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The Relation Between Spatial Anxiety and Spatial Skills Is Moderated by Visuospatial Working Memory and Grade Level

Xinhe Zhang[1], Elizabeth A. Gunderson[1]

[1] *Department of Psychological and Brain Sciences, Indiana University-Bloomington, Bloomington, IN, USA.*

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Corresponding Author: Elizabeth A. Gunderson, Department of Psychological and Brain Sciences, Indiana University-Bloomington, 1101 E. 10th St., Bloomington, IN 47405, United States. E-mail: eagunder@iu.edu

Abstract

Spatial skills are critical for learning in STEM areas and are affected by spatial anxiety and working memory. Prior work also showed that there are interaction effects between spatial anxiety and verbal working memory (WM) on spatial skills, such that the negative relation between spatial anxiety and spatial skills is stronger among higher- than lower-verbal WM children. To date, this interaction effect has not been found for visuospatial WM. However, a recent meta-analysis showed that both verbal WM and visuospatial WM are impaired by anxiety to a similar extent. The current study hypothesized that visuospatial WM interacts with spatial anxiety on spatial skills and that this interaction effect gets stronger as age increases. We investigated spatial anxiety, visuospatial WM, and two spatial skills (mental transformation and mental rotation) in 402 U.S. children in first to fourth grades. We found a significant three-way interaction of spatial anxiety, visuospatial WM, and grade level on mental transformation skill: only fourth-graders with high visuospatial WM showed a significant relation between spatial anxiety and lower mental transformation skills, whereas low-visuospatial WM fourth-graders and children in Grades 1 to 3 did not show this relation. However, this effect was not significant for children’s mental rotation skills. We discuss the results in terms of age-related differences in visuospatial WM and strategy use, as well as differences between the mental transformation and mental rotation tasks. Our findings indicate that the interaction effect between spatial anxiety and working memory on spatial skills extends beyond verbal WM to visuospatial WM and becomes more pronounced as children's age increases.

Keywords

spatial anxiety, mental transformation, mental rotation, visuospatial working memory

Highlights

- This study examined how spatial anxiety and visuospatial working memory (WM) interactively relate to spatial skills in 1st–4th graders.
- A negative link between spatial anxiety and mental transformation performance emerged only in 4th graders with high visuospatial WM.
- No interactive effect was found for mental rotation skills, highlighting differences in task demands and strategy use.
- Findings suggest that spatial anxiety can impair visuospatial WM (in addition to verbal WM), particularly in older children.

Spatial skills, the cognitive abilities involved in mentally manipulating visual images and reasoning about the spatial relations among shapes and locations, are strong predictors of success in science, technology, engineering, and mathematics (STEM) areas (e.g., Tian et al., 2023; Wai et al., 2009). For example, high school students' spatial skills predict their achievement in STEM eleven years later (Wai et al., 2009). Tracing this back even earlier in development, the spatial skills of children in fourth grade predict their likelihood of choosing a STEM major in college (Tian et al., 2023) and the spatial skills of preschoolers predict their math performance six months later (Ouyang et al., 2022). Spatial skills are also robustly linked to mathematics achievement at all ages (e.g., Atit et al., 2022; Gunderson & Hildebrand, 2021) and a recent meta-analysis showed that training children's spatial skills leads to far transfer to math achievement (Hawes et al., 2022). Given the importance of spatial skills for STEM achievement, identifying the sources of individual differences in spatial ability is important for both researchers and educators.

Prior studies have shown that both emotional factors (e.g., spatial anxiety; Lauer et al., 2018; Lawton, 1994) and cognitive factors (e.g., working memory; Kaufman, 2007; Wang et al., 2018; Wang & Carr, 2014; Zhang et al., 2022) can impact spatial skills. Although often studied separately, these emotional and cognitive factors occur together in real-world settings and studying them simultaneously can provide new insights. Indeed, one study of 1st and 2nd graders found that spatial anxiety and verbal WM interact, such that children with higher verbal WM showed a stronger negative relation between spatial anxiety and spatial skills than those with lower verbal WM (Ramirez et al., 2012). The researchers theorized that spatial anxiety impairs the ability of high-verbal-WM individuals to employ verbal-WM-intensive strategies, leading to a decline in performance (Ramirez et al., 2012). However, the nature and boundary conditions surrounding the relation between spatial anxiety, working memory, and spatial skills remain relatively unexplored. Here, we aimed to build on this prior work by examining a larger age range, with additional spatial skill measures. Further, whereas prior work has tested these relations with verbal WM, here we aimed to examine whether spatial anxiety and visuospatial WM interact to predict spatial skills. This work can inform our theories of the relation between anxiety and performance and has practical importance for understanding how to foster children's spatial skills and STEM achievement.

Spatial Anxiety and Spatial Performance

Spatial anxiety refers to anxious feelings directed towards spatial-related activities (Lyons et al., 2018; Ramirez et al., 2012). Spatial anxiety emerges early in preschool-age children and shows individual differences among children (Wong, 2017). Although relatively few studies with children have investigated the relation between spatial anxiety and spatial skills compared to other domains, such as math and reading (e.g., for math, see Gunderson et al., 2018; Ramirez et al., 2013; Vukovic et al., 2013; for reading, see Calvo et al., 1992), studies in the spatial domain have supported the negative relation between spatial anxiety and spatial skills (Alvarez-Vargas et al., 2020; Geer et al., 2024; Lyons et al., 2018). For example, Lauer et al. (2018) tested spatial anxiety and spatial reasoning ability among children aged 6 to 12 years old (1st to 5th grades) and found that the negative correlation between spatial anxiety and spatial performance appeared even in the youngest children in this age range. However, some studies with younger children have failed to find a correlation between spatial anxiety and spatial skills (e.g., for first graders, Geer, 2021; for preschoolers, Ouyang et al., 2022; Wong, 2017). Also, a meta-analysis of the relation between spatial skills and spatial anxiety found that the effect size of the relation between spatial skills and spatial anxiety was smaller for younger samples (r = -.08, 95%, CI [-.15, -.02]), although not significantly different from adults (Geer et al., 2024).

In addition to studies on the direct association between spatial anxiety and spatial skills, studies from other perspectives can also support the influence of spatial anxiety on spatial skills. Ouyang et al. (2022) found children with lower levels of spatial anxiety showed a stronger association between spatial perception and subitizing skill than children with higher levels of spatial anxiety. One potential explanation of this moderating function of spatial anxiety is that children with low spatial anxiety may rely on spatial processing when dealing with math problems. Given emerging evidence of the relation between spatial anxiety and spatial skills, it is important to understand how spatial anxiety exerts its negative influence, and whether there are individual differences in the link between anxiety and performance.

