manipulation, and navigation anxiety scores. Lastly, students with stronger mental rotation skills also had stronger perspective-taking skills, and both kinds of spatial skills varied by gender with female students performing lower than male students.

Relations Between Spatial Processing Factors, Math Anxiety, and Mathematics Achievement

As all three subscales of spatial anxiety and both measures of spatial skills were significantly correlated with math anxiety, we conducted linear regression analyses to examine if and how spatial processing factors potentially contributed to math anxiety in precalculus students (Model 1). To ensure that the relations between spatial processing factors and math anxiety were not driven by students' general level of anxiety, we controlled for general anxiety in the model (e.g., Delage et al., 2022). As correlational analyses indicated significant associations between gender, spatial processing factors, and math anxiety, and because prior research has shown that spatial anxiety for manipulation and navigation tasks are significant mediators between gender and math anxiety (Delage et al., 2022; Sokolowski et al., 2019), we also controlled for gender to ensure that results presented unique variances not potentially explained by the factor. Results, shown in Table 3, indicate that after controlling for general anxiety (β = .30) and gender (β = .06), imagery, mental manipulation, and navigation anxiety all positively contributed to math anxiety. Additionally, mental rotation (β = -0.10) was negatively associated with math anxiety, but perspective-taking had no relation.

Table 3

Linear Regression Models Examining the Relations Between Spatial Processing Factors, Math Anxiety, and Mathematics Achievement Controlling for General Anxiety and Gender

	Model 1			Model 2		
Measure	***b*** **(*SE*)**	**β**	***p***	***b*** **(*SE*)**	**β**	***p***
Intercept	28.48 (2.35)	–	–	92.88 (2.98)	–	–
sMARS[a]	–	–	–	-0.12 (0.04)	-0.13	< .01**
Gender[b]	1.69 (0.76)	0.06	.03*	-0.93 (0.89)	-0.04	.29
TAI[c]	0.51 (0.05)	0.30	< .01**	-0.12 (0.06)	-0.08	.06+
Imagery[d]	0.51 (0.08)	0.20	< .01**	0.08 (0.10)	0.03	.42
Manipulation[d]	0.62 (0.08)	0.24	< .01**	-0.07 (0.10)	-0.03	.46
Navigation[d]	0.21 (0.08)	0.09	.01*	0.17 (0.09)	0.08	.06†
MRT[e]	-0.35 (0.12)	-0.10	< .01**	-0.13 (0.14)	-0.04	.33
VOV[f]	-0.02 (0.08)	-0.01	.78	0.06 (0.09)	0.03	.51
R^2		0.38			0.02	

Note. βs are standardized betas. Numbers in parentheses are standard errors. The outcome variable for Model 1 is math anxiety and for Model 2 is final exam score.

[a]short Math Anxiety Rating Scale. [b]Gender was coded such that males = 0 and females = 1. [c]Trait Anxiety Inventory. [d]Subscales of the Spatial Anxiety Scale. [e]Mental Rotations Test. [f]Visualization of Views.

†$p < .10$. *$p < .05$. **$p < .01$.

As math anxiety and mathematics achievement were also correlated, we examined the relation between spatial processing factors, math anxiety, and final exam score in Model 2, again controlling for general anxiety and gender to ensure unique variance. Results, shown in Table 3, indicate that after controlling for general anxiety (β = -.09), and gender (β = -.03), math and navigation anxiety were significantly associated with students' final exam score, while the remaining spatial processing factors did not have significant relations.

Gender Differences in Spatial Processing Factors, Math Anxiety, and Mathematics Achievement

As correlational analyses indicated that spatial anxiety for mental manipulation and navigation tasks, spatial skills, math anxiety, and mathematics achievement varied by gender, and prior research indicates that gender differences persist on many measures of spatial skills (e.g., Miller & Halpern, 2013) as well as math anxiety (Beilock et al., 2010), we tested for gender differences for each measure using Mann-Whitney *U* comparisons due to violations of normality in the data examined. Results, summarized in Table 4, indicate significant gender differences in mental manipulation and navigation anxiety, math anxiety, general anxiety, mental rotation, perspective-taking, and the final exam. Females reported higher mental manipulation, navigation, math, and general anxiety. Males demonstrated higher performance on mental rotation and perspective-taking tasks, and on the final exam.

