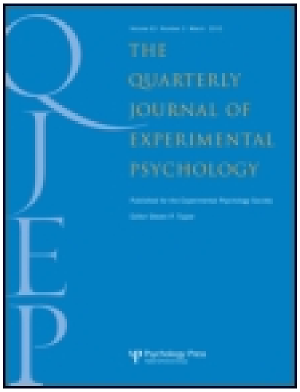

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Spatial anxiety relates to spatial abilities as a function of working memory in children

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Spatial ability is a strong predictor of students' pursuit of higher education in science and mathematics. However, very little is known about the affective factors that influence individual differences in spatial ability, particularly at a young age. We examine the role of spatial anxiety in young children's performance on a mental rotation task. We show that even at a young age, children report experiencing feelings of nervousness at the prospect of engaging in spatial activities. Moreover, we show that these feelings are associated with reduced mental rotation ability among students with high but not low working memory (WM). Interestingly, this WM × spatial anxiety interaction was only found among girls. We discuss these patterns of results in terms of the problem-solving strategies that boys versus girls use in solving mental rotation problems.

Keywords: Working memory; Spatial ability; Stress.

S*patial ability*—the ability to generate, retain, retrieve, and transform structured visual images (Casey, Nuttal, & Pezaris, 1997, 2001)—is a consistent predictor of student entry into science, technology, engineering, and mathematics (STEM) disciplines and careers, even after controlling for verbal and mathematical abilities (Benbow, Lubinski, Shea, & Eftekhari-Sanjani, 2000; Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009; Webb, Lubinski, & Benbow, 2007). Spatial ability predicts achievement in mathematics (Casey et al., 1997, 2001; Kyttälä, Aunio, Lehto, Van Luit, & Hautamäki, 2003) and the physical sciences (Humphreys, Lubinski, & Yao, 1993; Shea et al., 2001), and interventions that focus on improving spatial thinking have been shown to be effective at increasing success in engineering courses (Sorby, 2009).

Importantly, there are individual differences in spatial ability, and these differences emerge at a young age (Levine, Huttenlocher, Taylor, & Langrock, 1999). Given the importance of spatial ability for maths and science achievement, there has been an interest in understanding the biological (Hampson, 1995; Nelson, Lee, Gamboa, Roth, 2008) and experiential (Ebbeck, 1984; Levine,

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Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005; Newcombe & Sanderson, 1993) factors that contribute to variation in spatial ability. However, little work has examined how spatial ability is influenced by emotional (i.e., affective) factors. The present study examines whether students' anxiety about performing spatial tasks (what we refer to as spatial anxiety) relates to their spatial ability and, if so, whether this relation holds for all students or for particular subgroups of students. Understanding spatial anxiety and its relation to spatial ability may provide a new way of thinking about individual differences in spatial ability and eventually lead to interventions designed to decrease spatial anxiety and increase levels of spatial ability as well as achievement in STEM disciplines.

Ability and affect

We begin by exploring the relationship between affect and ability in mathematics, an achievement domain for which there has been extensive research on how situational stress brought on by evaluative pressures (Beilock & Carr, 2005), by a fear of mathematics (Ashcraft & Kirk, 2001), and by a fear of confirming an existing negative stereotype (Steele & Aronson, 1995) can lead to impairments in students' performance on difficult maths problems. These different stressors have been shown to impact performance by creating worries that interfere with working memory (WM), a short-term memory store involved in actively holding information in mind that is needed to complete complex tasks (Engle, 2002). Since WM processes are vital for ensuring optimal performance in maths, and individuals are limited in WM (Engle, 2002), worries related to performance failure can lead to performance decrements by forcing individuals to work under a dual mindset, where they must focus on the task at hand while attempting to inhibit irrelevant thoughts (Beilock, 2008, 2010).

Despite the relevance of spatial thinking in STEM achievement, only a few studies have translated the above-mentioned research on affect and maths into the domain of space—a domain that is strongly tied to maths and science (e.g., Casey et al., 1997; Wai et al., 2009). Nonetheless, there is some indication that, similar to maths performance, affective factors can derail spatial performance. For instance, it has been shown that women's performance on spatial tasks can be negatively impacted by the fear of confirming an existing gender stereotype about spatial abilities (Campbell & Collaer, 2009; Martens, Johns, Greenberg, & Schimel, 2006; McGlone & Aronson, 2006). Also, anxiety related to navigation has been found to be negatively associated with the use of an efficient orientation strategy while navigating one's environment (Lawton, 1994).

If spatial anxiety is negatively related to spatial performance in a similar way that maths anxiety is related to maths performance, then one might ask whether the mechanism for these relations is the same. As mentioned above, maths anxiety is thought to be negatively related to maths performance, in part, by leading to an online decrement in working memory. If the same is true for space, then some interesting predictions can be made. For instance, as in maths anxiety and maths performance, the relationship between spatial anxiety and performance on a spatial task may differ as a function of individual differences in WM.