Visuospatial Working Memory and Spatial Skills

Working memory (WM) can be separated into two components in terms of the content being processed and stored: visuospatial WM and verbal WM (Alloway et al., 2006; Repovš & Baddeley, 2006). Visuospatial WM temporarily maintains and processes action and visual-related information, whereas verbal WM temporarily maintains and processes verbalizable information (Cowan, 2017; Wang & Carr, 2014). Both visuospatial WM and verbal WM have limited capacity and show individual differences in that capacity (Barrett & Tugade, 2004; Conway & Engle, 1996; Shah & Miyake, 1996). Individual differences in visuospatial WM are consistently positively related to spatial skills (e.g., Garcia et al., 2022; Kaufman, 2007; Lehmann et al., 2014; Shah & Miyake, 1996). In contrast, studies of the relationship between spatial skills and verbal WM have shown mixed results. Some prior studies have found that children's mental rotation skill was related to their verbal WM measured by digit span tasks (Garcia et al., 2022; Lehmann et al., 2014). However, some adult studies have suggested verbal WM was not a predictor of mental rotation skill (Christie et al., 2013; Shah & Miyake, 1996). Even for studies showing that mental rotation skill is associated with both visuospatial WM and verbal WM, visuospatial WM contributes more to individual differences in mental rotation skill than verbal WM (Kaufman, 2007; Wang et al., 2018). Thus, both verbal WM and visuospatial WM might impact individuals' performance on spatial tasks and visuospatial WM might even matter more to spatial skill than verbal WM. Previous studies investigating the interactive effect of working memory and spatial anxiety on spatial skills have focused on verbal WM, however, few studies have examined whether there is an interactive effect of visuospatial WM and spatial anxiety on spatial skills. We aimed to investigate whether visuospatial WM interacts with spatial anxiety to affect spatial skills, similar to the previously-reported interaction between verbal WM and spatial anxiety on spatial skills (Ramirez et al., 2012).

When investigating the relationship between visuospatial WM and spatial skills, one inconsistency in prior studies is that some research treats visuospatial WM as a spatial skill whereas other research treats it as a domain-general ability that is separable from spatial skills. The present study considered that visuospatial WM and spatial skills, specifically mental transformation and mental rotation, are separable. Prior studies that used similar measures of visuospatial WM and spatial skill as the present study showed that modeling visuospatial WM and spatial skills as separate factors resulted in better model fit than loading them on one factor when conducting confirmatory factor analyses (Hawes et al., 2019; Miyake et al., 2001). Also, studies of individual differences in spatial skills have also considered visuospatial WM as a factor influencing spatial skills (Just & Carpenter, 1985; Lehmann et al., 2014). Thus, we considered visuospatial WM and spatial skills as separate factors in the present study, and further focused on how spatial anxiety and visuospatial WM interactively affect spatial skills.

Spatial Anxiety and Visuospatial WM

Compared to the links between spatial anxiety and spatial skills, and between visuospatial WM and spatial skills, the association between spatial anxiety and visuospatial WM is relatively under-investigated. However, the relationship between domain-general anxiety and WM has been widely studied. A meta-analysis of 177 studies showed that anxiety is negatively associated with both verbal WM and visuospatial WM (Moran, 2016). Domain-general anxiety has at least two distinct components, worry and anxiety arousal (Heller & Nitschke, 1998; Nitschke et al., 2001; York et al., 1987). Worry refers to verbal ruminations and negative thinking, whereas anxiety arousal refers to the physiological hyperarousal and somatic tension in response to perceived stressors. According to processing efficiency theory, worry specifically affects verbal WM (and not visuospatial WM) because worry is verbally coded and occupies verbal WM (Eysenck & Calvo, 1992; Eysenck et al., 2007). On the other hand, Shackman et al. (2006) proposed that anxiety arousal limits the neural resources of visuospatial WM due to the overlapping brain regions involved in anxiety and visuospatial WM in the right prefrontal cortex and posterior parietal cortex. Consistent with this, Shackman et al. (2006) found that anxiety arousal was negatively related to visuospatial WM but not verbal WM for undergraduates. Taken together, theory and evidence suggest that both verbal WM and visuospatial WM may be impaired by anxiety. Within the spatial skills domain, recent meta-analytic evidence confirms a small but significant negative correlation between spatial anxiety and visuospatial WM, primarily among adults (r = -.09; Geer et al., 2024). However, this relation remains underexplored in children. It is possible that the relation between spatial anxiety and visuospatial WM might not yet be established or be unstable for young children, as their visuospatial WM is still developing (Alloway et al., 2006).

Exploring whether spatial anxiety negatively relates to visuospatial WM for 1st to 4th graders can contribute to our understanding of the development of the interaction between visuospatial WM and spatial anxiety.

Spatial Anxiety, Visuospatial WM, and Spatial Skills

A well-established theory about how anxiety and WM might interact to influence performance is that anxiety takes up WM resources, reducing the available WM capacity for processing cognitive tasks, which leads to poorer performance (Ashcraft & Kirk, 2001; Beilock & DeCaro, 2007; Ramirez et al., 2012, 2013, 2016). This theory has been tested primarily in the math domain. Ashcraft and Kirk (2001) showed that undergraduates with high math anxiety had lower verbal WM (measured by computational digit span) and poorer mental calculation performance than undergraduates with low math anxiety. Furthermore, researchers have examined whether anxiety leads to a change in strategy use from higher- to lower-WM-demanding strategies in adults. Beilock and DeCaro (2007) manipulated the level of pressure to investigate the causal effect of induced anxiety on mathematics strategy use. They found that, under low pressure, individuals with high WM used WM-demanding strategies to perform well. However, under high pressure, high-WM individuals switched to using simpler strategies that relied less heavily on WM and thus performed more poorly. In contrast, individuals with low WM used low-WM-demanding strategies under both low and high pressure, and therefore performed similarly regardless of the pressure manipulation. This evidence suggests that when pressure restricted the available WM capacity, individuals switched to low-WM-demanding strategies and showed poor performance.

Building on this work in adults, researchers have examined math anxiety, WM, and mathematics strategy use in young children (Ramirez et al., 2013, 2016). As with adults, researchers theorized that when children have high WM capacity, those with low anxiety would tend to successfully rely on WM-intensive strategies, but when high-WM children have high anxiety, their WM capacity would be limited by anxiety, making them unable to use WM-intensive strategies. In contrast, for children with low WM capacity, their available WM may not be able to support WM-intensive strategies no matter their level of anxiety. Ramirez et al. (2013) examined this among 1st and 2nd-graders and showed that the correlation between math anxiety and lower math performance was significant only for children with high verbal WM but not for children with low verbal WM. Moreover, Ramirez et al. (2016) tested arithmetic strategies, math anxiety, verbal WM, and math performance for children in 1st and 2nd grades. This study found that high math anxiety was associated with more basic arithmetic strategies that rely less on WM, but that this was only the case for children with high verbal WM. When their working memory was not restricted by anxiety, high-verbal-WM children used advanced arithmetic strategies high in WM demand.