Table 4

Mann-Whitney U Tests Examining Differences Between Male and Female Students

	Male (n = 423)		Female (n = 380)			
Measure	***M***	***SD***	***M***	***SD***	***U***	***d***
sMARS[a]	64.17	16.87	70.12	17.49	64662.50**	-0.35
TAI[b]	43.44	9.93	45.94	10.20	68540.50**	-0.25
Imagery[c]	13.30	7.02	13.70	6.53	77820.00	-0.06
Manipulation[c]	11.80	6.77	13.04	6.73	72049.50*	-0.18
Navigation[c]	14.05	6.97	16.74	7.51	63364.00**	-0.37
MRT[d]	8.75	5.05	6.64	4.15	100428.50**	0.45
VOV[e]	11.34	7.69	8.60	6.46	98071.50**	0.39
FE[f]	82.18	16.85	81.00	14.99	87709.00*	0.07

[a]Math Anxiety Rating scale. [b]Trait Anxiety Inventory. [c]Subscales of the Spatial Anxiety Scale. [d]Mental Rotations Test. [e]Visualization of Views. [f]Final Exam.
*p < .05. **p < .01.

What Explains Gender Differences in Math Anxiety and Mathematics Achievement?

Mediation analyses were conducted to identify the role of spatial processes in explaining gender differences in math anxiety and mathematics achievement. All models were computed using the *lavaan* package for structural equation modeling in R (Rosseel, 2012). Significance was tested using robust maximum likelihood estimation (Li, 2016). Indirect effects were calculated as the product of coefficients, and the 95% confidence interval was determined by computing the indirect effect at the 2.5th and the 97.5th percentile. For each mediation analysis we report the following goodness-of-fit indices: chi-squared value and significance, Comparative Fit Index (CFI), robust Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR). All mediation analyses include TAI score as a covariate. For brevity, tables and figures for Mediation Models 1 and 2 are included in Appendix D.

Mediation Model 1: Do Spatial Skills Mediate the Relation Between Gender and Math Anxiety?

Regression analyses indicated a significant association between spatial skills and math anxiety, and Mann-Whitney *U* tests revealed significant differences in male and female students' math anxiety. Thus, in Mediation Model 1, we examined if small-scale (i.e., mental rotation) and large-scale (i.e., perspective-taking) spatial skills explain the link between gender and math anxiety. Results indicate the total indirect effect was significant (effect = 2.78, 95% CI [1.55, 4.01]) and accounted for 46.7% of the total effect, suggesting that performance on the two measures of spatial skills together mediated the relation between gender and math anxiety. When examining the distinct contribution of each type of spatial skills measure in mediating students' math anxiety, results show that the indirect effect of mental rotation was significant (indirect effect = 0.75, 95% CI [0.17, 1.34]) and accounted for 12.6% of the total effect. However, perspective-taking did not significantly mediate the relation.

Furthermore, analyses reveal that the direct effect from gender to math anxiety was also significant when spatial skills were not considered (effect = 3.17, 95% CI [0.96, 5.38]) indicating that the relation between gender and math anxiety is both direct and mediated by spatial skills. The chi-squared goodness-of-fit index for this model $\chi^2(df = 3, n = 803) = 207.236$, $p < .001$, was significant. The CFI was 0.574, RMSEA was 0.291, 95% CI [0.259, 0.324], and SRMR was 0.122.

Mediation Model 2: Does Spatial Anxiety Mediate the Relation Between Gender and Math Anxiety?

Regression analyses indicated a significant association between spatial anxiety and math anxiety, and Mann-Whitney *U* tests revealed a difference in math anxiety between genders. Thus, we conducted a mediation analysis to examine if and how the subtypes of spatial anxiety explained the link between gender and math anxiety. The total indirect effect for spatial anxiety was significant (effect = 2.81, 95% CI [1.32, 4.30]), suggesting that together the three types of spatial anxieties mediated the relation between gender and math anxiety. The total indirect effect accounted for 47.2% of the total effect.

Examining the distinct contribution of each subtype of spatial anxiety revealed that mental manipulation (indirect effect = 0.79, 95% CI [0.16, 1.41]) and navigation (indirect effect = 0.55, 95% CI [0.03, 1.06]) were significant independent mediators and accounted for 13.3% and 9.2% of the total effect, respectively, while imagery was not significant. This suggests that the relation between gender and math anxiety may be explained in part by mental manipulation and navigation anxieties. The chi-squared goodness-of-fit index for this model $\chi^2(df = 6, n = 803) = 430.995$, $p < .001$, was significant. The CFI was 0.475, RMSEA was 0.297, 95% CI [0.275, 0.319], and SRMR was 0.212.

Mediation Model 3: Do Mental Rotation Skill, Mental Manipulation Anxiety, and Navigation Anxiety Mediate the Relation Between Gender and Math Anxiety?

To align our investigative process with prior research (see Delage et al., 2022) we conducted an additional mediation model to determine how the specific affective and cognitive spatial processing factors found to be significant in our previous mediation models (i.e., mental rotation, mental manipulation anxiety, and navigation anxiety) uniquely mediate the relation between gender and math anxiety when taken together. Similar to Delage et al. (2022) the total indirect effect was significant (effect = 4.07, 95% CI [2.58, 5.57]), accounting for 68.4% of the total effect, and the direct effect was not significant.