Previous work on maths anxiety and choking under pressure in maths has shown that individuals with higher WM are actually the most affected by stress-related worries (Beilock & Carr, 2005; Ramirez, Gunderson, Levine, & Beilock, 2009). This is because high-WM individuals tend to rely heavily on WM-demanding problem-solving strategies such as difficult algorithms, which can fail under the burden of stress (Beilock & DeCaro, 2007). In contrast, low-WM individuals are less susceptible to performance decrements under stressful environments since they often rely on heuristic strategies that place a low demand on WM to begin with. Thus, based on prior findings on maths anxiety and maths performance, we predict that spatial anxiety will be negatively related to spatial ability and that this relationship will be particularly pronounced among those with higher WM.

Moreover, since anxiety can create worries that are verbal in nature (Beilock, 2010), and some students use verbal strategies while others use spatial strategies when solving tasks that tap spatial ability (e.g., mental rotation), another prediction can be made regarding the relation between spatial anxiety and spatial ability. Specifically, those students who rely heavily on verbal strategies to solve mental rotation problems should show the strongest relation between spatial anxiety and performance.

Interestingly, problem-solving strategy differences are precisely what is believed to characterize the sex differences that have been previously reported for spatial ability (Ehrlich, Levine, & Goldin-Meadow, 2006; Heil & Jansen-Osmann, 2008; Pezaris & Casey, 1991; Ratliff, Levine, & Saunders, 2009). For example, females have been reported to engage in more verbal strategies such as thinking of words for features (e.g., "the pointy part") and matching shapes based on those features, whereas males have been reported to engage in more spatial strategies such as mentally rotating one shape and comparing the resulting visual image with another shape (Halpern et al., 2007; Ratliff et al., 2009). Evidence for this comes from self-report (Eme & Marquer, 1999; Marquer, 1990) as well as from dual-task studies where individuals are asked to solve a spatial task while simultaneously holding either verbal or spatial information in memory (Pezaris & Casey, 1991; Ratliff et al., 2009). Results show that when girls, as young as 6 to 7 years of age, are asked to solve a spatial task, they perform more poorly when concurrently engaging in a verbal relative to spatial memory task, whereas boys show the opposite pattern (Pezaris & Casey, 1991; Ratliff et al., 2009).

Given that anxiety has been shown to create verbal worries and ruminations, we can think of anxiety as a type of verbal dual task. For instance, when students are made anxious by performance pressure, they typically perform poorly on maths problems that are verbal but not spatial in nature (DeCaro, Rotar, Kendra, & Beilock, 2010) and only on those problems that are WM intensive to begin with (Beilock, Rydell, & McConnell, 2007; DeCaro et al., 2010). Thus, the fact that females perform more poorly than males on a spatial task when engaged in a verbal dual task suggests that anxiety-related verbal worries may be more strongly associated with females' performance on a spatial task. Also, since the performance of high-WM individuals is characterized by an over-reliance on WM-intensive strategies, performance worries may be especially problematic for these individuals given that they tend to employ explicit algorithms that probably rely heavily on verbal aspects of the WM system (Beilock & DeCaro, 2007). Hence, the spatial task performance of females with high WM should show a pronounced negative relationship with spatial anxiety.

Current study

If one's spatial ability is negatively associated with spatial anxiety, then it is important to ascertain whether spatial anxieties are apparent in young children and whether these anxieties begin to interfere with performance on spatial tasks early in development. It is especially important to consider how spatial anxiety might influence the spatial ability of young children, as prior work suggests that sex differences in spatial ability are present among children as young as 4 years of age (Levine et al., 1999), and spatial abilities are implicated even early in life in mathematical thinking, including associating numerical magnitude and line length (de Hevia & Spelke, 2010), representing numbers linearly on a number line (Gunderson, Ramirez, Beilock & Levine, in press), and using base 10 blocks for learning (Newcombe, 2010). Indeed, spatial anxiety may represent a critical factor that contributes to sex differences in spatial ability early in development, and the fact that the plasticity of spatial skills is greater earlier in life (Uttal et al., in press) makes this an important age to examine our research questions regarding the spatial anxiety-spatial ability relation. Hence, we carried out the current investigation among first- and second-grade children whose spatial ability levels are likely to be highly malleable.

We narrowed our focus of spatial ability to mental rotation, as mental rotation is believed to be a particularly important spatial skill in science (e.g., Stieff, 2007; Wai et al., 2009) and one of the most sex-sensitive cognitive skills (Halpern et al., 2007; Hirnstein, Bayer, & Hausmann, 2009). We also obtained a measure of reading achievement in order to examine the specificity of the impact of spatial anxiety on mental rotation. Using a measure of reading achievement as a comparison task allows us to examine the possibility that our spatial anxiety measure is merely a proxy measure for general anxiety.