There is also some evidence from the math domain of a similar effect of visuospatial WM capacity on the anxiety-performance relation, at least for types of math tasks that benefit from spatial strategies (Cuder et al., 2023). In a recent study, Cuder et al. (2023) assessed Italian primary school students and found that the negative relation between math anxiety and math fluency was stronger for high- than low- visuospatial-WM students. The math fluency task involved vertically formatted addition and subtraction problems under a time limit, and the authors suggested that math anxiety hinders the use of visuospatial-WM-intensive strategies, such as mentally aligning the columns and the decomposition of operands in digits, on these problems. This result is consistent with the theory that math anxiety impedes visuospatial WM, which was most detrimental to the performance of students high in visuospatial WM.

Only a few studies have tested whether the interaction of anxiety and working memory on performance is present in the spatial domain. Ramirez et al. (2012) tested spatial anxiety, spatial achievement, and verbal WM for children in 1st and 2nd grades, and found interactive effects between spatial anxiety and verbal WM on mental transformation skills. That is, only for children with higher verbal WM, higher spatial anxiety was significantly related to poorer mental transformation skills. They also analyzed these effects separately for girls and boys, and found that only girls showed this significant interaction, but not boys. They theorized that high-verbal-WM girls rely on verbal-WM-intensive strategies which can be disrupted by anxiety-induced verbal ruminations, which then lead to poorer mental transformation performance. On the other hand, they argued that boys are more likely to rely on visuospatial-WM-intensive strategies which were not impaired by verbal ruminations, and thus, the spatial performance of both high-verbal-WM and low-verbal-WM boys were not influenced by their anxiety.

However, a similar study by Lauer et al. (2018), which examined visuospatial WM instead of verbal WM, did not replicate these findings. In a sample of 1st to 6th graders, Lauer et al. (2018) found no significant interaction between spatial anxiety, visuospatial WM, and gender on mental transformation skill, after controlling for grade level. These mixed results raise the possibility that spatial anxiety may be more disruptive to verbal WM than to visuospatial WM. Nonetheless, the wide age range in Lauer et al. (2018) could have masked developmental changes, as both visuospatial WM and spatial reasoning undergo rapid development across early and middle childhood. The interaction between spatial anxiety and visuospatial WM on spatial performance may thus vary with age—a possibility we discuss in the next section.

The Development of Spatial Anxiety, Visuospatial WM, and Spatial Skills

The primary school years represent a crucial period for children's cognitive development. Regarding visuospatial WM, Alloway et al. (2006) found large age-related improvements in working memory in a sample of 709 children aged 4 to 11 years. The average visuospatial WM level for 6.5-year-old children (approximately first grade) was a *z*-score of approximately -0.5, with a steady increase over age. By the age of 9.5 years (approximately fourth grade), the average visuospatial WM level reached a *z*-score of approximately 0.8, indicating a large increase of 1.3 *SD* during these three years. Similar developmental trajectories of visuospatial WM have been observed in other studies (Alloway & Alloway, 2013; Roberts et al., 2018; Swanson, 2017). In parallel, spatial abilities in primary school children also show significant improvement during this period (Hawes et al., 2015). The present study aimed to investigate the relationships among spatial anxiety, visuospatial WM, and spatial skills across 1st to 4th grades, given that children's WM and spatial skills are still developing during these years.

We predicted that the interactive effect between visuospatial WM and spatial anxiety on spatial skill would be stronger among older children than younger children. In order to compare with the findings of Ramirez et al. (2012) for verbal WM, Lauer et al. (2018) analyzed the 1st and 2nd graders separately from the full sample and found no interaction between visuospatial WM and spatial anxiety in predicting spatial skills. We reasoned that among younger children (e.g., 1st and 2nd graders), even those with high visuospatial WM for their age may still lack the visuospatial WM necessary to use effective spatial strategies, no matter their levels of spatial anxiety. Yet, older children with high visuospatial WM should be able to use visuospatial WM-intensive strategies when they have low spatial anxiety. But when high-visuospatial-WM older children have high spatial anxiety, their spatial performance may be affected because anxiety restricts their visuospatial WM and impairs their visuospatial-WM-intensive strategies. Consistent with this, a longitudinal study of 6-8-year-olds found that the development of mental rotation was fully predicted by the developmental increase in working memory (measured as a composite of visuospatial WM and verbal WM; Zhang et al., 2022). This supports the notion that young children might not have sufficient working memory capacity to support effective strategies for mental rotation.

Mental Transformation and Mental Rotation

Strategy use plays a central role in theories of why spatial anxiety (Lourenco & Liu, 2023) and WM (Wang & Carr, 2014) predict spatial skills. However, several widely-used measures of spatial skills that are often considered interchangeable differ substantially in the types of strategies that can lead to success. Specifically, some spatial tasks can be solved successfully by using either analytical strategies, such as mentally labeling and matching features (e.g., “the pointy part”, “the curvy part”), or visuospatial strategies such as mentally simulating rotation; we refer to these tasks as measuring *mental transformation*. Two commonly-used mental transformation tasks include the Children's Mental Transformation Task (Levine et al., 1999), in which children need to mentally combine two 2-D images into a single shape and choose the complete shape from four choices, and the Thurstone task (Thurstone, 1938), in which children are asked to choose which one of four shapes would form a square when put together with a target. These mental transformation tasks have been used in prior research showing a relation between children's spatial anxiety and spatial skills (Lauer et al., 2018; Ramirez et al., 2012).

However, analytical strategies like feature-matching cannot be used successfully in some other spatial tasks, such as the Letter Rotation task (Quaiser-Pohl et al., 2014), in which a rotated letter or number is presented, and children need to decide whether the stimulus was mirror-reversed or not. We refer to these tasks, which eliminate feature-matching strategies by employing mirror-reversed images as foils, as measuring *mental rotation*. Mental rotation tasks are expected to load heavily on visuospatial WM and spatial strategies since analytical strategies, such as feature-matching, cannot lead to a correct answer. We predicted that performance in both mental transformation and mental rotation tasks would be impaired by spatial anxiety for high-visuospatial-WM individuals, because both types of tasks can be solved by relying on visuospatial-WM-intensive strategies. However, performance on mental rotation tasks might be more related to spatial anxiety and visuospatial WM, because mental rotation tasks require spatial strategies for optimal performance, whereas mental transformation tasks can be solved effectively using either verbal-WM-intensive or visuospatial-WM-intensive strategies.