Mental rotation skills (indirect effect = 0.77, 95% CI [0.26, 1.28]), mental manipulation anxiety (indirect effect = 0.91, 95% CI [0.20, 1.62]), and navigation anxiety (indirect effect = 0.98, 95% CI [0.37, 1.58]) were all significant independent mediators and accounted for 12.9%, 15.3%, and 16.5% of the total effect, respectively. These results suggest that, taken together, mental rotation skills, mental manipulation anxiety, and navigation anxiety mediate the relation between gender and math anxiety, while accounting for unique and comparable variances in the model. This suggests that the relation between gender and math anxiety can be explained, in part by these factors. The chi-squared goodness-of-fit index for this model $\chi^2(df = 6, n = 803) = 251.419$, $p < .001$, was significant. The CFI was 0.615, RMSEA was 0.226, 95% CI [0.203, 0.249], and SRMR was 0.143. See Table 5 for a summary of the analysis and Figure 1 for a visual representation.

Table 5

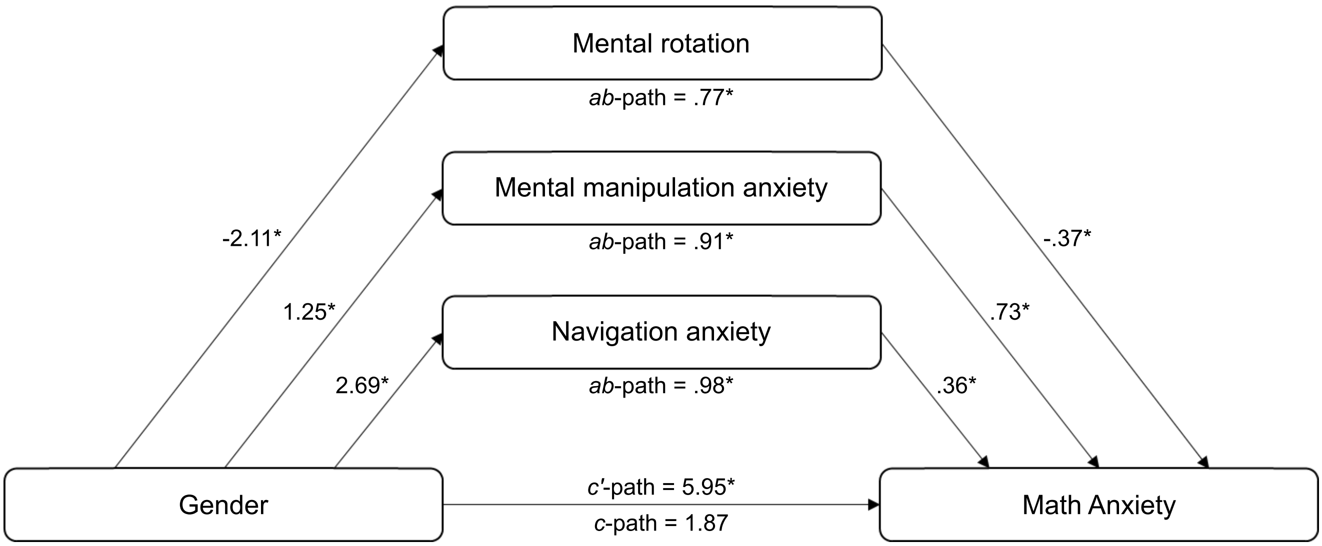
Mediation Analysis Examining How Mental Rotation, Manipulation Anxiety, and Navigation Anxiety Mediate the Relation Between Gender and Math Anxiety

Mediation Model 3	Coefficient	SE^a	p	% c'^b	95% CI
Model without mediator					
Gender ⟶ sMARS[c] (c')	5.95	1.21	< .01**		[3.57, 8.33]
Model with MRT[d], Manipulation[e], and Navigation[e] as mediators					
Gender ⟶ MRT (a)	-2.11	0.32	< .01**		[-2.75, -1.48]
Gender ⟶ Manipulation (a)	1.25	0.48	< .01**		[0.31, 2.18]
Gender ⟶ Navigation (a)	2.69	0.51	< .01**		[1.68, 3.69]
MRT ⟶ sMARS (b)	-0.37	0.11	< .01**		[-0.58, -0.15]
Manipulation ⟶ sMARS (b)	0.73	0.08	< .01**		[0.57, 0.89]
Navigation ⟶ sMARS (b)	0.36	0.09	< .01**		[0.19, 0.53]
Gender ⟶ sMARS (c)	1.87	1.03	.07	31.4	[-0.14, 3.89]
Indirect effects (a*b)					
Gender ⟶ MRT ⟶ sMARS	0.77	0.26	< .01**	12.9	[0.26, 1.28]
Gender ⟶ Manipulation ⟶ sMARS	0.91	0.36	.01*	15.3	[0.20, 1.62]
Gender ⟶ Navigation ⟶ sMARS	0.98	0.31	< .01**	16.5	[0.37, 1.58]
Gender ⟶ Total ⟶ sMARS	4.07	0.76	< .01**	68.4	[2.58, 5.57]

