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The Role of Spatial Anxiety in Mental Folding

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Abstract

The purpose of this study was to examine the development of mental folding using a new measure for six- to eight-year-olds, specifically with two goals: (1) to investigate the relationship between mental folding and spatial anxiety as a function of working memory, and (2) to get further insight into the differences between mental folding and mental rotation using various math and vocabulary tasks. No relationship was found between spatial anxiety and mental rotation or mental folding, nor between spatial anxiety and working memory. Unlike previous research, mental rotation performance and spatial anxiety levels did not differ as a function of gender. Mental folding was found to be more highly related to vocabulary, supporting prior research that suggested that mental folding is more likely to utilize verbal analytic strategies than mental rotation.

Keywords: mental folding, spatial tasks, gender difference, working memory

The Role of Spatial Anxiety in Mental Folding

Spatial ability—the ability to generate, retain, retrieve, and transform structured visual images (Casey, Nuttal, & Pezaris, 1997, 2001)—while necessary in its own right, is also a consistent predictor of 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). These abilities predict achievement in mathematics, making the relationship between spatial thinking and mathematics a topic of interest for many researchers. Some have tried to develop interventions that focus on improving spatial thinking, and a few promising studies with multiple age groups have found that spatial training could be used as a direct intervention for math skills (Sorby, 2009; Newcombe, 2010; Feng, Spence, and Pratt, 2007). Others look to spatial reasoning and ability to find out why certain groups are under-represented in STEM programs and careers. Most of that research, however, has been focused on one type of spatial ability above all the rest.

Mental rotation ability, which enables a person to imagine what a two- or three-dimensional object would look like if it were rotated, is believed to be a particularly important spatial skill (Stieff, 2007). In fact, many of the studies linking spatial and math abilities use mental rotation as a proxy for general spatial skill. Mental rotation specifically is associated with understanding numerical magnitudes (Casey, Dearing, Vasilyeva, Ganley, & Tine, 2011; Gunderson, Ramirez, Beilock, & Levine, 2012), applying measurement formulas, completing basic calculations (Casey et al., 2011), and interpreting diagrams of chemical reactions (Pribyl & Bodner, 1987). Even so, there are many other spatial tasks that people use regularly: navigation, wayfinding, mentally manipulating objects, and perspective taking are all important for tasks we do in our everyday lives. Other spatial tasks require different spatial abilities and can be categorized differently, generally along two dimensions: dynamic versus static skills along one, intrinsic versus extrinsic transformations along the other (Uttal et al, 2013; Newcombe and Shipley, 2015). Dynamic skills involve movement or transformation while static skills only involve object representation; whether a transformation is intrinsic or extrinsic depends on whether it is within- or between-objects (Hodgkiss et al, 2020). Dynamic skills can be further broken down into multiple factors, the most common of which are spatial visualization, spatial relations, and spatial orientation (Lohman, 1979). Mental rotation is dynamic, intrinsic, and classified as a spatial relations skill; to assume that mental rotation is a sufficient representative of all of these types of abilities may constrain what we can know about the capabilities of the human mind and how different cognitive processes are interrelated.

Mental rotation and mental folding

In 1982, Roger Shepard et al. published a series of influential papers showing that people can form a mental image of a two- or three-dimensional shape or object, and that they can transform those images in various ways, like rotating, bending, or folding them. At the time, these papers were groundbreaking, leading to an onslaught of papers investigating the existence of these skills and the implications thereof. Most of those papers, however, only focused on the ability to mentally rotate mental images of objects. Shepard argued that mental folding, the ability to mentally fold and unfold a two-dimensional (less often a three-dimensional) object, is very similar to mental rotation because both deal with the intrinsic properties of those images (Shepard & Cooper, 1982).

Imagine a paper airplane. There are many ways the airplane could be spatially manipulated, some intrinsic, some extrinsic (Chatterjee, 2008). An intrinsic spatial change is a change that is not defined with respect to another object, like rotating the paper airplane (mental rotation; a change with respect to the observer, a privileged relation) or unfolding it entirely (mental folding; a self-contained and internally specifiable change to the shape of the plane). An extrinsic change would be to throw the plane, thereby changing its location relative to something else (e.g. from inside the kitchen to outside the kitchen).

Mental rotation and mental folding, both being dynamic changes to the intrinsic spatial properties of shapes and objects, are often lumped together during the study of spatial abilities. They do have a lot in common, both in terms of underlying cognitive processes and neurological bases (Harris, Hirsh-Pasek, & Newcombe, 2013). Both abilities are associated with activation in the parietal lobe (Jaušovec and Jaušovec 2012; Milivojevic et al. 2003; Unterrainer et al. 2000), and they seem to develop in children at similar rates. Moreover, training on one skill appears to improve performance on the other; Wright (2008) trained one group on mental rotation and another on volumetric folding, and both groups showed improved performance on both the trained and untrained tests, suggesting that mental rotation and mental folding are tapping a common skill that can be trained.

All of that said, mental rotation and mental folding differ in a few key ways that make a distinction necessary. Mental rotation is a rigid transformation and mental folding is not, which is to say that mental rotation does not change the shape of an object, and mental folding does (Harris, Hirsh-Pasek, & Newcombe, 2013). In addition, the distances between points in the object are not changed by rotation but are changed by folding. There is also some evidence that mental folding more readily allows for analytic strategies, rather than or in addition to spatial strategies, than mental rotation does (Lohman, 1979). Spatial problems generally allow for two strategies: the first is to solve it as intended, by mentally folding or rotating the object holistically; the second is to solve the problem through a predominately verbal-analytic approach, usually by attending to individual parts separately. Lohman (1979) suggested that since folding often requires multiple steps, it is more amenable to analytic strategies; some have even suggested that mental folding solutions always include an analytic component and that mental rotation tests never elicit this strategy (Linn and Petersen, 1985). That said, there are individual differences in strategy for mental rotation tests as well (Bethell-Fox and Shepard, 1988; Cooper, 1980; Kail et al., 1979; Kung and Hamm, 2010; Searle and Hamm, 2012). A subclass of people, sometimes called “non-rotators,” do not ever seem to solve mental rotation problems by mentally rotating the object as a whole (Geiser et al., 2006); Xu and Franconeri (2015) argued that the human visual system is not suited for keeping multiple features attached to multiple parts, which suggests that nobody really rotates holistically. It therefore appears that while both spatial tasks can use both strategies, mental folding is more vulnerable to a mixed or entirely non-spatial approach.

Psychometrically, mental rotation and mental folding are often categorized differently amongst dynamic spatial abilities. Lohman (1979) argued that mental rotation acts as a type of spatial relations task, while mental folding is a form of visualization. Like the strategy differences between mental folding and rotation, Guilford et al. (1952) found that solutions for difficult visualization tasks involve more verbal reasoning than spatial relations tasks do, making them difficult to compare. The involvement of non-spatial reasoning would support the idea that current mental folding tests are psychometrically different from mental rotation tests because they are a less pure measure of dynamic spatial transformations.

Mental rotation, along with being linked to success in math and science fields, is also one of the most sex-sensitive cognitive skills (Halpern et al., 2007; Hirnstein, Bayer, & Hausmann, 2009); men consistently perform better on mental rotation tasks than women. This has been the object of a great deal of attention; if women do not perform well on the tasks that predict entry into STEM, what can/should be done to increase women's participation in STEM? Is this an innate difference, or a socialized difference? While there is some controversy about the onset of the gender difference, at least a subset of spatial transformation tasks show gender differences by the preschool years (Levine et al, 1999). In contrast, mental folding, interestingly, does not show gender differences at any age (Harris, Newcombe, & Hirsh-Pasek, 2013). While we do not know why the gender difference exists in one but not the other, recent research has suggested that it may be caused by individual differences in working memory (Ramirez, Gunderson, Levine, and Beilock, 2012).