The Present Study

The current study examined whether U.S. children's spatial anxiety interacts with visuospatial WM to predict lower spatial performance. We predicted that, among high-visuospatial-WM individuals, spatial anxiety would be negatively associated with spatial performance. This is based on the theory that high-visuospatial-WM individuals primarily rely on visuospatial-WM-intensive strategies under low spatial anxiety conditions, but when their visuospatial-WM is restricted by high spatial anxiety, these visuospatial-WM-intensive strategies would be disrupted, leading to poorer performance. In contrast, we theorized that low-visuospatial-WM individuals would not rely on visuospatial-WM-intensive strategies, and would therefore not show strategy disruptions under conditions of anxiety. Therefore, low-visuospatial-WM individuals would not show the relation between spatial anxiety and spatial performance.

Second, we predicted that the interactive effect of spatial anxiety and visuospatial-WM on spatial skills would be more pronounced among older students than younger students (i.e., we predicted an interaction between spatial anxiety, visuospatial-WM, and grade level on spatial skills). This is because, compared to younger children, older children's visuospatial-WM is higher (Alloway et al., 2006), which increases the possibility of using visuospatial-WM-intensive strategies under low anxiety. This would, in turn, increase the association between anxiety and performance among older, high- visuospatial-WM children.

Third, we explored whether the spatial anxiety and visuospatial-WM interaction would occur in the same way for mental transformation and mental rotation. Because mental rotation tasks must be solved using visuospatial-WM-intensive strategies, and mental transformation tasks may be solved using visuospatial-WM- or verbal-WM-intensive strategies, we predicted that the mental rotation task would show a stronger interactive effect between spatial anxiety and visuospatial-WM than the mental transformation task. We focused our study on children in grades 1 to 4 of primary school (typically ages 6 to 10 years). We chose this age range based on prior research showing that the relationship between spatial anxiety and spatial performance emerges at the start of primary school, but not before (Lauer et al., 2018; Wong, 2017). Further, understanding the early predictors of individual differences in spatial skills is important for setting children onto positive trajectories in spatial skill development at the start of formal schooling.

Method

Participants

The participants were 402 U.S. children in 1st to 4th grades (first grade: N = 111 (51 boys, 60 girls); second grade: N = 103 (45 boys, 58 girls); third grade: N = 106 (49 boys, 57 girls); fourth grade: N = 82 (31 boys, 51 girls)). These children were assessed at the third time-point of a larger longitudinal study (Gunderson & Hildebrand, 2021; Ren et al., 2019; Tian et al., 2022). We examined the third time-point because it was the only time at which spatial anxiety was assessed. From the larger study, we excluded kindergarten children (N = 83) because they were tested using different spatial skills tasks than the 1st to 4th-graders, who all completed the same tasks. We also excluded children whose grade level was not recorded (N = 1), had repeated a grade (N = 1), or did not complete at least one of the focal measures in the current study (N = 2).

Parents reported their children's demographic information. The analytic sample was 43.5% Black or African American, 17.4% White, 11.4% Hispanic, 9.7% Multiracial, 4.0% Asian or Asian American, 0.2% American Indian or Alaskan

Native, 0.2% Native Hawaiian or Other Pacific Islander, 0.2% Other, and 13.2% not reported. The highest education of either parent averaged 14.72 years, where 14 years refers to an Associate's degree (SD = 2.38, $N_{education}$ = 351). The annual family income averaged \$48,592 (SD = \$31,138, N_{income} = 332).

Procedure and Materials

Children completed two one-on-one testing sessions under the administration of a trained experimenter. The time between the two sessions averaged 4.37 days (SD = 3.46 days). The mental transformation, mental rotation, and visuospatial working memory tasks were completed in one of four randomly-assigned pseudorandom orders. Because it was supplementary to the core task battery, spatial anxiety was always assessed as one of the final three measures in the second session.

Mental Transformation

To test children's mental transformation skill, we used the Mental Rotation subtest of Thurstone's Primary Mental Abilities (PMA) test (Thurstone, 1938). Children were asked to choose which one of four shapes would form a square when put together with the target shape. First, children were shown a square and a rectangle and told the definition of each shape by the experimenter. Then, children practiced four trials with feedback. After practicing, children completed 16 testing trials without feedback. Percentage accuracy was recorded. The internal consistency was low (McDonald's $\omega_{\text{first grade}}$ = 0.54, $\omega_{\text{second grade}}$ = 0.64, $\omega_{\text{third grade}}$ = 0.51, and $\omega_{\text{fourth grade}}$ = 0.57).

Mental Rotation

We used the Letter Rotation task (Quaiser-Pohl et al., 2014) to measure children's mental rotation skill. Children were asked to choose which two of the four rotated letters matched the target letter. Two of the choices were rotated mirror images of the target letter and two were rotated target letters. First, children were shown two examples with the correct answers provided and practiced two trials with feedback. Then, children completed 16 testing trials without feedback. Percentage accuracy was recorded. The internal consistency was good for all four grades (McDonald's $\omega_{\text{first grade}}$ = 0.86, $\omega_{\text{second grade}}$ = 0.88, $\omega_{\text{third grade}}$ = 0.82, and $\omega_{\text{fourth grade}}$ = 0.82).

Visuospatial Working Memory

We used the Dot Matrix subtest of the Automated Work Memory Assessment (Alloway, 2007) to assess children's visuospatial WM capacity. The Dot Matrix task is a spatial span task that involves the sequential storage of spatial locations without an explicit processing requirement. We used a spatial span task because, for young children like those in our study, this type of task serves as a proxy for visuospatial WM while minimizing task complexity and reducing confounding factors like language or executive interference (e.g., Simms et al., 2015). Although some scholars have argued that spatial span tasks may reflect visuospatial short-term memory more so than working memory (e.g., Alloway et al., 2005), others suggest that they still engage domain-specific working memory resources, particularly when they involve increased memory load and sequencing demands (e.g., Conway et al., 2003). In each trial of this task, a 4 X 4 grid was shown on the computer, and red dots appeared in a sequence of locations on the grid, one at a time. Then children were asked to point to where the dots appeared in order. The number of dots started from one and increased by one dot. Each number of dots continued for six trials. The task ended when children incorrectly answered three consecutive trials with the same number of dots. We used the raw score and normed standardized score of this task to record children's performance.

Spatial Anxiety

We used an 8-item questionnaire (Ramirez et al., 2012) to measure children's spatial anxiety. In this task, children were asked, for example, "How do you feel when a friend asks you how to get from school to your house?". See Appendix, Figure A1 for all items. Children were asked to point to one of five emotion faces ranging from "not nervous at all, very calm" (far left, scored 1) to "very, very nervous" (far right, scored 5) to indicate their response. The internal consistency was low in the current sample (McDonald's $\omega_{\text{first grade}}$ = 0.66, $\omega_{\text{second grade}}$ = 0.63, $\omega_{\text{third grade}}$ = 0.46, and $\omega_{\text{fourth grade}}$ = 0.58).