To reiterate—we predict that spatial anxiety negatively relates to spatial ability but that this relation will vary as a function of individual differences in WM. Moreover, we expect that the Spatial Anxiety × WM interaction will be stronger among girls than boys in view of the verbal worry component of anxiety and girls' reliance on verbal problem-solving strategies on spatial tasks such as mental rotation.

Such a pattern of results would not only have important educational implications, but also suggest an interesting theoretical account for the emergence and maintenance of sex differences in spatial ability. In addition, showing that spatial anxiety is associated with the mental rotation ability of individuals who are characterized by a reliance on verbal problem-solving strategies would suggest a more nuanced role of WM involvement in spatial ability than previously assumed. Specifically, our findings have the potential to highlight the fragility of verbal processes in spatial problem solving in the context of anxieties about performance.

Method

Participants

This research was conducted as part of a larger study investigating how teacher affective factors impact early student learning (Beilock, Gunderson, Ramirez, & Levine, 2010). Signed parental consent forms were returned by 162 students (87 girls, 75 boys). The average age of our final sample was 7.05 years ($SD = 0.59$) with a range from 5.40 to 8.84. The average annual family income was \$36,910 ($SD = \$26,409$).

Student task

Mental rotation task. The short form of the Thurstone Primary Mental Abilities Test: Mental Rotation subtest (Thurstone, 1974) was used as our measure of mental rotation. The task presents children with items where a shape on the left is paired with four shapes on the right that are rotated at various angle. The goal of the task is to choose which of the four shapes can combine with the shape on the left to make a square. The task begins with each child being presented with a square and rectangle and the experimenter explaining the difference between the two. The child is then given four practice trials to understand the goals of the task. The child is asked, "Which of these four shapes on the right would make a square when put together with the shape on the left?" After completing the practice trials, children are given eight test trials that compose the child's score on the mental rotation subtest.

Total digit span. As a measure of WM, we used the total digit span score, which is a composite of the child's forward and backward spans as measured by the Digit Span subtest on the Wechsler Intelligence Scale for Children–Third Edition (WISC–III; Wechsler, 1991). The forward digit span task is a commonly used measure of immediate verbal short-term memory, whereas the backward digit span task is often used as a measure of executive attention in neuropsychological and developmental research (Carlson, Moses, & Breton, 2002; Diamond, Kirkham, & Amso, 2002). During both of these tasks, children are read a series of digits (e.g., "4, 9, 2") at a rate of one digit per second and are asked to repeat them back. In the forward digit span task, the child is asked to immediately repeat the series of digits back to the experimenter in the same order as they were presented ("4, 9, 2"). If the child repeats both trials of the same set size successfully, they move on to two more trials of a set size that is one digit longer. This process continues until the child misses both trials of a particular length or they reach the maximum 8-item set size. In the backward digit span task, children are asked to repeat a series of digits in the reverse order from the presentation order. For example, if the experimenter says “6, 2, 9”, the child is supposed to repeat back “9, 2, 6”. As for forward span, this process continues until the child misses a particular length. Since the backward digit span task is a more challenging variation of the forward span task, the items go up to a maximum length of 7 digits. We combined the number of correct trials on the forward and backward digit span tasks to create a composite total digit span score. Thus, the total digit span score is a combined measure of immediate short-term memory (forward span) and executive attention processes (backward span), which are the two critical components of WM (Engle, 2002). The total digit span task is also ideal for the present research purposes, since it has been shown to be a measure of phonological rather than spatial WM (Swanson, 2004), making it a suitable task for avoiding an association with spatial anxiety.

Woodcock–Johnson III Letter–Word Identification subtest. Student reading achievement was assessed using the Letter–Word Identification subtest of the Woodcock–Johnson III Tests of Achievement (WJ Letter–Word ID task; Woodcock, McGrew, & Mather, 2001), a nationally normed, comprehensive test battery used for assessing the academic achievement of individuals aged 2 through 90 years. This task requires students to correctly read single letters and words at increasing levels of difficulty as a means of testing children’s word-decoding skills. It is administered using a basal (6 items in a row correct) and ceiling (6 items in a row incorrect) level. Because of experimenter error, a few participants only completed between 3 and 5 items instead of the required number for the basal or ceiling level. These participants were scored as if they had completed the full basal or ceiling level. Moreover, excluding these participants did not alter the significance of the results reported below in any way. We used the *W* score, a transformation of the raw score into a Rasch-scaled score with equal intervals (a score of 500 is the approximate average performance of a 10-year-old), in all analyses involving the Letter–Word Identification task.