Working memory, spatial anxiety, and spatial ability

Working memory is a cognitive system with a limited capacity that can hold information temporarily (Models of Working Memory, 1999); it is a short-term memory store involved in actively holding information in the mind that is needed to complete complex tasks (Engle, 2002). It is the form of memory that people use from moment to moment; the average adult cannot hold more than five or six pieces of information in their working memory at a time. There are several different kinds of working memory: verbal working memory works separately from visual-spatial working memory, so somebody who is very good at one form may suffer in another.

Since working memory is essential for success in mathematics—for remembering numbers and formulas, or for remembering past steps in solving a problem whilst completing the next step—and individuals are limited in working memory (Engle, 2002), anything that interferes with working memory can be detrimental to the accomplishment of whatever that memory system is used for. In some cases, worries related to performance failure lead to performance decrements by forcing people to work with depleted working memory due to irrelevant thoughts (Beilock, 2008, 2010). That relationship has been seen most often in mathematics, but in recent years spatial anxiety and working memory have been linked regarding spatial ability (Ramirez, Gunderson, Levine, and Beilock, 2012).

Ramirez et al. (2012) found a significant relationship between mental transformation and spatial anxiety, with spatial anxiety showing a negative relationship with mental rotation ability for girls with high working memory but not for girls with low working memory, nor for boys in general. This was not a fully unprecedented finding: previous work on math anxiety and choking under pressure has suggested that high working memory individuals are the most negatively affected by stress-related worries (Beilock & Carr, 2005; Ramirez, Gunderson, Levine, & Beilock, 2009), most likely because high working memory individuals tend to rely heavily on working memory-demanding problem-solving strategies, like difficult algorithms, which can fail under the burden of stress (Beilock & DeCaro, 2007). Individuals with low working memory are less likely to experience performance issues under stressful conditions—they often rely on heuristic strategies that place a low demand on working memory to begin with.

Girls consistently report higher levels of spatial anxiety, and mental rotation studies have suggested that spatial anxiety can interfere with verbal working memory due to the verbal ruminations that people with spatial anxiety engage in during spatial tasks (Ramirez, Gunderson, Levine, and Beilock, 2012). That gives a great deal of significance to problem-solving strategies, which some researchers believe are the cause of gender differences for spatial tasks. Women 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, while men seem 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). These trends have been found in both self-report (Eme & Marquer, 1999; Marquer, 1990) and dual-task studies where individuals are asked to simultaneously solve a spatial task and hold either verbal or spatial information in memory (Pezaris & Casey, 1991; Ratliff et al., 2009). Results show that when six- to seven-year-old girls are asked to solve a spatial task, they perform more poorly when simultaneously engaging in a verbal relative to spatial memory task, whereas boys show the opposite pattern (Pezaris & Casey, 1991; Ratliff et al., 2009). Relating this back to the Ramirez findings, since girls are more likely than boys to use verbal working memory strategies, spatial anxiety would be more of a hindrance for girls than boys.

There has not been an equivalent study done with spatial anxiety and mental folding, but we believe that there could be a great deal to learn from such a study; unlike mental rotation, mental folding does not show significant gender difference. There is some evidence that the gender difference may be attributed to mental rotation being a rigid transformation, but that only shifts the question of why there are gender differences for mental rotation to why there are gender differences for rigid but not non-rigid transformations (Harris, Hirsh-Pasek, & Newcombe, 2013). To do a similar study with mental folding could give further insight into the relationship between working memory, gender, and spatial ability.

The present study

In the current study, we examine the development of mental folding using a new measure for six- to eight-year-olds. The overall purpose of the project is to compare how mental folding and mental rotation relate to various tasks (like mathematic and vocabulary measures). We also investigate whether spatial anxiety is related to children's mental folding ability as a function of individual differences in working memory. Our intention is to get a closer look at mental folding's lack of a gender difference by including working memory measures; we expect to see, as other studies have shown, that spatial anxiety has a negative effect on mental rotation performance in children (especially girls) with high working memory. We hypothesize that a similar relationship will be found between spatial anxiety and working memory for mental folding, but without the gender difference; because mental folding involves verbal working memory strategies, it is likely that the verbal ruminations caused by spatial anxiety do not affect one gender more than another. If boys are as likely to use verbal strategies on mental folding tasks as girls, then the low-versus-high working memory pattern shown in the Ramirez study would show up in mental folding regardless of gender.

Methods

Participants

The 46 participants, 23 girls and 23 boys, ranged from six- to eight-years-old (72 to 102 months, M = 86.5 months, SD = 9.101). 9 were in kindergarten, 14 were in first grade, and 16 were in second grade, with 7 participants (two six-year-olds, three seven-year-olds, and 2 eight-year-olds) not reporting their grade. Many were recruited from the University of Chicago Infant Database, but some responded to an advertisement posted on social media. Each participant was given a ten-dollar gift card as compensation.

Materials

Paper Folding: We developed a new paper folding measure for children, consisting of fourteen multiple choice questions. Participants were shown a series of pictures of somebody folding a piece of paper in half and poking a hole through the folded sheet (see *Figure 1*). The multiple-choice questions asked what the paper would look like if it was unfolded again; in addition to the correct choice, there were four foils for each question. Foils included the fold being along the wrong axis, the paper having one hole instead of two, and differences in hole location. We chose the foils after a pilot run of the measure in which the children drew what they expected the paper to look like; the foils were the most common mistakes the children made.

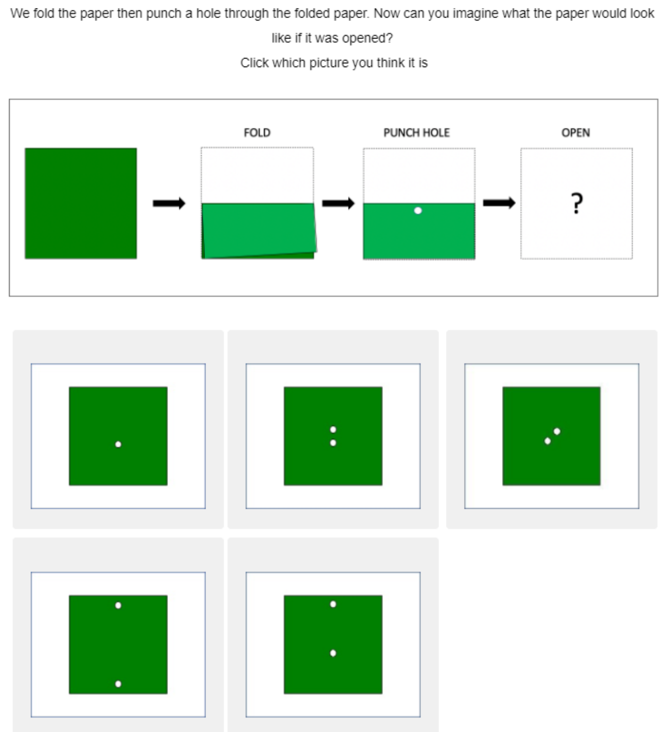


Figure 1 Example of a paper folding question, with the paper up above and the possible end results down below.

Mental Rotation: to compare with the paper folding results, we included a twelve-item two-dimensional mental rotation task (Mix et al, 2018). The participant would be presented with an unfamiliar target shape (i.e., forms based on manipulating components of capital letters so they were no longer recognizable as letters), and underneath there would be four shapes that were similar to the target (see *Figure 2*). Two were the exact same shape, but rotated. The other two, the foils, were rotated mirror images of the target. Participants were tasked with indicating which two were the same as the target. The task was introduced with two practice items, and children received feedback on the correctness of their answers in the form of animations rotating the correct answers to match the target. Mix et al. (2018) had the children complete the task in a paper booklet (kindergarten: α = .77; third grade: α = .86); we translated it into a virtual format.