Missing Data

For each measure, if participants skipped more than half of the items, their data were excluded. There were no missing data on grade or gender. The percentage of missing data was 25.6% for spatial anxiety, 6.5% for visuospatial working memory, 7.5% for mental transformation, and 3.5% for mental rotation. To test the randomness of the missing data, we conducted the Little's missing completely at random (MCAR) test. The result of the MCAR test suggested that the current data is missing completely at random, $\chi^2(180) = 200.42$, $p = .142$. Participants' data were included in an analysis if they had complete data for that analysis.

Analytic Approach

Before our main analyses, we examined the normality and skewness of each measure. The absolute value of skewness and kurtosis of each measure was less than two, and based on visual inspection of histograms, the distribution of each measure was approximately normal with no obvious outliers. Thus, we did not exclude any cases. To analyze the interactive effect of spatial anxiety and visuospatial WM on spatial skills within each grade, we standardized scores within each grade and used these standardized scores in our main analysis.

Results

Preliminary Analyses

Table 1 and Table 2 show the descriptive statistics of each measure by grade, prior to standardization within grade level. We conducted one-way ANOVAs to test for differences across grade levels. There was no significant grade-level difference in spatial anxiety ($F[3, 159.78] = 1.52$, $p = .212$, est.$\omega^2 = 0.004$)[1], while the grade-level differences in visuospatial WM, mental transformation, and mental rotation skills were significant (visuospatial WM: $F[3, 372] = 45.89$, $p < .001$, $\eta_p^2 = 0.270$; mental transformation: $F[3, 368] = 16.27$, $p < .001$, $\eta_p^2 = 0.117$; mental rotation: $F[3, 208.46] = 33.66$, $p < .001$, est.$\omega^2 = 0.196$).

Table 1

Descriptive Statistics of All Measures for the Sample Overall

Variable	*N*	*M*	*SD*	Skewness	Kurtosis
Age (Years)	402	8.02	1.44	-1.52	7.66
Spatial Anxiety	299	2.72	0.78	0.11	-0.22
Visuospatial WM (Raw Score)	376	17.35	4.91	-0.24	0.19
Mental Transformation (Accuracy)	372	0.59	0.17	-0.24	-0.08
Mental Rotation (Accuracy)	388	0.57	0.29	-0.25	-1.30

The associations among all measures (standardized within grade level) are presented in Table 3. Girls' spatial anxiety (*M* = 0.09, *SD* = 0.99) did not significantly differ from boys' (*M* = -.11, *SD* = 0.99), $t(297) = 1.73$, $p = .084$, $d = .20$. Also, there were no significant gender differences in visuospatial WM (girls: *M* = -0.05, *SD* = 0.94; boys: *M* = 0.06, *SD* = 1.07; $t(332.25) = 0.97$, $p = .331$, $d = .10$), mental transformation (girls: *M* = -0.06, *SD* = 0.93; boys: *M* = 0.08, *SD* = 1.07; $t(370) = 1.35$, $p = .178$, $d = .14$), or mental rotation (girls: *M* = -0.07, *SD* = 0.96; boys: *M* = 0.09, *SD* = 1.04; $t(386) = 1.51$, $p = .133$, $d = .15$).

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1) Because the Levene's tests suggested the variances were unequal for spatial anxiety and mental rotation, we conducted Welch's one-way ANOVA tests and used est.ω^2 as the effect size.

Table 2

Descriptive Statistics of All Measures by Grade Level

	1st grade			2nd grade			3rd grade			4th grade		
Variable	***N***	***M***	***SD***	***N***	***M***	***SD***	***N***	***M***	***SD***	***N***	***M***	***SD***
Age (Years)	111	6.61	0.74	103	7.66	0.29	106	8.61	1.26	82	9.63	1.17
Spatial Anxiety	88	2.77	0.89	87	2.75	0.80	64	2.79	0.64	60	2.55	0.68
Visuospatial WM (Raw Score)	105	14.02	4.43	98	16.63	4.42	101	18.85	3.96	72	21.08	3.94
Mental Transformation (Accuracy)	108	0.51	0.16	99	0.58	0.17	98	0.62	0.15	67	0.66	0.13
Mental Rotation (Accuracy)	108	0.38	0.27	100	0.58	0.29	104	0.66	0.24	76	0.72	0.23

Table 3

Correlations Among All Measures

Variable	**1**	**2**	**3**	**4**	**5**
1. Gender (0 = girls, 1 = boys)	–				
2. Spatial Anxiety	-.10 (*n* = 299)	–			
3. Visuospatial WM	.05 (*n* = 376)	-.06 (*n* = 286)	–		
4. Mental Transformation	.07 (*n* = 372)	-.10 (*n* = 281)	.28*** (*n* = 349)	–	
5. Mental Rotation	.08 (*n* = 388)	-.01 (*n* = 290)	.14** (*n* = 363)	.37*** (*n* = 388)	–

Note. The scores of spatial anxiety, visuospatial WM, mental transformation, and mental rotation were standardized within grade-level.
**$p < .01$. ***$p < .001$.