[a]Standard error. [b]Percent of the total effect (c') accounted for by the indirect effect (a*b). [c]short Math Anxiety Rating scale. [d]Mental Rotations Test. [e]Subscales of the Spatial Anxiety Scale. We controlled for TAI score in this analysis.
*$p < .05$. **$p < .01$.

Figure 1

Visual Representation of Mental Rotation Skills, Mental Manipulation Anxiety, and Navigation Anxiety as Mediators of the Relation Between Gender and Math Anxiety



Note. *indicates a significant 95% confidence interval. We controlled for TAI score in this analysis.

Mediation Model 4: Does Math Anxiety Mediate the Relation Between Gender and Postsecondary Precalculus Achievement?

Finally, as regression analyses revealed that math anxiety was significantly associated with final exam score, and as Mann-Whitney *U* tests revealed significant differences in male and female students' math anxiety and final exam score, we conducted a fourth mediation model to examine if math anxiety mediated the relation between gender and final exam score. Results, shown in Table 6, indicate the total indirect effect was significant (effect = -0.82, 95% CI [-1.32, -0.32]) and accounted for 69.5% of the total effect, suggesting that math anxiety partially mediated the relation between gender and final exam score. The chi-squared goodness-of-fit index for this model $\chi^2(df = 1, n = 803) = 142.906, p < .001$, was significant. The CFI was 0.291, RMSEA was 0.420, 95% CI [0.368, 0.475], and SRMR was 0.135. See Figure 2 for a visual representation.

Table 6

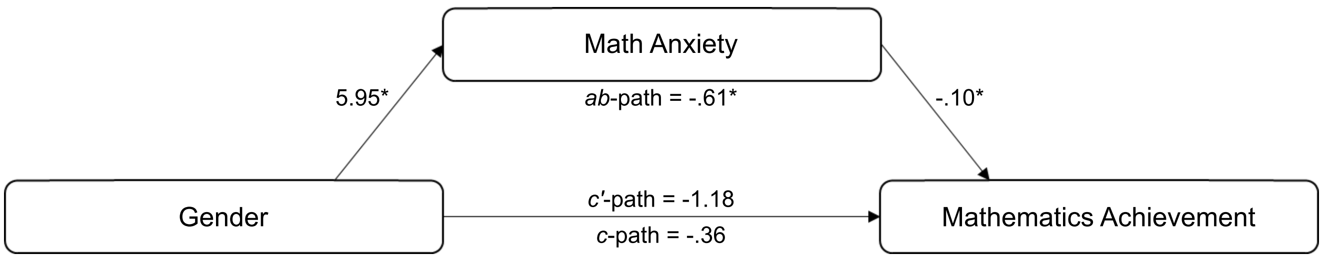
Mediation Analysis Examining if Math Anxiety Mediates the Relation Between Gender and Precalculus Achievement

Mediation Model 4	Coefficient	*SE*[a]	*p*	% *c'*[b]	95% CI
Model without mediator					
Gender ⟶ Final Exam (*c'*)	-1.18	1.12	.29		[-3.38, 1.02]
Model with sMARS[c] as mediator					
Gender ⟶ sMARS (*a*)	5.95	1.21	< .01**		[3.57, 8.33]
sMARS ⟶ Final Exam (*b*)	-0.10	0.04	< .01**		[-0.18, -0.03]
Gender ⟶ Final Exam (*c*)	-0.36	1.12	.75	30.5	[-2.56, 1.83]
Indirect effects (*a*b*)**					
Gender ⟶ sMARS ⟶ Final Exam	-0.62	0.26	.02*	52.5	[-1.12, -0.11]
Gender ⟶ Total ⟶ Final Exam	-0.82	0.26	< .01**	69.5	[-1.32, -0.32]

[a]Standard error. [b]Percent of the total effect (*c'*) accounted for by the indirect effect (*a***b*). [c]short Math Anxiety Rating scale. We controlled for TAI score in this analysis.
$^{*}p < .05$. $^{**}p < .01$.

Figure 2

Visual Representation of Math Anxiety as Mediator of the Relation Between Gender and Mathematics Achievement



Note. *indicates a significant 95% confidence interval. We controlled for TAI score in this analysis.