Child Spatial Anxiety Questionnaire (CSAQ). We developed an 8-item Child Spatial Anxiety Questionnaire based on the Mathematics Anxiety Rating Scale for Elementary children (MARS-E: Suinn, Taylor, & Edwards, 1988), a measure that was constructed for fourth–sixth graders. Since spatial ability is called upon during a variety of academic tasks, we presented children with questions about a range of spatial activities that might make them nervous. Also, because most classroom activities are evaluative in nature, we phrased the questions in a way that matched how a classroom activity might be conducted. For example, some items asked children to report their attitude about solving particular academic problems (e.g., “How do you feel when your teacher asks you whether these shapes are rectangles and why?”). Other items asked children about specific situations in which they might have to complete challenging spatial activities (e.g., “How would you feel if your teacher asked you to build this house out of these blocks in 5 minutes?”).

Using Cronbach’s alpha, reliability for our 8-item spatial anxiety questionnaire was found to be .56. This alpha coefficient level is not uncommon among psychology research studies investigating young children’s attitudes (Erdley, Cain, Loomis, Dumas-Hines, & Dweck, 1997; Giles & Heyman, 2003). This is particularly true of scales with few items since Cronbach’s alpha is highly influenced by the number of items in a scale. We purposely kept the spatial anxiety scale short (the number of items used was much lower than that on adult and adolescent maths anxiety measures, which typically contain 26–95 items) to reduce fatigue of our child participants and to fit all of our assessments into the 20-min period allotted to us by the schools for each child session.

Procedure

Students were tested across two sessions, an achievement assessment session followed by an anxiety assessment session. The sessions were no more than two weeks apart and took place during the first three months of the school year. All students were assessed one at time by a research assistant in a quiet area of the school.

During the achievement session, children were told that they would play a number game (digit span task), a shape game (mental rotation task), and a word game (WJ Letter–Word ID task). Half of the children received the WJ Letter-Word ID task, mental rotation task, and digit span task in this order and the other half in the reverse order. On average, the achievement session took 15 min to complete.

During the anxiety session, the Child Spatial Anxiety Questionnaire (CSAQ) was embedded within other questionnaires for a larger study. Children were introduced to the CSAQ as a question-and-answer game (see Appendix). We asked children to answer each question using a sliding scale that featured a calm face on the far right, a seminervous face in the middle, and an obviously nervous face on the far left (see Appendix, Figure A1). Students' responses were scored using a ruler on the back of the sliding scale (which was not visible to children) that went from 0 (not nervous) to 16 (very nervous). The average across the 8 items was used as the child's total CSAQ score. We used the word "nervous" when probing children and began the spatial anxiety session by giving students examples of what it means to be nervous (e.g., "being given a really hard problem or looking down from the top of a really tall building"). Children were generally excited to play the CSAQ game as they were told that we would be using the smiley face instrument. Before presenting children with questions from the CSAQ, all the children were given a simple definition and several examples of what it means to be "nervous". In particular, we told them:

> Now I'm going to ask you some questions about what kinds of things make you feel nervous or anxious or tense. Do you know what it means to be nervous? Sometimes people feel nervous when they are worried about something or are afraid they might not know the answer. I want you to tell me how nervous each thing makes you feel. See, this side means "very, very nervous", this would mean "a little nervous", this means "in the middle", this would mean "not very nervous, sort of calm", and this side means "not nervous at all, very calm". Let's try one. How nervous do you feel when you're looking down from the top of the building? What if you were really nervous, where would you put this slider? What if you were only a little nervous? What if you were not nervous at all? Let's try another question. How nervous would you feel if you were chased by a loud barking dog?

These examples were meant to give children an understanding of what we meant by nervous and to orient them on how to properly use the sliding scale instrument. Importantly, we encouraged children to use the full range of the sliding scale and not just the area above which the faces were placed. Once children had completed the anxiety session, they were thanked for their participation and were escorted back to their classroom.

Results

Four students (3 boys and 1 girl) were excluded from the study because they did not complete at least one of the tasks or left school before the study was complete. From the remaining sample of 158 students, 90 were first graders (44 male, 46 female), and 68 were second graders (28 male, 40 female).

Child Spatial Anxiety Questionnaire

Overall, children's responses on the CSAQ ranged from 1.50 to 13.75 (maximum 16) with a mean of 7.13 ($SD = 2.95$). Thus, even in early elementary school, there is marked variability in spatial anxiety, with some students reporting experiencing feelings of nervousness associated with spatial activities (i.e., spatial anxiety) and others not reporting these feelings of nervousness at all .