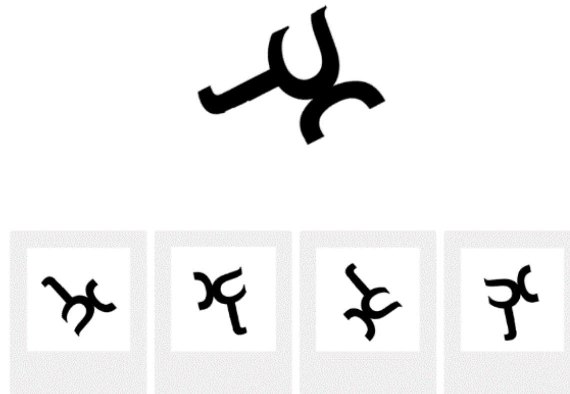


Figure 2 Example of a mental rotation problem.

Child Spatial Anxiety Questionnaire (CSAQ): this assessment was based on the Mathematics Anxiety Rating Scale for Elementary children, but adapted to focus on spatial skills (MARS-E: Suinn, Taylor, & Edwards, 1988). The questions we asked were still geared to measure a participant's spatial anxiety, but the questions were more age appropriate (i.e. how do you feel being asked to say which direction is right or left; how do you feel when you have to solve a maze like this in one minute? [Show child a picture of a maze]). To answer the question, the participants were presented with a five-item smiley-face scale. '1' showed a very happy face, '3' a neutral face, and '5' a very anxious face. The average across the eight answers was used as the child's CSAQ score.

Total Digit Span: as a measure of verbal working memory, 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 and the backward digit span task is often used as a measure of executive attention (Carlson, Moses, & Breton, 2002; Diamond, Kirkham, & Amso, 2002), which are the two critical components of working memory. During both of these tasks, children were read a series of digits (e.g., "4, 9, 2") at a rate of one digit per second and were asked to repeat them back. In the forward digit span task, the child was 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 repeated both trials of the same set size successfully, they moved on to two more trials of a set size that was one digit longer. This process continued until the child missed both trials of a particular length or they reached the maximum 8-item set size.

In the backward digit span task, children were asked to repeat a series of digits in the reverse order from the presentation order (so "6, 2, 9" becomes "9, 2, 6"). As with the forward span, this process continued until the child missed 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 working memory (Engle, 2002). In terms of the present research, the total digit span task has been shown to be a measure of phonological rather than spatial working memory (Swanson, 2004), making it an appropriate measure for evaluating the effects of spatial anxiety without tapping into spatial abilities.

Woodcock-Johnson Applied Problems Subtest: this 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, measures quantitative reasoning, math knowledge, and math achievement by having children complete math problems that require the construction of mental mathematics models via language comprehension, application of math knowledge, calculation skills, and quantitative reasoning. The problems grow more difficult further into the test, allowing participants to begin on a page that is appropriate for their age and ability level.

To establish a basal, the participant must answer five problems in a row correctly; if the participant makes a mistake, the researcher must go back to the previous page, continuing to move backward until the participant answers five questions correctly in a row. To establish a ceiling, the participant must answer at least five questions in a row incorrectly; pages must be completed entirely, so the last of the incorrect answers must also be the last question on a page.

Woodcock-Johnson Picture Vocabulary Subtest: this subtest, also from the Woodcock-Johnson III Tests of Achievement, measures language development and lexical knowledge. It consists of a large packet, each page with six pictures on it; the vocabulary words grow more difficult the farther participants go, again allowing them to begin on a page that is appropriate for their age and ability level. Like the Applied Problems subtest, the Picture Vocabulary subtest requires that researchers establish a basal and a ceiling, this time of six (in)correct items in a row.

Procedure

The current study is part of a larger project investigating the relationship between various spatial skills (specifically mental rotation and mental folding), math, and working memory. The study was conducted over a Zoom video call, with all but one participant finishing in one session. After filling out virtual consent and demographic forms, the participants joined a Zoom meeting with a researcher. To begin, the researcher would share their own screen to show participants the Woodcock-Johnson Applied Problems set; the researcher would read the questions out loud, filling out a Qualtrics form to keep track of the participant's responses. Then, using the same methodology, the researcher would share the Woodcock-Johnson Picture Vocabulary set with the participant and record answers on the Qualtrics form.

After the Woodcock-Johnson measures, the researcher would send a link to another Qualtrics survey to the participant, having the child share their screen as they went through the rest of the measures; the researcher would give instructions and answer questions as needed. The paper folding and mental rotation tasks were administered in a random order, followed by the spatial anxiety task, then digit span.

For the digit span measure, the survey screen was blank aside from a block of text telling the participant to wait to move on until the research told them to; the arrow button was on a timer to prevent premature continuation. The researcher read the number sequences from their own screen and kept track of the participant's answers. The forward digit span task was administered first, then the backward digit span task, as specified in the test manual.

Results

Seven students (4 male, 3 female) participated before the addition of the WJ Applied Problems, Vocabulary, and digit span tasks. They were excluded from the results for tests that involve those tasks, but in the interest of improving power they were included in the descriptive statistics for the other tasks and in analyses that involved the other tasks.

Descriptive Statistics - Boys and Girls												
	PF		MR		SA		WM		WJ AP		WJ Vocab	
	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male
Valid	23	23	23	23	23	23	22	19	20	19	20	19
Missing	0	0	0	0	0	0	1	4	3	4	3	4
Mean	7.522	7.87	6.435	8.435	2.484	2.217	9.409	9.368	33.5	35.526	26	26.526
Std. Deviation	3.752	4.049	4.305	3.678	0.709	0.606	3.362	3.004	7.03	7.019	4.856	6.177
Minimum	0	0	0	0	1	1.5	2	1	18	19	18	18
Maximum	12	12	13	13	4	3.5	18	14	46	46	34	41

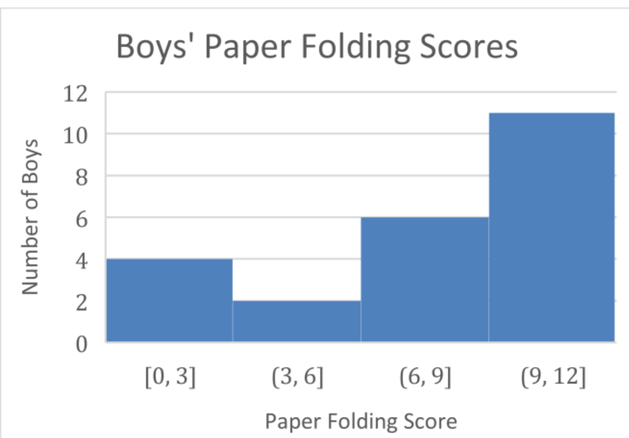
Table 1 The descriptive statistics of boys and girls for each task.

Descriptive Statistics - 6- and 8-year-olds												
	PF		MR		SA		WM		WJ AP		WJ Vocab	
	6	8	6	8	6	8	6	8	6	8	6	8
Valid	17	11	17	11	17	11	17	9	15	9	15	9
Missing	0	0	0	0	0	0	0	2	2	2	2	2
Mean	6	8.727	6.353	9.727	2.537	2.216	8.588	11.667	30.667	38.222	25.8	25.667
Std. Deviation	4.458	3.552	4.256	2.796	0.618	0.5	1.698	3.202	3.83	6.261	6.213	4.387
Minimum	0	0	0	4	1.375	1.625	5	8	26	27	18	19
Maximum	12	12	13	13	3.75	3	12	18	40	46	41	32

Table 2 The descriptive statistics of 6- and 8-year-olds, to show the role of age in performance on each task.

Paper folding

There were 12 items on the Paper Folding task, and scores ranged from 0 (only in children who did not understand that there would be two holes after unfolding the paper) to 12, which was the highest possible score (M = 7.696, *SD* = 3.864). Paper folding scores and age (in months) were positively correlated, r(46) = 0.404, *p* = 0.005. As we expected, performance on the paper folding task did not differ as a function of gender, t(44) = -0.302, p = 0.764. Both the boys' and girls' scores were skewed left.