Discussion

Research has established that both cognitive and affective processes play a role in student learning and achievement in a domain (e.g., Ashcraft & Kirk, 2001). Moreover, these processes are interrelated (e.g., Brosch et al., 2013), and interact with student demographics to influence learning and performance (e.g., Atit et al., 2020). In the domain of mathematics, spatial skills, spatial anxiety, and math anxiety have been identified as interrelated processes that interact with students' gender to influence mathematics achievement (e.g., Daker et al., 2022). However, how these processes are shaped by the educational context is unknown. This study examined the role of gender on the relations between spatial skills, spatial anxiety, math anxiety, and mathematics achievement in students enrolled in a postsecondary precalculus course.

Linear analyses revealed that after controlling for gender and general anxiety, all three spatial anxiety subscales (i.e., Imagery, Mental Manipulation, and Navigation), as well as small-scale spatial skills (i.e., mental rotation), were significantly related to students' math anxiety. However, only math anxiety was significantly related to students' precalculus achievement. Additionally, gender differences were found across almost all measures, with female students reporting higher mental manipulation, navigation, math, and general anxieties than their male peers. Females also underperformed on mental rotation and perspective-taking tasks, as well as on the final exam. Mediation analyses revealed that after controlling for general anxiety, mental manipulation and navigation anxiety, and mental rotation skills partially mediate the relation between gender and math anxiety, while imagery anxiety and perspective-taking skills were not significant mediators in the relation. Furthermore, the observed gender difference in final exam scores was mediated by math anxiety.

The patterns of significance and effect sizes present in these findings are in line with prior research (see Delage et al., 2022; Ferguson et al., 2015; Maloney et al., 2012), suggesting that variance in math anxiety is similar between studies performed within a laboratory context to those conducted in a postsecondary academic context. However, differences in the proportions of the total indirect effect mediated by each factor suggest that mental manipulation anxiety plays a more prominent role within a laboratory setting, whereas small-scale spatial skills, and mental manipulation and navigation anxiety factor proportions are approximately equalized in an academic context, where the pertinent measures were completed by students as part of regular coursework.

Also consistent with prior findings on gender differences in math anxiety (e.g., Delage et al., 2022), our study showed that female precalculus students experienced higher math anxiety then their male peers. Moreover, results from our study are in line with research indicating that spatial processing factors have important relations to gender differences in math anxiety (Delage et al., 2022). Delage and colleagues (2022) found that small-scale spatial skills, manipulation anxiety, and navigation anxiety help potentially explain gender differences in math anxiety with manipulation anxiety being the strongest mediator. Similarly, our analyses also indicate that small-scale spatial skills, manipulation anxiety, and navigation anxiety partially mediate gender differences in math anxiety. However, navigation anxiety is the strongest mediator of the relation. The divergence in findings between the study by Delage and colleagues (2022) and our study may be attributed to differences in the student participants and the context in which the data was collected. Delage and colleagues (2022) recruited participants from the undergraduate student research pool consisting primarily of volunteer psychology students who completed the measures during a one-hour session in a research lab. In our study, participants were undergraduate students enrolled in an introductory precalculus course sequence who completed the measures as part of their required coursework. As much research has shown that affective factors are situated and are shaped by the participants' environment (e.g., Bedrosian & Nelson, 2013), identifying if and how the drivers of gender differences in math anxiety differ across educational contexts is a critical question for future research.

Akin to prior research that has found that spatial processing factors contribute to math anxiety (e.g., Delage et al., 2022; Ferguson et al., 2015; Maloney et al., 2012), our study found that both spatial skills and spatial anxiety were significantly associated with precalculus students' math anxiety. Maloney and colleagues (2012) suggested that individuals with poor spatial skills may be more challenged when solving mathematics problems, resulting in higher math anxiety. Ferguson and colleagues (2015) showed that after accounting for gender and general anxiety, individuals' spatial anxiety for navigational tasks and small-scale spatial skills are significant predictors of math anxiety, while large-scale spatial skills are not. In our study, after controlling for gender and general anxiety, small-scale spatial skills and all three subscales of spatial anxiety were found to mediate or relate directly to students' math anxiety. The expanded set of significant spatial anxieties present in our study were detectable due to our use of the Spatial Anxiety Survey (Lyons et al., 2018), versus Lawton's (1994) Spatial Anxiety Scales used in the study conducted by Ferguson and colleagues (2015) which only examines spatial anxiety for navigational tasks. Additionally, Ferguson and colleagues (2015) recruited Mechanical Turk users from across the U.S. to participate in their research, the majority of which reported being college graduates, while participants for our study were undergraduate students enrolled in an introductory precalculus course at a large four-year university. While research indicates that the relation between spatial skills and mathematics achievement does not vary between grade levels (Atit et al., 2022), whether the relations between spatial processing factors and math anxiety vary by educational attainment is unknown. As math anxiety hinders mathematics learning and achievement in individuals at all grade levels (e.g., Ferguson et al., 2015; Hembree, 1990), further studies should seek to understand if and how the relations between spatial processing factors and math anxiety vary across levels of education to inform about the most effective timing to implement interventions aimed at reducing math and spatial anxiety in students.