Children's responses on the CSAQ did not differ as a function of grade, $t(156) = 1.103$, $p > .20$, but did differ as a function of gender, $t(156) = 2.206$, $p = .029$. Overall, the mean CSAQ score was higher for girls ($M = 7.59$, $SD = 2.98$) than for boys ($M = 6.56$, $SD = 2.84$; see Figure 1). Children's responses on the CSAQ were normally distributed for boys and girls independently, suggesting that despite girls having higher levels of reported spatial anxiety than boys as reflected by their higher scores on the CSAQ, both boys and girls showed variation in their levels of spatial anxiety.

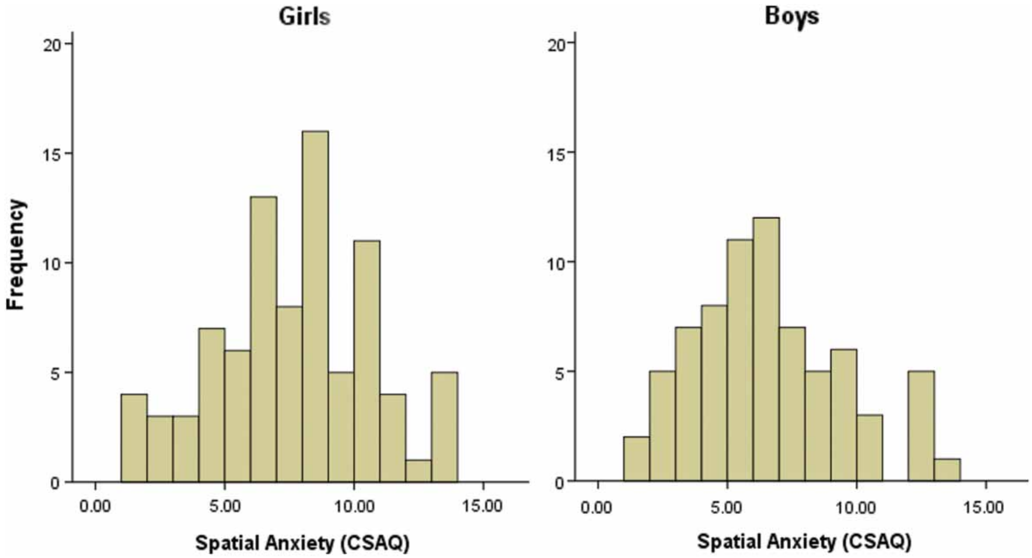

Figure 1. *Histogram displaying the distribution of children's CSAQ (Child Spatial Anxiety Questionnaire) scores for boys and girls separately.*

Working memory

Children's performance on the total digit span task was normally distributed, with a mean of 10.13 ($SD = 2.70$). As expected, children's performance on the total digit span differed by grade, $t(156) = -3.45$, $p < .01$, with second-grade children performing significantly better ($M = 10.95$, $SD = 2.71$) than first graders ($M = 9.51$, $SD = 2.52$). There were not significant gender differences in how children performed on the total digit span, $t(156) = 1.52$, $p > .05$, and both boys' and girls' performance on the total digit span was normally distributed.

The relation of spatial anxiety to mental rotation as a function of WM

Our main goal was to investigate whether spatial anxiety was related to children's mental rotation ability as a function of individual differences in WM. To address this question, we regressed children's mental rotation scores on their spatial anxiety scores, WM (using total digit span), and the interaction of Spatial Anxiety × WM. We also included children's grade level as a covariate. There was a significant main effect of WM ($\beta = .54$, $t = 2.77$, $p < .01$), but no effect of grade

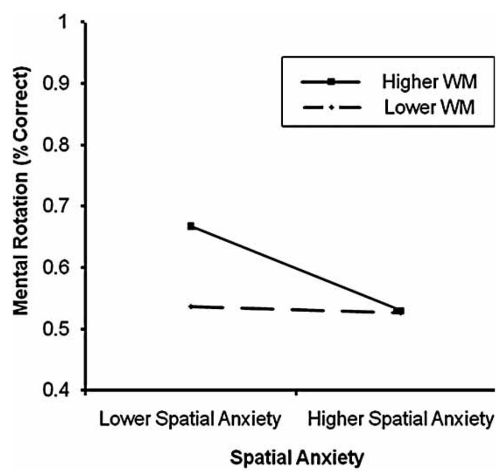

Figure 2. *Students' mental rotation ability as a function of individual differences in working memory (WM) and spatial anxiety. Working memory and spatial anxiety are plotted at 1 standard deviation above and below the mean. Children relatively higher in WM showed a pronounced negative relation between spatial anxiety and mental rotation.*

($\beta = .06$, $t = 0.75$, $p > .05$) or spatial anxiety ($\beta = .41$, $t = 1.45$, $p > .05$). However, there was a significant Spatial Anxiety × WM interaction ($\beta = -.74$, $t = -1.97$, $p = .05$). Figure 2 plots the predicted mental rotation ability of children at

± 1 standard deviation from the mean in spatial anxiety and WM.