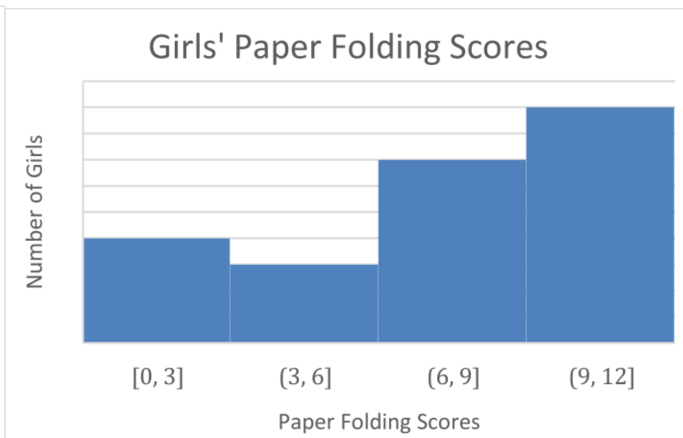


Figure 3 Histograms displaying the distribution of children's paper folding scores for boys (left) and girls (right) separately.

Mental rotation

There were 14 items on the mental rotation task and two correct answers for each question; for a participant's answer to be counted as correct, they needed to find both correct answers. Children's scores on the mental rotation task ranged from 0 to 13 (out of a possible 14), with a mean of 7.435 (*SD* = 4.086).

Mental rotation and age (in months) were found to have a small but significant positive correlation, r(46) = 0.329, *p* = 0.025. Contrary to prior research, performance on the mental folding task did not vary as a function of gender, t(44) = -1.694, p = 0.097, though boys' (M = 8.435, SD = 3.678) did do better on average than girls (M = 6.435, SD = 4.305), suggesting that the lack of statistical significance is due to power. The distribution of the boys was skewed left, but the girls followed a bimodal distribution (see *Figure 4)*.

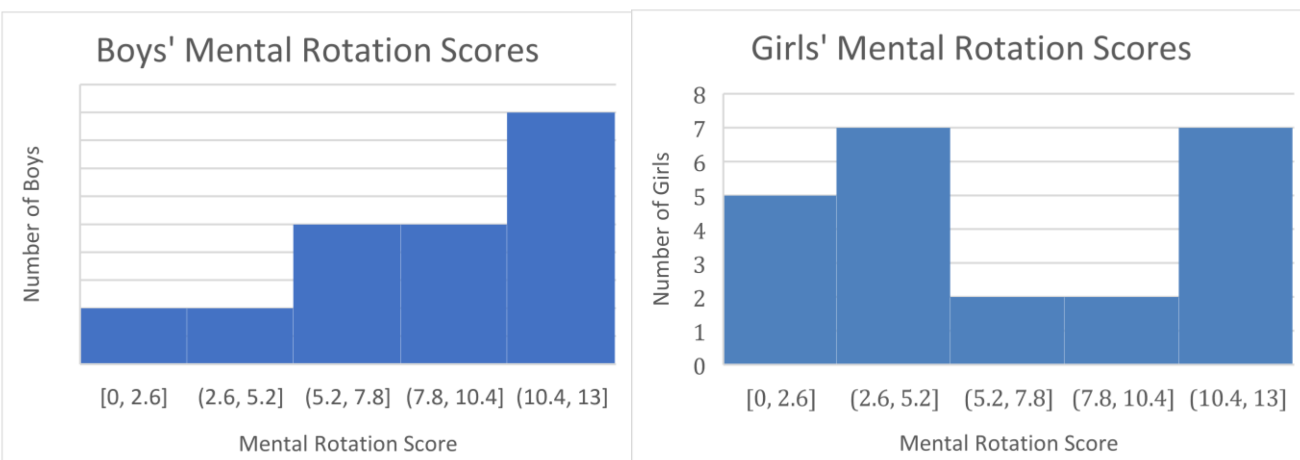


Figure 4 Histograms displaying the distribution of children's mental rotation scores for boys (left) and girls (right) separately.

Spatial anxiety

Children's scores on the CSAQ ranged from 1 to 4 (with 5 as the highest possible score, reflecting the most anxiety), with a mean of 2.351 (*SD* = 0.666). Even in early elementary school, there is clear variability in spatial anxiety; some students report experiencing feelings of nervousness associated with spatial activities (i.e., spatial anxiety), while others do not report these feelings of nervousness at all.

Children's scores on the CSAQ did not differ as a function of age, F(2, 43) = 1.071, *p* = 0.352, nor did they differ as a function of gender, t(44) = 1.369, p = .178. While the gender difference was not significant, only the girls had a normal distribution (M = 2.484, *SD* = .709). The boys' scores were skewed right (i.e. most of the boys reported less anxiety), with most of their scores falling between 1.5 and 2.5 (M = 2.217, *SD* = .606) (see *Figure 5*).

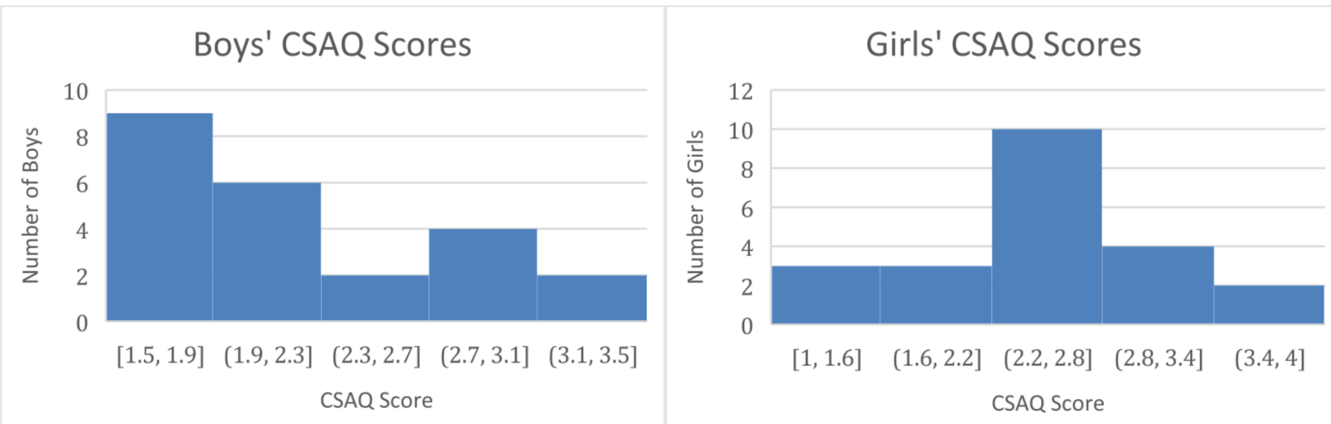


Figure 5 Histograms displaying the distribution of children's CSAQ (Child Spatial Anxiety Questionnaire) scores for boys (left) and girls (right) separately.

Digit span

Children's performance on the total digit span task was normally distributed, with a mean of 9.39 (*SD* = 3.161). As expected, performance on the total digit span differed by age, F(2, 38) = 3.402, *p* = .044. There were no significant gender differences in how children performed on the total digit span, t(39) = 0.041, *p* = .968, and both boys' and girls' performance on the total digit span were normally distributed. Digit span and age (in months) were moderately correlated, r(39) = 0.342, *p* = 0.033.

Linear Regressions

In an effort to replicate the Ramirez findings, we ran a multiple linear regression analysis to investigate how spatial anxiety is related to mental rotation as a function of individual differences in working memory. To do so, we regressed children's mental rotation scores on their spatial anxiety scores, working memory (using total digit span), and the interaction of spatial anxiety × working memory, with WJ Vocab and age (months) as controls. Only 19.6% of the variance in the data could be attributed to the predicter variables. Neither spatial anxiety (B = 0.064, p = 0.871), working memory (B = 0.031, p = 0.959), the interaction between spatial anxiety and working memory (B = 0.346, p = 0.209), vocabulary (B = 0.075, p = 0.136), nor age (B = 0.187, p = 0.760) significantly contributed to the model. Overall, the model was not a significant predicter of mental rotation (F (5, 33) = 1.609, p = 0.185).