While the results of this study were calculated using robust linear and mediation modeling methods, future research should attempt to minimize the presence of the primary limitations herein. One limitation of this study is that the measures were assigned as coursework. As a result, participant responses on the measures may have been influenced by the knowledge that the course instructor would be aware of their responses (although specific survey responses had no impact on overall course grade), potentially introducing bias. Additionally, as many students chose to complete the measures outside the classroom, some contextual bias may have been introduced for some measures. Relatedly, some participants did not complete all of the measures, requiring the use of data imputation methods in order to conduct the planned analyses. Research on the effects of data imputation indicates that imputing missing data can in some instances bias resulting parameter estimates (e.g., Cox et al., 2014). Another source of bias may be the potential activation of stereotype threat introduced by demographic questions about gender which are included in the Course Entry Survey. Finally, as this was a correlational study, no causal inferences can be made. Therefore, future studies should address these limitations by ensuring more comprehensive survey completion, disentangling survey responses with instructor grading procedures, narrowing the range of contexts of measures and randomizing their order of administration, and establishing causal relations between factors by conducting additional studies which permit causal inferences.

Conclusion

In conclusion, this study highlights the need to continue exploring additional factors, in conjunction with cognitive and affective factors, underlying gender-based disparities in postsecondary mathematics performance. In particular, our study suggests that math anxiety hinders precalculus achievement in all students, and that spatial anxiety and small-scale spatial skills potentially contribute to students' math anxiety. Thus, if causal relations are confirmed, interventions aimed at mitigating students' math anxiety should aim to improve students' small-scale spatial skills and diminish their anxieties associated with spatial tasks. Additionally, this study revealed gender disparities in postsecondary mathematics achievement. Analyses indicate that differences in spatial processing factors potentially contribute to gender differences in math anxiety, which in turn explain gender differences in achievement. These findings underline the importance of gaining a greater understanding of the complex relations between student gender, spatial processing factors, and math anxiety in the development and implementation of efforts aimed at improving postsecondary students' mathematics outcomes and persistence and retention in STEM major programs.

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Competing Interests: The authors declare no conflicts of interest in the publication of this research.

Author Contributions: All contributing authors have been listed in alphabetical order after the first three authors.

Ethics Statement: This study was approved by the Institutional Review Board at the University of California, Riverside (Protocol Number HS-21-114; Title of Study: A New Mathematics Gateway). The authors adhered to all ethical guidelines required under the Responsible Conduct of Research (RCR) framework (research.ucr.edu/orc).

Data Integrity and Confidentiality: All data collected during this study were anonymized to protect participant privacy, and access to the data was restricted to authorized research personnel.

Data Availability: All data and calculation scripts for this study are publicly available (Wilbur et al., 2024S-a, 2024S-b).

Supplementary Materials

The Supplementary Materials contain the following items:

- Research data (Wilbur et al., 2024S-a)
- Code (Wilbur et al., 2024S-b)
  - Analysis
  - Missingness, multicollinearity, imputation

Index of Supplementary Materials

Wilbur, R. C., Atit, K., Agrawal, P., Carrillo, B., Lussier, C. M., Noack, D., Poon, Y. S., & Weisbart, D. (2024S-a). *Supplementary materials to "Examining the role of spatial and mathematical processes and gender in postsecondary precalculus"* [Research data]. PsychOpen GOLD. https://doi.org/10.23668/psycharchives.15569

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Appendices

Appendix A

Table A.1

Participants' Reported Race/Ethnicity

Race/Ethnicity	*n*	% total
Asian/Asian American	438	53.41%
Chicano/Latino	206	25.12%
White	68	8.29%
Two or More Races	33	4.02%
Other/Prefer not to say	24	2.93%
Black/African American	23	2.80%
Domestic Unknown	14	1.71%
International	8	0.98%
Pacific Islander	5	0.61%
Native American	1	0.12%

Note. The ethnicity categories presented here are informed by those used by the University of California, Riverside Office of Institutional Research (2023).

Appendix B

Figure B.1

Sample Final Exam Problems

R1. The line L passes through the points $(2,3)$ and $(5,9)$.

a. Find an equation for L.

b. If $L_{\perp}$ is perpendicular to L, then what is the slope of $L_{\perp}$?