As Figure 2 shows, the relation between children's spatial anxiety and mental rotation score differs as a function of WM. For students who were relatively high in WM, a pronounced negative relation was evident between spatial anxiety and mental rotation ability. However, this negative relation between spatial anxiety and mental rotation was not apparent among students who were relatively low in WM.

We also considered whether our spatial anxiety questionnaire might simply be measuring general feelings of anxiety instead of students' anxieties about performing spatial tasks in particular. If so, then it is possible that our spatial anxiety measure would relate to students' reading achievement as well. To test this, we ran the analysis described above with reading achievement as the outcome variable and found a significant effect of grade ($\beta = .42$, $t = 6.55$, $p < .01$) and a marginally significant effect of WM ($\beta = .28$, $t = 1.88$, $p = .06$) but not spatial anxiety ($\beta = .02$, $t = .09$, $p > .05$) or the critical interaction of Spatial Anxiety × WM ($\beta = .21$, $t = 0.72$, $p > .05$, see Figure 3). This suggests that children's spatial anxiety scores on the CSAQ are not a proxy for general academic anxiety, but rather are specifically related to spatial tasks.

The relation of spatial anxiety to mental rotation as a function of WM and gender

We next explored whether the Spatial Anxiety × WM interaction varied for boys and girls. As detailed above, since past work suggests that females tend to adopt verbal problem-solving strategies on mental rotation tasks whereas males tend to adopt a more spatial approach (Pezaris & Casey, 1991; Ratliff et al., 2009), we expected girls' performance to be particularly related to spatial anxiety.

To test this prediction, we ran our original model with mental rotation ability as a dependent variable across girls and boys separately. For boys, we found that grade, WM, spatial anxiety, and the interaction between WM and spatial anxiety were not significant predictors of mental rotation ability (all $p > .30$). Although, as seen in

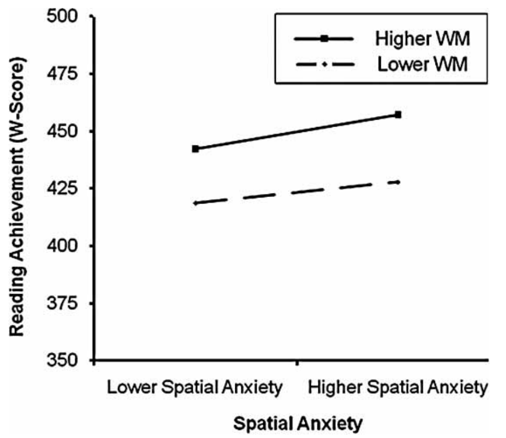

Figure 3. *Students' reading achievement as a function of individual differences in working memory (WM) and spatial anxiety. Working memory and spatial anxiety are plotted at 1 standard deviation above and below the mean. Children relatively higher in WM showed higher reading achievement than low-WM children. However, these differences do not appear to be dependent upon spatial anxiety.*

Figure 4, when explored on its own, WM was marginally related to mental rotation ability in boys (controlling for grade; $p = .09$). In contrast, for girls, we found that grade was not a significant predictor ($p > .05$) but that WM ($\beta = .89$, $t = 2.95$, $p < .01$), spatial anxiety ($\beta = .95$, $t = 2.37$, $p < .05$), and the critical WM × Spatial Anxiety interaction ($\beta = -1.47$, $t = -2.69$, $p < .01$) were all significant predictors of mental rotation ability. As shown in Figure 4, spatial anxiety showed a marked negative relationship with mental rotation ability for girls with high WM but not girls with low WM, nor for boys in general.

The lack of a relationship between spatial anxiety and WM for boys is not due to a lack of variation in their spatial anxiety or total digit span scores. Our results showed that boys' scores on the digit span task did not differ from girls' scores, and that their scores on this test were normally distributed. Further, although boys' scores on the CSAQ were lower than girls' scores, their scores on this test also were normally distributed (see Table 1).

We should note that we also explored the full three-way interaction, in which we regressed