Despite the lack of significant results, we wanted to see if, in terms of how spatial anxiety affected spatial tasks for low versus high working memory children, our results were directionally consistent with Ramirez et al. To do so, we calculated the z-scores of each age group (six-, seven-, and eight-year olds) for the spatial anxiety, working memory, paper folding, and mental rotation tasks. Since some of the tasks showed an age difference, we wanted to ensure that the younger children were not getting lower scores by virtue of their age alone. Unlike Ramirez et al., there was no discernable spatial anxiety × working memory interaction (see *Figure 6*).

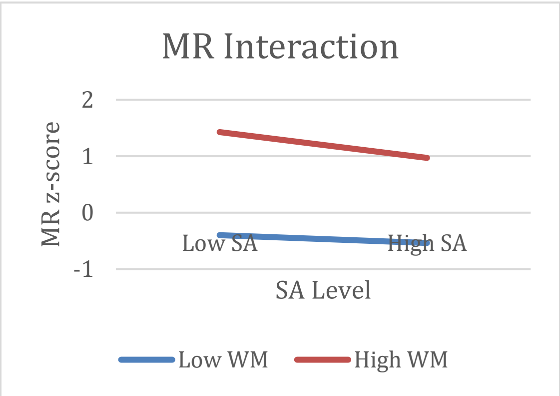


Figure 6 Students' mental rotation ability as a function of individual differences in working memory and spatial anxiety. High and low spatial anxiety and working memory were determined by a median split of z-scores.

Like Ramirez et al., we next explored whether boys and girls were affected differently by the spatial anxiety × working memory interaction. To do so, we took the original model and ran it across boys and girls separately. For boys, the model accounted for 54.5% of the variance in the data, and was a significant predicter of mental rotation, F (5, 13) = 3.114, p = 0.046. Spatial anxiety (B = -1.062, p = 0.048) and vocabulary (B = 0.287, p = 0.041) were significant predictors of boys' mental rotation ability, but working memory (B = -1.512, p = 0.063), spatial anxiety × working memory (B = 0.399, p = 0.065), and age (B = 1.787, p = 0.074) did not significantly contribute to the model. In contrast, the model only accounted for 25.7% of variance in the girls' data; it was not a significant predictor of their mental rotation ability, F (5,14) = 0.966, p = 0.471. Neither spatial anxiety (B = 0.470, p = 0.424), working memory (B = 0.320, p = 0.780), spatial anxiety × working memory (B = -0.094, p = 0.869), vocabulary (B = 0.075, p = 0.638), nor age (B = -0.062, p = 0.950) were significant predictors of girls' mental rotation ability.

Directionally, the boys' relationship between spatial anxiety and mental rotation ability as a function of working memory looked how we expected: spatial anxiety interfered with mental rotation, but not as a function of working memory. High spatial anxiety girls, on the other hand, performed better than those with low spatial anxiety (see *Figure 7*), which is not consistent with prior research.

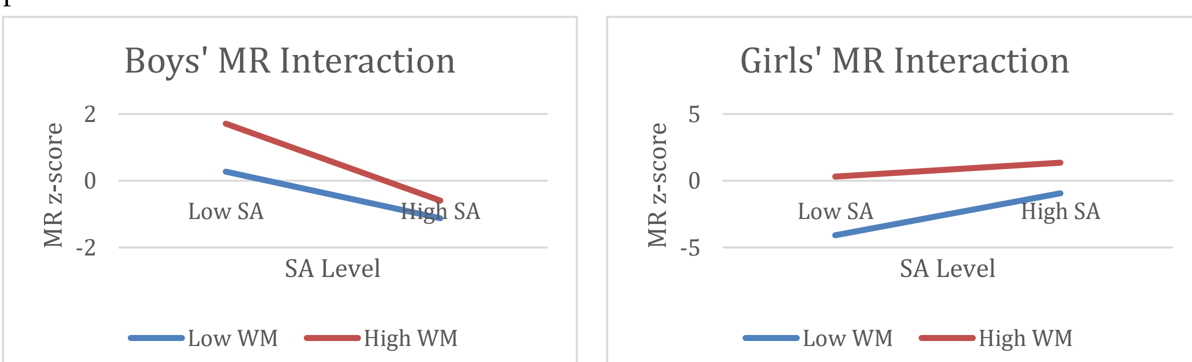


Figure 7 Boys' (left panel) and girls' (right panel) mental rotation ability as function of individual differences in working memory and spatial anxiety. High and low spatial anxiety and working memory were determined by a median split of z-scores.

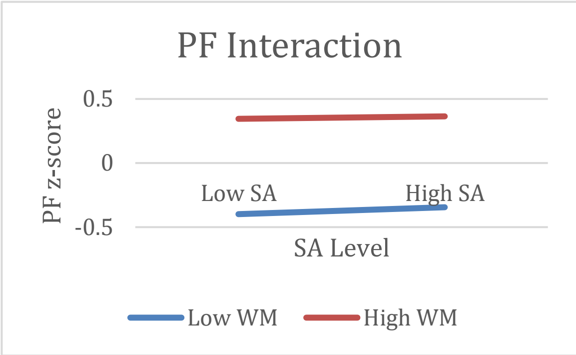


Figure 8 Students' paper folding ability as a function of individual differences in working memory and spatial anxiety. High and low spatial anxiety and working memory were determined by a median split of z-scores.

For the sake of comparison, we ran the same regressions using paper folding instead of mental rotation. When we regressed paper folding on children's CSAQ scores, working memory, the interaction of spatial anxiety and working memory, vocab, and age, the model accounted for 34.7% of the variance in the data; the model was a significant predicter of paper folding, F(5, 33) = 3.504, p = 0.012. Most of the predicter variables—spatial anxiety (B = -0.284, p = 0.423), working memory (B = -0.206, p = 0.700), and age (B = 0.391, p = 0.479)—did not contribute significantly to the model; spatial anxiety × working memory (B = 0.539, p = 0.033) and vocabulary (B = 0.230, p = 0.019) did play a significant role in predicting performance on the paper folding task.

Directionally, paper folding performance was affected by individual differences in working memory, but not spatial anxiety (see *Figure 8*); while this is not consistent with the trends observed by Ramirez et al., it is consistent with the relationship we observed in mental rotation.

Then we ran the model across boys and girls separately. The model accounted for 40.4% of the variance in the data, but it was not a significant predicter of boys' paper folding, F (5, 13) = 1.763, p = 0.190. Spatial anxiety (B = -0.885, p = 0.180), working memory (B = -0.912, p = 0.303), spatial anxiety × working memory (B = 0.209, p = 0.373), vocabulary (B = 0.167, p = 0.270), and age (B = 1.529, p = 0.170) did not significantly contribute to the model. For girls, the model accounted for 42.8% of variance in the data, but it was not a significant predictor of their paper folding ability, F (5, 14) = 2.096, p = 0.127. As with the boys, spatial anxiety (B =

0.032, *p* = 0.950), working memory (B = 0.073, *p* = 0.942), spatial anxiety × working memory (B = 0.680, *p* = 0.187), vocabulary (B = 0.288, *p* = 0.053), and age (B = -0.029, *p* = 0.973) did not significantly contribute to the model.

Directionally, we expected to see the same trend in boys and girls: low working memory children would not be highly impacted by spatial anxiety, and high working memory children would be negatively impacted by spatial anxiety. Boys did show that pattern, but low working memory girls performed better if they experienced high spatial anxiety, while high working memory girls were not affected by spatial anxiety (see *Figure 9*).