R2. Recall that 3 feet is one yard and 60 seconds is one minute. Calculate the acceleration $7\,\frac{\mathrm{ft}}{\mathrm{s}^2}$ in units of yards and minutes.

R3. Suppose that a line segment L passes through the points $(1,3)$ and $(2,5)$.

a. Find the point on L that is a distance of 2 from the point $(1,3)$ and that lies to the right of $(1,3)$.

b. Find the point on the line segment L whose distance from $(1,3)$ is one third the length of the line segment L.

R4. Suppose that L is a line of slope 5 that intersects the origin. Where does L intersect the unit circle?

Appendix C

Figure C.1

Course Entry Survey

Please respond to the items below in regards to yourself.

1) Name: ________________________________

2) Gender

Male	Female	Non-binary/ third gender	Prefer to self-describe: ________________	Prefer not to answer

3) Age: _______________

4) Race/Ethnicity:

American Indian/Native American/Alaska Native
Asian/Asian American
Black/African American
Hispanic/Latinx
Native Hawaiian/Other Pacific Islander
White/European
Prefer not to say
Other: __________________________

5) Undergraduate Major/Concentration: _________________________________

6) Are you a first-generation college student?

Yes	No

7) Is English your first language?

Yes	No

Appendix D

Table D.1

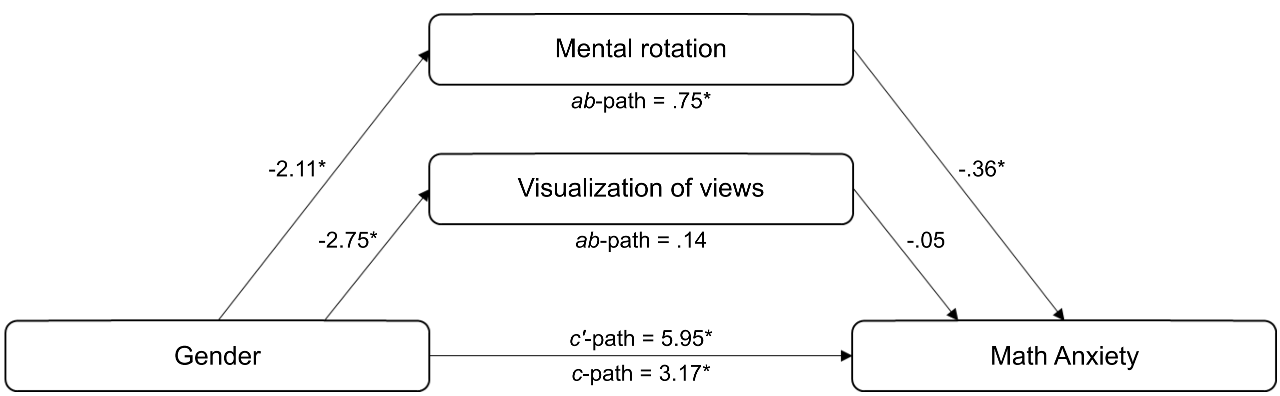
Mediation Model 1: Mediation Analysis of Spatial Skills as Mediators of the Relation Between Gender and Math Anxiety

Mediation Model 1	Estimate	*SE*[a]	*p*	% *c'*[b]	95% CI
Model without mediators					
Gender ⟶ sMARS[c] (*c'*)	5.95	1.21	< .01**		[3.57, 8.33]
Model with MRT, VOV as mediators					
Gender ⟶ MRT[d] (*a*)	-2.11	0.32	< .01**		[-2.75, -1.48]
Gender ⟶ VOV[e] (*a*)	-2.75	0.50	< .01**		[-3.73, -1.77]
MRT ⟶ sMARS (*b*)	-0.36	0.13	< .01**		[-0.61, -0.11]
VOV ⟶ sMARS (*b*)	-0.05	0.09	.54		[-0.22, 0.12]
Gender ⟶ sMARS (*c*)	3.17	1.13	< .01**	53.3	[0.96, 5.38]
Indirect effects (*a *b*)**					
Gender ⟶ MRT ⟶ sMARS	0.75	0.30	.01*	12.6	[0.17, 1.34]
Gender ⟶ VOV ⟶ sMARS	0.14	0.24	.54	2.4	[-0.32, 0.61]
Gender ⟶ Total ⟶ sMARS	2.78	0.63	< .01**	46.7	[1.55, 4.01]

Note. [a]Standard error. [b]Percent of the total effect (*c'*) accounted for by the indirect effect (*a***b*). [c]short Math Anxiety Rating scale. [d]Mental Rotations Test. [e]Visualization of Views test. We controlled for TAI score in this analysis.
**p* < .05. ***p* < .01.