Main Analyses

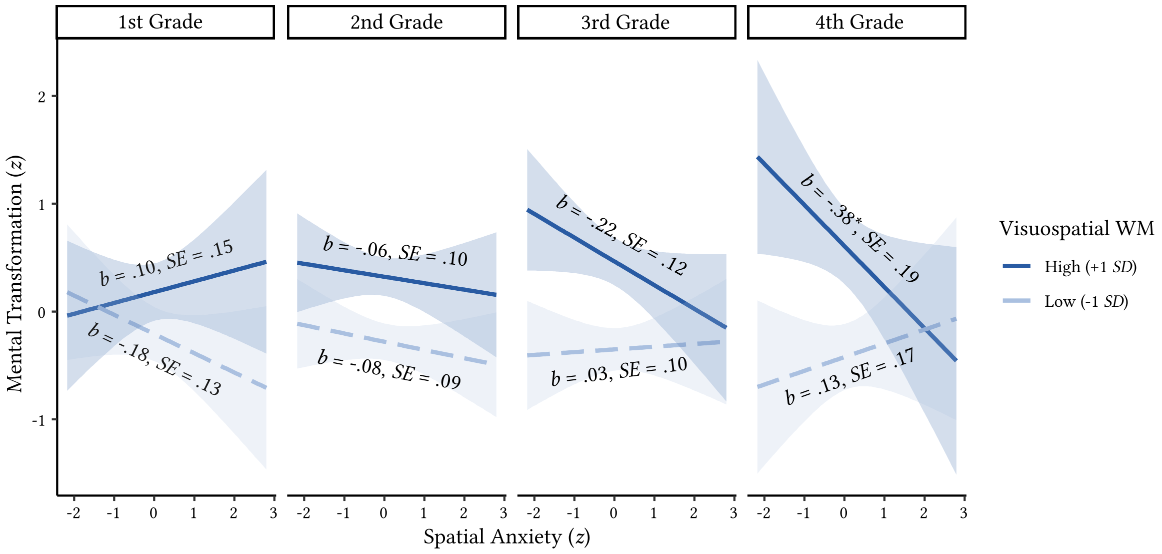
Mental Transformation

To examine our main hypotheses, we regressed children's mental transformation scores on their grade level, spatial anxiety scores, visuospatial WM scores, and their interactions (see Appendix, Table B1 for full regression results with listwise deletion, and Table B3 for full regression results with full information maximum likelihood [FIML] estimation). All predictors were treated as continuous variables. There was a significant main effect of visuospatial WM (β = .34, t = 5.56, p < .001), but no significant main effect of spatial anxiety (β = -.08, t = -1.28, p = .203). However, the results of the regression model showed a significant interactive effect of grade level, spatial anxiety, and visuospatial WM on mental transformation (β = -.14, t = -2.02, p = .044). To interpret this three-way interaction. We performed simple slope analyses to test the slopes of spatial anxiety on mental transformation within each grade level for individuals who were low (1 *SD* below the mean) versus high (1 *SD* above the mean) in visuospatial WM, and plotted these estimated effects in Figure 1A. We found that spatial anxiety was significantly negatively associated with mental transformation for fourth graders with high visuospatial WM (b = -0.38, t = -2.04, p = .04) but not for fourth graders with low visuospatial WM (b = 0.13, t = 0.76, p = .45). For students younger than fourth grade, the association between spatial anxiety and mental transformation did not significantly differ from zero for students with low or high visuospatial WM.

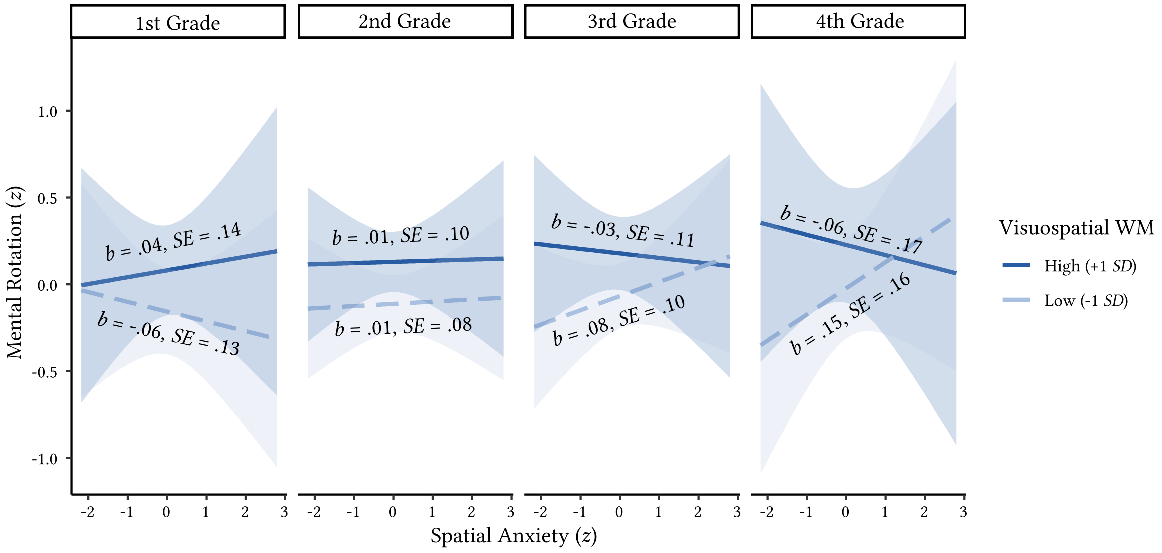
Figure 1

Model-Estimated Values of the Relationships Among Children’s Spatial Anxiety, Visuospatial WM, and (A) Mental Transformation Skill as well as (B) Mental Rotation Skill Within Grade Level

A. Model-estimated effect on mental transformation



B. Model-estimated effect on mental rotation



Note. Model-estimated values are based on regression model results (see Appendix Tables B1 and B2). All measures are standardized within grade level. Visuospatial WM is plotted at one standard deviation below and above the average level. Only in fourth grade, children with high visuospatial WM showed a significant negative association between spatial anxiety and mental transformation. No statistically significant interactive effect between spatial anxiety and visuospatial WM on mental rotation was found in any grade.

$^{*}p < .05$.

Mental Rotation

We also conducted the same regression analyses for children's mental rotation scores (see Appendix, Table B2 for full regression results with listwise deletion, and Appendix, Table B4 for full regression results with FIML estimation). Similarly to mental transformation, the results showed a significant main effect of visuospatial WM (β = .12, t = 2.04, p = .043), but no significant main effect of spatial anxiety (β = .02, t = .86, p = .777). However, unlike for mental transformation, the results for mental rotation showed a non-significant interactive effect of grade level, spatial anxiety, and visuospatial WM (β = -.06, t = -.83, p = .406). Further, when performing the simple slope analyses within each grade level, at high versus low levels of visuospatial WM, none were significantly different from zero. Nevertheless, we note that, when visualizing the results for mental rotation (see Figure 1B), the pattern is similar as for mental transformation, but less pronounced and with greater variability.

Discussion

Spatial anxiety and WM are important sources of individual differences in spatial skills, and the present study adds to the evidence that this anxiety-performance link varies by children's WM capacity. Specifically, we found an interaction among spatial anxiety, visuospatial WM, and grade level on mental transformation skill. This suggests that U.S. children with higher visuospatial WM and in higher grade levels are more affected by spatial anxiety than children with lower visuospatial WM and in lower grade levels. This finding is consistent with the theory that anxiety arousal competes with visuospatial WM for neural resources and disrupts the usage of visuospatial WM-intensive strategies in spatial tasks. However, we did not find the interactive effect between spatial anxiety, visuospatial WM, and grade for mental rotation skill. Below, we discuss each of these findings in turn.

The Interaction of Spatial Anxiety, Visuospatial WM, and Grade on Mental Transformation

The first main finding of this study was the significant three-way interaction of children's spatial anxiety, visuospatial WM, and grade level on mental transformation performance. By fourth grade, high- visuospatial-WM children showed a negative relation between spatial anxiety and mental transformation performance, whereas low- visuospatial-WM children did not. However, this relation was not present in first to third grades. Considering the grade difference in visuospatial WM and the significant main effect of visuospatial WM on mental transformation performance, one possible explanation for this is that older children may be more capable than younger children of adopting effective visuospatial-WM-intensive strategies in mental transformation tasks when their spatial anxiety is low. When older children with high visuospatial WM have high spatial anxiety, their available visuospatial WM is impaired by spatial anxiety, so they need to adopt less-efficient strategies, such as comparing partial features between the target and choices, leading to lower mental transformation performance. However, among younger children, those with higher visuospatial WM than their cohorts may still not have sufficient visuospatial WM capacity to deploy visuospatial-WM-intensive strategies, meaning that they would need to use lower- visuospatial-WM-intensive strategies regardless of their level of spatial anxiety. Thus, because they are capable of more advanced strategies, older children's mental transformation performance is more susceptible to the anxiety-induced impairments than younger children's performance.