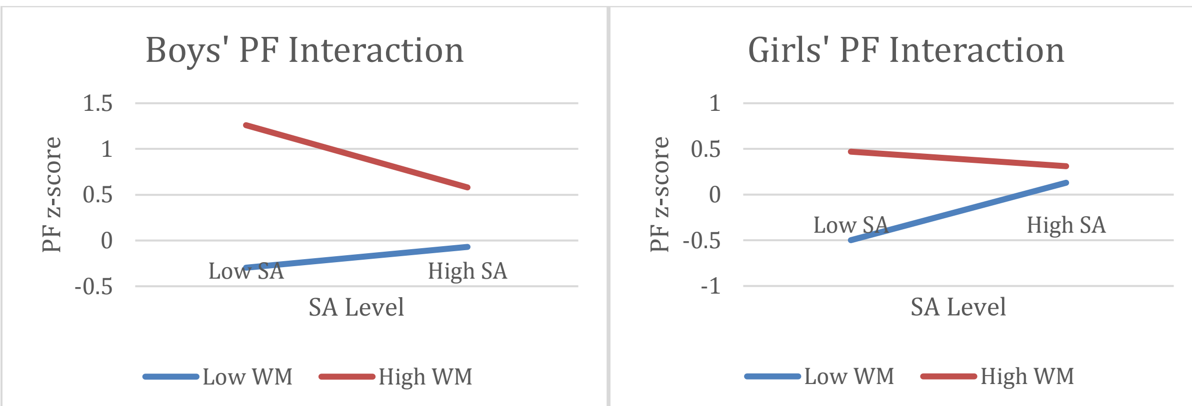


Figure 9 Boys' (left) and girls' (right) paper folding ability as a function of individual differences in working memory and spatial anxiety. High and low spatial anxiety and working memory were determined by a median split of z-scores.

Correlations

Paper folding and mental folding, as we expected, were moderately positively correlated, r(39) = 0.433, *p* = 0.009; girls had a slightly stronger correlation, r(46) = 0.500, *p* = 0.015, than boys, r(46) = 0.462, *p* = 0.027. Even so, the spatial abilities did not share correlations with all of the same tasks. While mental folding was not significantly correlated with the vocabulary task, r(39) = 0.270, *p* = 0.096, paper folding was, r(39) = 0.340, *p* = 0.034. Paper folding was related to performance on the digit span task, r(39) = 0.364, *p* = 0.027; mental rotation was not, r(39) = 0.277, *p* = 0.080.

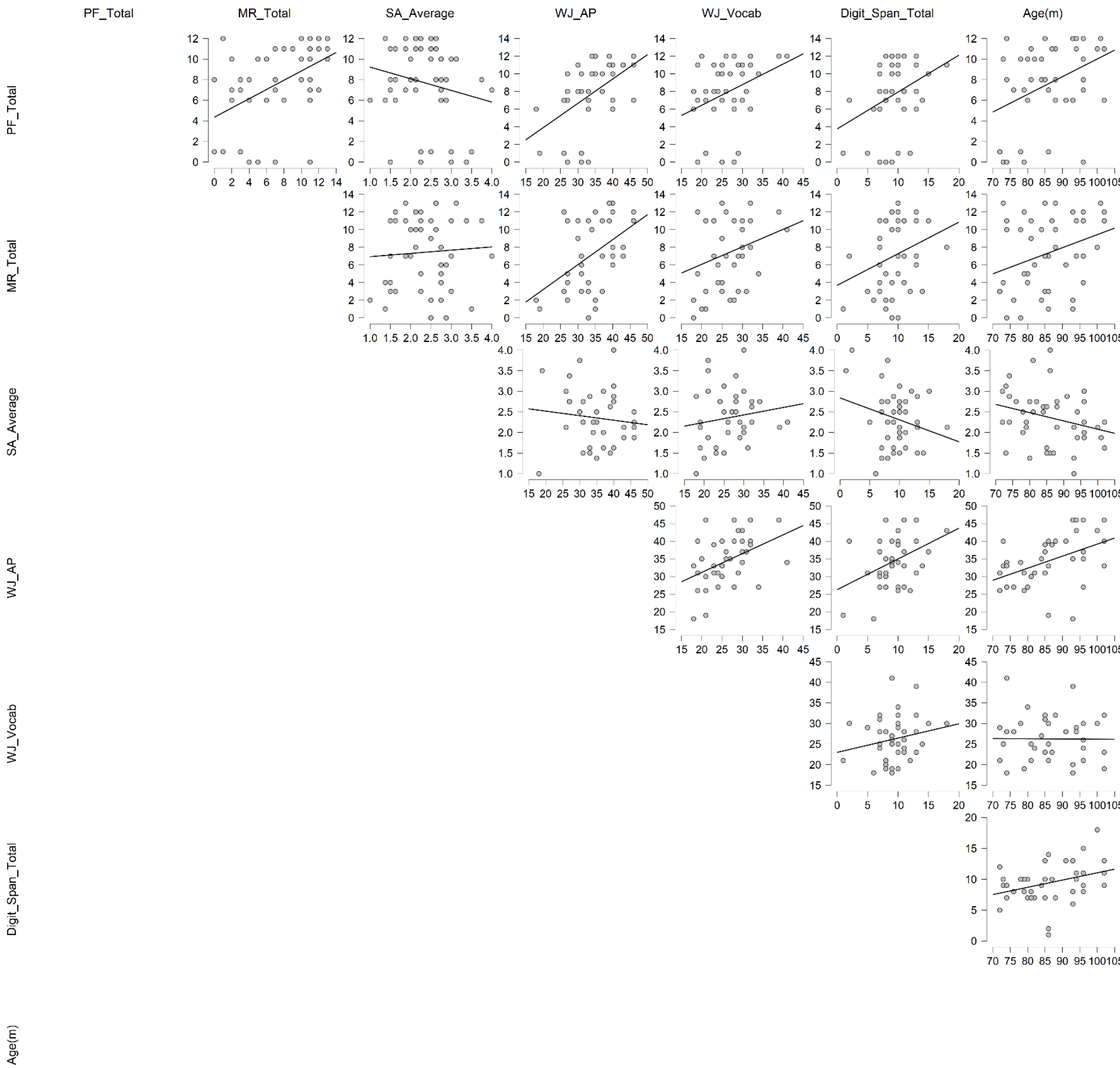


Figure 4 Scatterplots showing the correlations between variables.

Spatial anxiety was not related to paper folding, r(44) = -0.195, p = 0.194, or mental rotation, r(44) = 0.060, p = 0.691. It was also not significantly correlated with working memory, r(44) = -0.244, p = 0.125, which is to say that our study failed to replicate Ramirez et al. (2012)'s results. Spatial anxiety was not highly related to performance on either spatial task, and working memory did not play a role in that relationship.

Discussion

The purpose of this study was to examine the development of mental folding using a new measure for six- to eight-year-olds, specifically in two capacities: to investigate the relationship between mental folding and spatial anxiety as a function of working memory, and to get further insight into the differences between mental folding and mental rotation. Mental rotation and mental folding were correlated, which we expected based on the overlapping cognitive processes and neurological bases of the two spatial skills (Harris, Hirsh-Pasek, & Newcombe, 2013). The finding that mental folding and mental rotation were slightly more related in girls supported our hypothesis that girls would use a more analytic strategy for both tasks, while boys might use a more holistic strategy on mental rotation and more analytic strategy on mental folding.

When it comes to the relationship between spatial performance, spatial anxiety, and working memory, the results did not entirely support our hypotheses, especially regarding the impact of gender. Mental rotation, which normally does show a gender difference, was not correlated with gender, spatial anxiety, or working memory. While we did not expect to see a gender difference on the paper folding task, we did still anticipate that spatial anxiety would differ as a function of gender and would be related to the spatial tasks. As such, the lack of a gender difference and lack of correlation with mental folding and mental rotation did not support our hypotheses.