Figure D1

Mediation Model: Visual Representation of Spatial Skills as Mediators of the Relation Between Gender and Math Anxiety



Note. *indicates a significant 95% confidence interval. We controlled for TAI score in this analysis.

Table D.2

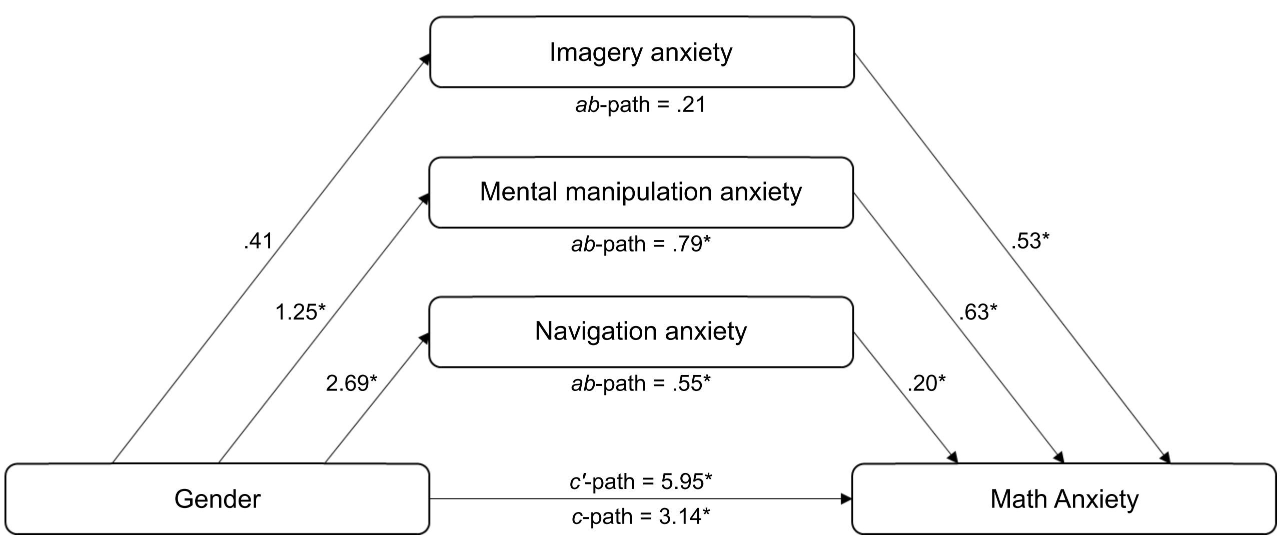
Mediation Model 2: Mediation Analysis of Spatial Anxiety Subscales as Mediators of the Relation Between Gender and Math Anxiety

Mediation Model 2	Coefficient	*SE*[a]	*p*	% *c'*[b]	95% CI
Model without mediator					
Gender ⟶ sMARS[c] (*c'*)	5.95	1.21	< .01**		[3.57, 8.33]
Model with Imagery, Manipulation, and Navigation as mediators					
Gender ⟶ Imagery[d] (*a*)	0.40	0.48	.40		[-0.53, 1.34]
Gender ⟶ Manipulation[d] (*a*)	1.25	0.48	< .01**		[0.31, 2.18]
Gender ⟶ Navigation[d] (*a*)	2.69	0.51	< .01**		[1.68, 3.69]
Imagery ⟶ sMARS (*b*)	0.53	0.08	< .01**		[0.36, 0.69]
Manipulation ⟶ sMARS (*b*)	0.63	0.08	< .01**		[0.47, 0.79]
Navigation ⟶ sMARS (*b*)	0.20	0.09	.02*		[0.03, 0.38]
Gender ⟶ sMARS (*c*)	3.14	1.01	< .01**	52.8	[1.17, 5.11]
Indirect effects (*a *b*)**					
Gender ⟶ Imagery ⟶ sMARS	0.21	0.25	.40	3.5	[-0.28, 0.71]
Gender ⟶ Manipulation ⟶ sMARS	0.79	0.32	.01*	13.3	[0.16, 1.41]
Gender ⟶ Navigation ⟶ sMARS	0.55	0.26	.04*	9.2	[0.03, 1.06]
Gender ⟶ Total ⟶ sMARS	2.81	0.76	< .01**	47.2	[1.32, 4.30]

Note. [a]Standard error. [b]Percent of the total effect (*c'*) accounted for by the indirect effect (*a***b*). [c]short Math Anxiety Rating scale. [d]Subscales of the Spatial Anxiety Scale. We controlled for TAI score in this analysis.
**p* < .05. ***p* < .01.

Figure D2

Mediation Model: Visual Representation of Spatial Anxiety Subscales as Mediators of the Relation Between Gender and Math Anxiety



Note. *indicates a significant 95% confidence interval. We controlled for TAI score in this analysis.