Further, the interaction between spatial anxiety and visuospatial WM on mental transformation skill supports the theory that spatial anxiety restricts available visuospatial WM and impairs the visuospatial-WM-intensive strategies that are typically used by high-visuospatial-WM children. Combined with prior findings on verbal WM (Ramirez et al., 2012) and visuospatial WM (Lauer et al., 2018), our results indicate that spatial anxiety may impair not only verbal WM but also visuospatial WM. Although Lauer et al. (2018) did not find an interactive effect of spatial anxiety and visuospatial WM on spatial performance, they did not test whether this relation changed with age; together with our findings, these results suggest that the effect of spatial anxiety on visuospatial WM may only be significant for older children. There are at least two possible accounts that would explain these findings. One possibility is that visuospatial WM and verbal WM might be affected separately by different components of anxiety. Some prior work suggests that visuospatial WM is restricted by anxiety arousal because anxiety arousal activates the right prefrontal cortex and posterior parietal cortex which overlap with brain areas of visuospatial WM (Shackman et al., 2006). In contrast, verbal WM is restricted by the worry component of anxiety, such that verbal WM resources are taken up by worry-induced verbal ruminations (Eysenck & Calvo, 1992; Eysenck et al., 2007). A second possibility is that spatial anxiety might impair the central executive function of working memory. If so, then both verbal-WM-intensive and visuospatial-WM-intensive strategies might be impaired at the same time due to the impaired central executive. The results of this study cannot exclude either of these possibilities since we did not test central executive function or verbal WM. In future studies, visuospatial WM, visuospatial WM and central executive functioning should be tested at the same time to examine these possibilities directly.

The Lack of Interaction of Spatial Anxiety, Visuospatial WM, and Grade on Mental Rotation

In addition to mental transformation skill, we also investigated the interactive effect of spatial anxiety and visuospatial WM on mental rotation skill. We had predicted that the interactive effect between spatial anxiety and visuospatial WM would be stronger for mental rotation than for mental transformation. This was based on the assumption that the mental rotation task should rely more on visuospatial WM, because mental rotation tasks are less likely to be solved by analytical strategies such as feature-matching than mental transformation tasks. However, we did not find the expected interactive effect between spatial anxiety, visuospatial WM, and grade level on the mental rotation task. Nevertheless, it is worth noting that, although not significant, the pattern of relations between spatial anxiety and visuospatial WM on mental rotation was similar to the pattern of relations with mental transformation among fourth graders (see Figure 1). We speculate that the interactive effect between spatial anxiety and visuospatial WM on mental rotation for fourth graders might exist but with a smaller effect size, such that our study was underpowered to detect it. This non-significant result might be due to the larger variance in mental rotation skill than mental transformation skill in the current sample, and the weaker correlation between visuospatial WM and mental rotation compared to the correlation between visuospatial WM and mental transformation. Both of these factors may have made it more difficult to detect the expected effects in mental rotation performance than mental transformation performance.

Another potential explanation for this is that children's spatial anxiety may have been less aroused during the mental rotation task than the mental transformation task. This is plausible given that the stimuli in the mental rotation task were letters, which might be perceived as a verbal task (rather than spatial) and therefore fail to arouse spatial anxiety. This possibility is in line with findings in the math domain that visuospatial WM moderated the link between math anxiety and math performance only in math tasks that required spatial presentation and processes (Ashkenazi & Danan, 2017; Cuder et al., 2023). Future studies should use mental rotation tasks that have more spatial elements to re-examine the interactive effect on mental rotation skill. Also, exploring how children perceive tasks and what types of tasks elicit spatial anxiety might contribute to our understanding of the relationship between spatial anxiety, visuospatial WM, and spatial skills.

Limitations

This study has several limitations. First, we did not test two components of working memory, verbal WM and central executive function. Consequently, we cannot directly compare the anxiety-induced impairments on verbal WM, visuospatial WM, and central executive function. Nevertheless, we, for the first time, showed that the relation between spatial anxiety and spatial performance depends on visuospatial WM, building on prior work finding this effect for verbal WM. Further studies could measure all components of working memory to explore whether anxiety affects verbal WM and visuospatial WM at the same time by restricting the central executive function, or separately via different mechanisms. Additionally, we did not assess children's general anxiety during testing, which limits our ability to control and discern the effect of general anxiety on their performance. This limitation leaves the possibility that maybe both general anxiety and spatial anxiety impairs available visuospatial WM in spatial activities. Nevertheless, the primary aims of our study were to investigate the possibility that visuospatial WM may be restricted by spatial anxiety in a similar fashion as verbal WM in spatial activities and to examine developmental change in this interaction effect. The design of the current study is appropriate for these purposes. Future research should measure both general anxiety and spatial anxiety when exploring the roles of general anxiety and domain-specific anxiety in domain-specific performance.

Another limitation is that we did not directly measure the strategies children used in the spatial tasks. We theorize that children use different strategies depending on whether they have high- versus low- visuospatial-WM, based on prior studies in the math domain (Beilock & DeCaro, 2007; Ramirez et al., 2016) and prior theories in the spatial domain (Lourenco & Liu, 2023; Wang & Carr, 2014). It will be important for further studies in the spatial domain to investigate the difference in strategy use between individuals with high working memory and with low working memory, to directly examine whether and how spatial anxiety leads to changes in strategy use on spatial tasks. Finally, this study investigated grade-level differences via a cross-sectional, correlational design. Although this contributes to our understanding of how the association between spatial anxiety and performance varies between younger children and older children, this design does not allow us to determine causal relationships and cannot exclude the possibility of cohort differences as a potential explanation for differences between grade levels. Experimental designs and longitudinal studies are required to understand how anxiety and working memory affect spatial performance in the long term.

In addition, the reliability of the measure of mental transformation skill was low. This task was chosen because it has been used to measure children with the similar age range as the present study (Gunderson et al., 2012; Ramirez et al., 2012). One possible reason for the low internal consistency reliability is that this task may measure more than one latent factor because children may use different strategies to solve it. For example, children could use either analytical strategies (e.g., mentally labeling and matching spatial features), or visuospatial strategies (e.g., mentally rotation and composition); this differs from the mental rotation task, which by design prevents analytical strategies. Nevertheless, future research should examine the latent factors measured by this task and the individual differences in strategies used in this task and other spatial tasks.