Similarly, we failed to replicate the Ramirez et al. (2012) results; they found that spatial anxiety showed a negative relationship with mental rotation ability for girls with high working memory but not girls with low working memory or for boys in general, giving a possible explanation for the gender difference on mental rotation tasks. We replicated their analyses, and while boys' performance on mental folding could be predicted by their spatial anxiety (which Ramirez et al. did not find) and vocabulary scores (which they did not test for, though we did not expect vocabulary to matter in a population that often uses dominantly spatial strategies on this task), none of the other measures were significant for either population or the participants as a whole. The model did predict some of the variance for paper folding, interestingly; the spatial anxiety-working memory interaction and vocabulary contributed significantly to the full group of participants, though the model was not a significant predictor of performance for boys and girls separately. The failure to replicate Ramirez et al. was most likely the result of our having too few participants, but the way paper folding's link with spatial anxiety × working memory did not affect one gender over the other was in line with our hypotheses.

The fact that vocabulary contributed to the paper folding model and was correlated with mental folding but not mental rotation suggests that the ability to use verbal strategies on a spatial problem relies on the ability to verbalize the steps being taken. A child that knows the word 'diagonally,' for instance, may be better at identifying which of the multiple-choice options is symmetrical along a diagonal axis than a child who does not. While our vocabulary task did not include spatial or math terms, that could be an interesting dimension to include in the future. Since mental folding is more susceptible to verbal strategies than mental rotation, mental folding being more highly correlated with vocabulary is understandable.

Similarly, mental folding was related to the digit span task—a verbal working memory measure—while mental rotation was not. The fact that having high verbal working memory was more beneficial for mental folding could support the theory that it is more vulnerable to verbal analytic strategies (Lohman, 1979).

We also found that the relationship between age and mental folding was stronger than the relationship between age and mental rotation; it is possible that the ability to expect symmetrical placement of the holes upon unfolding the paper is related to whether or not a child has developed a linear (as opposed to logarithmic) understanding of numbers and space (Gunderson et al., 2012). People tend to mentally link numbers and space: studies show that people imagine numbers along a line, with small numbers on the leftmost side and larger numbers on the right (Dehaene et al., 1993), and individuals with hemi-spatial neglect will err in the same direction whether bisecting a line or bisecting a numerical interval (Zorzi, Priftis, & Umiltà, 2002). Given that relationship, children who do not yet have a linear representation of numbers may struggle to recognize symmetry in space as well.

While the measures worked remarkably well, given that many were not initially designed to be used virtually, the fact remains that we had a more difficult time giving each child the same experience going through our study. We could not control for internet quality, difficulties using Zoom, or the number of distractions the participants dealt with. In short, virtual research makes it more difficult to provide children with a standardized testing experience, and it is possible that those inconsistencies impacted our results. On a similar vein, on average the study lasted for around an hour, ranging from 40 to 90 minutes; given the age of the participants, boredom and fatigue could have affected the amount of effort given.

The largest limitation we faced, which we have already touched upon, was the low number of participants. Too few participants limited the power of the study, and some of the results suggest that involving more children could yield significant findings. This lack of power could have obscured a relationship between mental rotation and gender or the interaction between spatial anxiety and working memory. Observing the development of a skill, especially with children being assessed virtually, ultimately required more participants and data than we had. To include more participants would increase the power of the study and give more accurate insight into the existence of relationships between measures.

Beyond increasing the number of participants, future research on this topic would do well to look further into different types of math measures. We had no reason to believe that one spatial task would be more related to the Woodcock-Johnson Applied Problems than the other, though paper folding was marginally more related than mental rotation. Since mental rotation has been used to assess how math and spatial skills are related, investigating how mental folding related to those same math skills could show interesting dimensions of the relationship between math and spatial ability (like the relationship between mental folding and the number line). Future iterations could also use missing term problems; Cheng and Mix (2014) found that mental rotation training improves performance on missing term problems. They theorized that improvement on the missing term problems may have resulted from an improved ability to re-model the problems into an easier format (i.e. changing 9 - __ = 5 to __ = 9 – 5). If children solve these problems by mentally transforming equations into a more conventional format, that would suggest a weaker link with mental folding.

The correlational differences we found between mental folding and mental rotation, especially regarding mental folding's relationship with vocabulary and verbal working memory, support Lohman's assertion that mental folding and mental rotation are psychometrically different (a form of visualization and spatial relation, respectively). That supports our earlier argument that mental rotation ought not be treated as a proxy for all spatial skills and gives credence to the idea that spatial ability could illuminate the workings of other cognitive abilities.

In conclusion, the current study failed to find any potential reason for the lack of a gender difference in mental folding, namely in regard to working memory acting as a moderator between spatial anxiety and mental folding. All the same, we did highlight some of the differing skills related to mental folding and mental rotation, and in doing so created points to build on in future research.

References

Beilock, S.L. (2008). Math performance in stressful situations. *Current Directions in Psychological Science, 17*(5), 339–343.

Beilock, S.L. (2010). Choke: What the secrets of the brain reveal about getting it right when you have to, New York, NY: Free Press, Simon & Schuster.

Beilock, S.L. Carr, T.H. (2005). When high-powered people fail: Working memory and “choking under pressure” in math. Psychological Science, *16*(2), 101–105.

Beilock, S.L. DeCaro, M.S. (2007). From poor performance to success under stress: Working memory, strategy selection, and mathematical problem solving under pressure. *Journal of Experimental Psychology: Learning, Memory & Cognition*, *33*(6), 983–998.

Benbow, C. P., Lubinski, D., Shea, D. L., & Eftekhari-Sanjani, H. (2000). Sex differences in mathematical reasoning ability at age 13: Their status 20 years later. *Psychological Science, 11*(6), 474–480. https://doi.org/10.1111/1467-9280.00291

Bethell-Fox, C. E., & Shepard, R. N. (1988). Mental rotation: Effects of stimulus complexity and familiarity. *Journal of Experimental Psychology: Human Perception and Performance, 14*(1), 12.

Caplan, P. J., MacPherson, G. M., & Tobin, P. (1985). Do sex-related differences in spatial abilities exist? A multilevel critique with new data. *American Psychologist, 40*(7), 786–799. https://doi-org.proxy.uchicago.edu/10.1037/0003-066X.40.7.786

Carlson, S.M. Moses, L.J. Breton, C. (2002). How specific is the relation between executive function and theory of mind? Contributions of inhibitory control and working memory. *Infant and Child Development, 11*, 73–92.

Casey, M.B., Dearing, E., Vasilyeva, M., Ganley, C. M., & Tine, M. (2011). Spatial and numerical predictors of measurement performance: The moderating effects of community income and gender. *Journal of Educational Psychology*, *103*(2), 296–311. https://doi.org/10.1037/a0022516

Casey, M.B. Nutall, R.L. Pezaris, E. (1997). Mediators of gender differences in mathematics college entrance test scores: A comparison of spatial skills with internalized beliefs and anxieties. *Developmental Psychology, 33*(4), 669–680.

Casey, M.B. Nutall, R.L. Pezaris, E. (2001). Spatial–mechanical reasoning skills versus mathematics self-confidence as mediators of gender differences on mathematics subtests using cross national gender based items. *Journal for Research in Mathematics Education, 32*(10), 28–57.

Chatterjee, A. (2008, August). The neural organization of spatial thought and language. In *Seminars in speech and language* (Vol. 29, No. 03, pp. 226-238). © Thieme Medical Publishers.

Cheng, Y.L., & Mix, K. (2014). Spatial Training Improves Children's Mathematics Ability. *Journal of Cognition and Development, 15*, 11 - 2.

Cooper LA (1980) Spatial information processing: strategies for research. In: Snow RE, Federico P, Montague WE (eds) *Aptitude, learning, and instruction: cognitive process analysis*, vol 1. Erlbaum, Hillsdale, NJ, pp 149–176

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, *122*, 371–396. doi:10.1037/0096-3445.122.3.371

Diamond, A., Kirkham, N., & Amso, D. (2002). Conditions under which young children can hold two rules in mind and inhibit a prepotent response. *Developmental psychology, 38*(3), 352.

Eme, P.-E. Marquer, J. (1999). Individual strategies in a spatial task and how they relate to aptitudes. *European Journal of Psychology of Education*, *14*(1), 89–108.