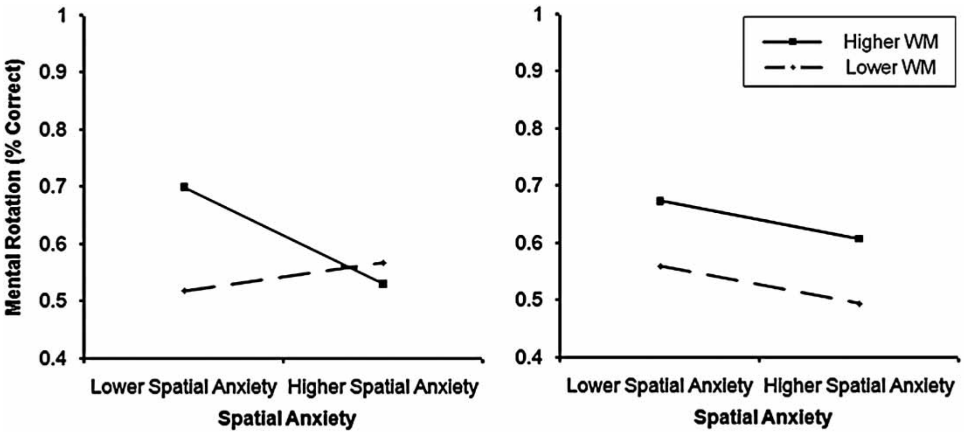

Figure 4. *Girls' (left panel) and boys' (right panel) mental rotation ability as function of individual differences in working memory (WM) and spatial anxiety. Working memory and spatial anxiety are plotted at 1 standard deviation above and below the mean. Girls with higher WM showed a pronounced negative relation between spatial anxiety and mental rotation. This was not true of boys.*

Table 1. *Overall and gender-divided descriptive statistics for total digit span, mental rotation, reading achievement, spatial anxiety, and child age*

	All students (N = 158) Mean (SD)	*Boys (N = 72) Mean (SD)*	*Girls (N = 86) Mean (SD)*
Total digit span	10.13 (2.69)	9.77 (2.75)	10.43 (2.62)
Mental rotation task	4.58 (1.61)	4.61 (1.66)	4.54 (1.58)
Reading *W* score	437.03 (34.54)	432.88 (38.93)	440.46 (30.25)
CSAQ*	7.13 (2.95)	6.56 (2.84)	7.59 (2.98)
Child age (years)	7.05 (0.59)	7.01 (0.62)	7.09 (0.57)

Note: CSAQ = Child Spatial Anxiety Questionnaire.
*Gender difference present at $p > .05$.

mental rotation ability on WM, spatial anxiety, gender, and their interactions. The Gender × WM × Spatial Anxiety interaction ($\beta = 1.46$, $t = 1.70$, $p = .09$) was marginally significant. This marginal three-way interaction is probably due to a lack of statistical power, given that, as discussed above, boys and girls showed markedly different patterns of mental rotation ability as a function of spatial anxiety and WM.

Discussion

Why are individual differences in spatial ability present at a young age? The current study investigated spatial anxiety as a potential correlate of individual differences in spatial ability.

We show evidence that spatial anxiety is present early in elementary school, and that children's responses on the CSAQ were negatively related to mental rotation but not to reading scores, suggesting that spatial anxiety is specifically related to the spatial domain. This finding, in itself, is interesting since one might not think that children could develop such a specific form of anxiety at such a young age. Furthermore, spatial anxiety was significantly higher in girls than in boys, which is in line with prior work in adults showing that women report greater anxiety than men when performing spatial tasks (Lawton, 1994; Moe, Meneghetti, & Cadinu, 2009).

We also found that not all children showed a negative relation between spatial anxiety and mental rotation ability. Rather, individual differences in spatial anxiety were more strongly associated with mental rotation ability among children who were higher in WM than among children who were lower in WM. This is consistent with research showing that high-stress situations are likely to negatively impact the maths achievement of high- but not low-WM adults (Beilock & Carr, 2005) and children (Ramirez et al., 2009). High-WM individuals tend to rely on WM-intensive strategies that are quite successful during low-stress situations. However, during high-stress situations, high-WM individuals cope with the added burden of performance worries by switching to strategies that are less WM-intensive but also less effective, leading to lower accuracy levels (Beilock, 2008; Beilock & Carr, 2005; Ramirez et al., 2009). This is not the case for individuals with low WM, who generally rely on less effective heuristic strategies that place a low demand on WM and are thus less susceptible to anxiety-related performance decrements.

Moreover, based on the idea that spatial anxiety leads to verbal performance-related ruminations, we predicted that children who rely on problem-solving strategies that are WM intensive (e.g., high-WM children) and verbal in nature (e.g., girls) should be most likely to show a negative relation between spatial anxiety and spatial ability. This is exactly what we found.

Spatial anxiety may place high-WM girls at the greatest disadvantage by robbing them of the verbal WM resources that they have come to rely on to support their performance on spatial tasks such as mental rotation. Hence, while spatial anxiety is defined as a fear about engaging in spatial tasks, the worries associated with this fear may place a cognitive load directly on verbal resources, suggesting a more nuanced explanation of how domain anxiety may be processed by the WM system and impact performance on spatial tasks.