Lastly, the spatial anxiety measured in the present study was not specific to small-scale spatial anxiety, and included items related to both small-scale (e.g., block building, shape analysis) and large-scale spatial thinking (e.g., navigation, maps). If there were a closer match between the measures of spatial anxiety and spatial skills, we may have found a stronger effect of spatial anxiety on spatial skills. Future research using more targeted measures of spatial anxiety, for example, adapting the mental manipulation subscale developed by Lyons et al. (2018) for children, may further illuminate the relations described here.

Conclusions

The current study explored the role of visuospatial WM in the spatial anxiety-performance link for U.S. 1st to 4th graders, a significant contribution to the understanding of the complex spatial anxiety-performance link. We showed that spatial anxiety interacts with visuospatial WM and grade level to predict mental transformation performance, and that the negative relation of spatial anxiety and mental transformation performance was present only for the oldest students in our sample (4th graders) who were high in visuospatial WM. This raises new theoretical questions regarding the mechanisms through which worry and anxiety arousal impact visuospatial WM and verbal WM, and how the spatial anxiety-performance link changes with age as a function of children's developing WM capacity and strategy use. This study also has practical implications by suggesting that children with different levels of spatial anxiety and working memory capacity may benefit from different types of interventions to alleviate the impacts of anxiety on performance.

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Ethics Statement: The ethical approval was obtained via Temple University Institutional Review Board.

Data Availability: Due to the fact that the current study is part of a longitudinal project with other ongoing research, the data cannot be made publicly available at this time. The data supporting the findings of this study can be requested from the corresponding author.

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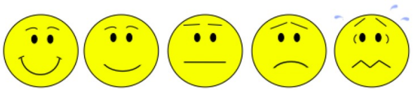
Appendices

Appendix A: Child Spatial Anxiety Questionnaire

Figure A1

The 8-Item Child Spatial Anxiety Questionnaire

Items	
1. How do you feel when you are asked to point to a certain place on a map, like this one? [Show card with image of US map.]	○ 1 ○ 2 ○ 3 ○ 4 ○ 5
2. How would you feel if you were given this problem: John is taller than Mary, and Mary is taller than Chris. Who is shorter, John or Chris?	○ 1 ○ 2 ○ 3 ○ 4 ○ 5
3. How do you feel being asked to say which direction is right or left?	○ 1 ○ 2 ○ 3 ○ 4 ○ 5
4. How do you feel when a friend asks you how to get from school to your house?	○ 1 ○ 2 ○ 3 ○ 4 ○ 5
5. How do you feel when you have to solve a maze like this in one minute? [Show child card with maze]	○ 1 ○ 2 ○ 3 ○ 4 ○ 5
6. How do you feel if you are asked to measure something with a ruler?	○ 1 ○ 2 ○ 3 ○ 4 ○ 5
7. How do you feel when your teacher asks you whether these shapes are rectangles and why? [Show child card with similar shapes]	○ 1 ○ 2 ○ 3 ○ 4 ○ 5
8. How would you feel if your teacher asked you to build this house out of these blocks in 5 min? [Show child card with picture of legos.]	○ 1 ○ 2 ○ 3 ○ 4 ○ 5

Note. Items are from Ramirez, G., Gunderson, E. A., Levine, S. C., & Beilock, S. L., 2012, Quarterly Journal of Experimental Psychology, 65, p. 474.
1 = not nervous at all, very calm, 2 = not very nervous, sort of calm, 3 = in the middle, 4 = a little nervous, 5 = very, very nervous.

Appendix B

Table B1

Regression Model Predicting Mental Transformation From Spatial Anxiety, Visuospatial WM, Grade Level, and Their Interactions, With Listwise Deletion

Predictor	**β**	***SE***	***p***
Intercept	0.04	0.06	.562
Grade	0.04	0.06	.532
Spatial anxiety	-0.08	0.06	.203
Visuospatial WM	0.34	0.06	< .001***
Grade x Spatial anxiety	-0.03	0.06	.610
Grade x Visuospatial WM	0.12	0.06	.065
Spatial anxiety x Visuospatial WM	-0.04	0.07	.512
Grade x Spatial anxiety x Visuospatial WM	-0.14	0.07	.044*
R^2 (%)	12.40		
F-stat	5.28***		
F-stat degrees of freedom	(7, 261)		

Note. Spatial anxiety, visuospatial WM, and mental transformation scores were standardized within grade level.
**p* < .05. ****p* < .001.

Table B2

Regression Model Predicting Mental Rotation From Spatial Anxiety, Visuospatial WM, and Grade Level and Their Interactions, With Listwise Deletion

Predictor	**β**	***SE***	***p***
Intercept	0.03	0.06	.649
Grade	0.05	0.06	.390
Spatial anxiety	0.02	0.06	.777
Visuospatial WM	0.12	0.06	.043*
Grade x Spatial anxiety	0.02	0.06	.736
Grade x Visuospatial WM	0.00	0.06	.972
Spatial anxiety x Visuospatial WM	-0.02	0.06	.718
Grade x Spatial anxiety x Visuospatial WM	-0.06	0.07	.406
R^2 (%)	2.05		
F-stat	.808		
F-stat degrees of freedom	(7, 270)		

Note. Spatial anxiety, visuospatial WM, and mental rotation scores were standardized within grade level.
**p* < .05.

Table B3

Regression Model Predicting Mental Transformation From Spatial Anxiety, Visuospatial WM, Grade Level, and Their Interactions, With FIML Estimation

Predictor	**β**	***SE***	***p***
Intercept	-0.01	0.05	.879
Grade	0.01	0.05	.841
Spatial anxiety	-0.08	0.06	.132
Visuospatial WM	0.29	0.05	< .001***
Grade x Spatial anxiety	-0.03	0.05	.594
Grade x Visuospatial WM	0.05	0.05	.262
Spatial anxiety x Visuospatial WM	-0.05	0.06	.841
Grade x Spatial anxiety x Visuospatial WM	-0.12	0.06	.044*
R^2 (%)	10.05		

Note. Spatial anxiety, visuospatial WM, and mental transformation scores were standardized within grade level.
$^{*}p < .05$. $^{***}p < .001$.

Table B4

Regression Model Predicting Mental Rotation From Spatial Anxiety, Visuospatial WM, and Grade Level and Their Interactions, With FIML Estimation

Predictor	**β**	***SE***	***p***
Intercept	< 0.01	0.05	.987
Grade	< 0.01	0.05	.958
Spatial anxiety	< 0.01	0.05	.998
Visuospatial WM	0.14	0.05	.008*
Grade x Spatial anxiety	0.01	0.05	.892
Grade x Visuospatial WM	-0.02	0.05	.625
Spatial anxiety x Visuospatial WM	-0.03	0.07	.640
Grade x Spatial anxiety x Visuospatial WM	-0.05	0.06	.390
R^2 (%)	2.35		

Note. Spatial anxiety, visuospatial WM, and mental rotation scores were standardized within grade level.
$^{*}p < .05$.

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