Engle, R.W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science*, *11*(1), 19–23.

Feng, J., Spence, I., & Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychological science, 18*(10), 850-855.

Geiser, C., Lehmann, W., & Eid, M. (2006). Separating "rotators" from "nonrotators" in the mental rotations test: A multigroup latent class analysis. *Multivariate Behavioral Research, 41*(3), 261-293.

Guilford, J. P., Fruchter, B., & Zimmerman, W. S. (1952). Factor analysis of the Army Air Forces Sheppard Field battery of experimental aptitude tests. *Psychometrika, 17*(1), 45-68.

Gunderson, E. A., Ramirez, G., Beilock, S. L., & Levine, S. C. (2012). "The relation between spatial skill and early number knowledge: The role of the linear number line": Correction to Gunderson et al. (2012). *Developmental Psychology*, *48*(5), 1241. https://doi.org/10.1037/a0028593

Halpern, D. Benbow, C. Geary, D.C. Gur, R. Hyde, J. Gernsbacher, M.A. (2007). The science of sex differences in science and mathematics. *Psychological Science in the Public Interest, 8*(1), 1–52.

Harris, J., Hirsh-Pasek, K. & Newcombe, N.S. Understanding spatial transformations: similarities and differences between mental rotation and mental folding. *Cogn Process*, *14***,** 105–115 (2013). https://doi.org/10.1007/s10339-013-0544-6

Harris, J., Newcombe, N. S., & Hirsh-Pasek, K. (2013). A new twist on studying the development of dynamic spatial transformations: Mental paper folding in young children. *Mind, Brain, and Education*, 7(1), 49-55.

Hirnstein, M., Bayer, U., & Hausmann, M. (2009). Sex-specific response strategies in mental rotation. *Learning and Individual Differences*, *19*(2), 225–228. https://doi.org/10.1016/j.lindif.2008.11.006

Hodgkiss, A., Gilligan-Lee, K., Thomas, M., Tolmie, A., & Farran, E. (2020). The developmental trajectories of spatial skills in middle childhood.

Jaušovec, N., & Jaušovec, K. (2012). Sex differences in mental rotation and cortical activation patterns: Can training change them?. *Intelligence*, *40*(2), 151-162.

Kail, R., Carter, P., & Pellegrino, J. (1979). The locus of sex differences in spatial ability. *Perception & Psychophysics*, *26*(3), 182-186.

Kaufman, S. B. (2007). Sex differences in mental rotation and spatial visualization ability : Can they be accounted for by differences in working memory capacity? *Intelligence (Norwood)*, *35*(3), 211–223.

Kung, E., & Hamm, J. P. (2010). A model of rotated mirror/normal letter discriminations. *Memory & Cognition*, *38*(2), 206-220.

Levine, S. C., Huttenlocher, J., Taylor, A., & Langrock, A. (1999). Early sex differences in spatial skill. *Developmental Psychology*, *35*(4), 940–949. https://doi.org/10.1037/0012-1649.35.4.940

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child development*, 1479-1498.

Lohman DF (1979) Spatial ability: a review and reanalysis of the correlational literature. Technical report no. 8. Aptitude Research Project, School of Education, Stanford University, Stanford, CA

Lohman DF, Nichols PD (1990) Training spatial abilities: effects of practice on rotation and synthesis tasks. *Learn Individ Differ, 2*(1):67–93

Marquer, J. (1990). Reaction times and verbal reports in the study of strategies: A reply to Evans. *Quarterly Journal of Experimental Psychology*, *42*(1), 171–172.

Milivojevic, B., Johnson, B. W., Hamm, J. P., & Corballis, M. C. (2003). Non-identical neural mechanisms for two types of mental transformation: event-related potentials during mental rotation and mental paper folding. *Neuropsychologia, 41*(10), 1345-1356.

Mix, K. S., Hambrick, D. Z., Satyam, V. R., Burgoyne, A. P., & Levine, S. C. (2018). The latent structure of spatial skill: A test of the 2× 2 typology. *Cognition, 180*, 268-278.

Miyake, A., & Shah, P. (Eds.). (1999). *Models of working memory: Mechanisms of active maintenance and executive control*. Cambridge University Press.

Newcombe, N. S. (2010). Picture this: Increasing math and science learning by improving spatial thinking. *American Educator, 34*(2), 29.

Newcombe, N. S., & Shipley, T. F. (2015). Thinking about spatial thinking: New typology, new assessments. In J. Gero (Ed.), *Studying visual and spatial reasoning for design creativity* (pp. 179–192). New York: NY: Springer. https://doi.org/10.1007/978-94-017-9297-4_10

Pezaris, E. Casey, M.B. (1991). Girls who use “masculine” problem-solving strategies on a spatial task: Proposed genetic and environmental factors. *Brain & Cognition*, 17, 1 1–22.

Pribyl, J.R. & Bodner, G.M. (1987). Spatial ability and its role in organic chemistry: A study of four organic courses. *Journal of Research in Science Teaching*, *24*(3), 229–240.

Ramirez, G. Gunderson, E.A. Levine, S.C. Beilock, S.L. (2009). The influence of math anxiety on young children's math achievement, Poster presented at the Midwestern Psychological Association, Chicago, IL May.

Ramirez, G., Gunderson, E. A., Levine, S. C., & Beilock, S. L. (2012). Spatial Anxiety Relates to Spatial Abilities as a Function of Working Memory in Children. *Quarterly Journal of Experimental Psychology*, *65*(3), 474–487. https://doi.org/10.1080/17470218.2011.616214

Ratliff, K.R. Saunders, J. Levine, S.C. (2009). The cognitive basis of individual differences in children's mental transformation skill, Poster presented at the annual Psychonomics Society, Boston, MA November.

Searle, J. A., & Hamm, J. P. (2012). Individual differences in the mixture ratio of rotation and nonrotation trials during rotated mirror/normal letter discriminations. *Memory & cognition*, *40*(4), 594-613.

Shepard, R. N., & Cooper, L. A. (1986). *Mental images and their transformations*. The MIT Press.

Siegler, R. S., & Booth, J. L. (2004). Development of Numerical Estimation in Young Children. *Child Development*, *75*(2), 428–444.

Sorby, S. A. (2009). Educational research in developing 3-D spatial skills for engineering students. *International Journal of Science Education, 31*(3), 459-480.

Stieff, M. (2007). Mental rotation and diagrammatic reasoning in science. *Learning and instruction*, *17*(2), 219-234.

Suinn, R. M., Taylor, S., & Edwards, R. W. (1988). Suinn Mathematics Anxiety Rating Scale for Elementary School Students (MARS-E): Psychometric and Normative Data. *Educational and Psychological Measurement*, *48*(4), 979–986. https://doi.org/10.1177/0013164488484013

Swanson, H. L. (2004). Working memory and phonological processing as predictors of children's mathematical problem solving at different ages. *Memory & cognition*, *32*(4), 648-661.

Unterrainer, J., Wranek, U., Staffen, W., Gruber, T., & Ladurner, G. (2000). Lateralized cognitive visuospatial processing: Is it primarily gender-related or due to quality of performance?. *Neuropsychobiology*, *41*(2), 95-101.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, 139, 352–402. https://doi.org/10.1037/a0028446

Wechsler, D., & Kodama, H. (1949). *Wechsler intelligence scale for children* (Vol. 1). New York: Psychological corporation.

Woodcock, R. W., McGrew, K. S., & Mather, N., (2001). Woodcock-Johnson III examiner's manual. Itasca, IL: Riverside.

Wright, R., Thompson, W. L., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic bulletin & review*, *15*(4), 763-771.

Xu, Y., & Franconeri, S. L. (2015). Capacity for visual features in mental rotation. *Psychological science*, *26*(8), 1241-1251.

Zorzi, M., Priftis, K., & Umilta`, C. (2002, May 9). Brain damage: Neglect disrupts the mental number line. *Nature*, *417*, 138 –139. doi:10.1038/417138a