Our work is consistent with the view that spatial and verbal working memory are somewhat separable and fuelled by different pools of resources (Shah & Miyaki, 1996). Indeed, this is one of the most prominent views of working memory (Baddeley, 1986; Baddeley & Logie, 1999; Friedman & Miyake, 2000) because of its ability to account for many findings in the human working memory and maths problem-solving literature (Beilock et al., 2007). Our work, however, does not exclude a unitary view of working memory. After all, the ability to control attention (i.e., executive attention) is believed to be domain-general and the driving force underlying success on many complex problem-solving tasks (Engle, 2002). Rather, we suggest that for individuals who have a tendency to rely heavily on working memory (and particularly verbal aspects of this system) to solve spatial tasks, those higher in spatial anxiety may be most likely to perform below their potential. This of course does not mean that there are not other routes to poor performance. For instance, it is likely that spatial problem solving can be impaired when there is a large enough load on general executive attention resources (Campbell & Collaer, 2009; Martens et al., 2006; McGlone & Aronson, 2006).

Finally, several limitations of this study are important to highlight. First, due to the correlational nature of our data, we are unable to establish that the demonstrated relations between gender, WM, anxiety, and spatial ability are causal in nature. For instance, while we suspect that verbal worries brought on by domain anxiety can interfere with the verbal problem-solving strategies that high-WM girls employ, we cannot provide direct evidence for this. Future research is needed to causally demonstrate the specific influence that spatial anxiety has on the WM subsystems and spatial task performance in general. In addition, it is important for future work to ascertain the problem-solving strategies of boys and girls prior to and during an encounter with a domain for which they are made anxious. Such an investigation could give us important insights into the coping strategies of anxious participants, particularly those with higher WM.

It is also the case that one could argue that the WJ reading achievement task is highly knowledge dependent with minimal demands on WM, which may make it an inappropriate task for demonstrating that spatial anxiety is specific to space. While this is a reasonable objection, it is important to consider that many of the words children encountered were probably unfamiliar to them, which would have required WM-dependent phonemic coding skills, which have been repeatedly shown to be highly WM dependent (Katz, Shankweiler, & Liberman, 1981; Swanson, Zheng, & Jerman, 2009). In support of this idea, our WM measure was predictive of reading achievement even after controlling for grade (a potential proxy for reading knowledge).

From a more applied, educational perspective, we believe it will be important for future research to also consider the factors that give rise to spatial anxiety. Such work may allow researchers and educators to develop effective interventions that can help students deal with spatial anxiety and encourage greater spatial learning. For example, in the maths anxiety literature, it has been suggested that adult expectations, negative stereotypes about women and maths, and female teachers' own maths anxiety are all factors that can create maths anxiety in children (Beilock et al., 2010; Beilock & Ramirez, in press; Gunderson, Ramirez, Levine, & Beilock, in press). Undoubtedly, similar factors play a role in shaping children' spatial anxiety—after all, girls reported significantly higher spatial anxiety than boys by first and second grade. It is also possible that a lack of engagement in activities that foster spatial development may serve to exacerbate gender differences in spatial ability that could ultimately contribute to spatial anxiety (Ebbeck, 1984; Levine et al., 2005; Newcombe & Sanderson, 1993; Terlecki & Newcombe, 2005). While lower competence on spatial tasks may contribute to the development of spatial anxiety, our work suggests that this relationship may be perpetuated by an online effect on WM of spatial anxiety. To this end, spatial anxiety may also serve as a mediator in the relationship between experiential factors and spatial ability.

In conclusion, the current study demonstrates that spatial anxiety is negatively associated with the spatial ability of high-WM girls. These students may be particularly vulnerable to poor performance on spatial tasks under the burden of spatial anxiety because they rely on WM-intensive verbal strategies that are derailed by the verbal ruminations that likely accompany spatial anxiety. Since spatial ability is a key component of success in maths and science, understanding the development of spatial anxiety, the precise skills it impacts, and how to circumvent its negative effects are key steps in reducing gender differences in spatial problem solving and increasing female representation in maths and science.

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APPENDIX

Child Spatial Anxiety Questionnaire items

1. How do you feel being asked to say which direction is right or left?
2. How would you feel if your teacher asked you to build this house out of these blocks in 5 minutes? [Show child card with picture of Lego]
3. 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?*
4. 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]
5. How do you feel when your teacher asks you whether these shapes are rectangles and why? [Show child card with similar shapes]
6. How do you feel when you have to solve a maze like this in one minute? [Show child card with maze]
7. How do you feel if you are asked to measure something with a ruler?
8. How do you feel when a friend asks you how to get from school to your house?

Children answered the questions using a sliding scale (see Figure A1).

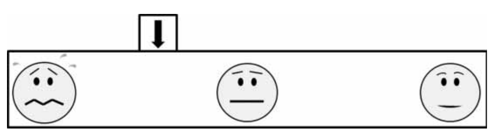

Figure A1. *Sliding scale used by the children to answer the questions.*