British Journal of Developmental Psychology (2016)

The British Psychological Society

www.wileyonlinelibrary.com

The space-math link in preschool boys and girls: Importance of mental transformation, targeting accuracy, and spatial anxiety

Wang I. Wong*

Department of Psychology, University of Hong Kong, Hong Kong

Spatial abilities are pertinent to mathematical competence, but evidence of the space-math link has largely been confined to older samples and intrinsic spatial abilities (e.g., mental transformation). The roles of gender and affective factors are also unclear. This study examined the correlations between counting ability, mental transformation, and targeting accuracy in 182 Hong Kong preschoolers, and whether these relationships were weaker at higher spatial anxiety levels. Both spatial abilities related with counting similarly for boys and girls. Targeting accuracy also mediated the male advantage in counting. Interestingly, spatial anxiety moderated the space-math links, but differently for boys and girls. For boys, spatial abilities were irrelevant to counting at high anxiety levels; for girls, the role of anxiety on the space-math link is less clear. Results extend the evidence base of the space-math link to include an extrinsic spatial ability (targeting accuracy) and have implications for intervention programmes.

Statement of contribution

What is already known on this subject?

- Much evidence of a space-math link in adolescent and adult samples and for intrinsic spatial abilities.

What does this study add?

- Extended the space-math link to include both intrinsic and extrinsic spatial abilities in a preschool sample.
- Showed how spatial anxiety moderated the space-math link differently for boys and girls.

Spatial abilities are crucial for mathematical achievement (Mix & Cheng, 2012), and both show male advantages (Miller & Halpern, 2014). However, unlike adults and adolescents, the space-math link in young children is not well documented (Mix & Cheng, 2012). Additionally, besides mental rotation, the consequences of other spatial abilities are largely unknown. Finally, how the space-math link is moderated by gender and affective factors is currently unclear. These questions are pertinent to understanding women's underrepresentation in science and technology fields (Ceci & Williams, 2007; Hyde, Lindberg, Linn, Ellis, & Williams, 2008; Miller & Halpern, 2014), and to interventions of spatial and mathematical abilities.

Mathematical ability

Findings regarding gender differences in mathematical ability vary. Most studies found small to negligible male advantages in mean performance (Else-Quest, Hyde, & Linn, 2010;

*Correspondence should be addressed to Wang I. Wong, Department of Psychology, 6/F, Jockey Club Tower, Centennial Campus, University of Hong Kong, Pokfulam, Hong Kong, Hong Kong (email: iwwong@hku.hk).

DOI:10.1111/bjdp.12161

Hyde *et al.*, 2008; Miller & Halpern, 2014), and apparent male advantages at top tails of score distributions (Benbow, 1988; Mills, Ablard, & Stumpf, 1993; Wai, Cacchio, Putallaz, & Makel, 2010). The male advantage becomes more apparent in high school, when mathematical problems become more spatial than computational (Halpern *et al.*, 2007; Hyde, Fennema, & Lamon, 1990; Miller & Halpern, 2014). A study using nationally representative samples even reported a male advantage in mean performance at first grade (Rathbun, West, & Hausken, 2004). Notably, Penner and Paret (2008) reported a similar male advantage in difficult mathematics among kindergartners. These male advantages are thought to be caused in part by male advantages in spatial abilities (Mix & Cheng, 2012).

Spatial abilities and the space-math link

Spatial abilities have traditionally been categorized as spatial perception (determining spatial relationships with respect to body orientation), mental rotation (mentally visualizing rotated objects), or spatial visualization (manipulating spatial information in multisteps with multiple solution strategies; overlaps with mental rotation and spatial perception) (Linn & Peterson, 1985). Meta-analysed gender differences are moderate to large for mental rotation, moderate for spatial perception, and negligible for spatial visualization (Linn & Peterson, 1985; Voyer, Voyer, & Bryden, 1995).

There is strong evidence of moderate-to-high correlations between spatial ability and mathematical competence in school-age and college students (Casey, Nuttall, Pezaris, & Benbow, 1995; Friedman, 1995; van Garderen, 2006; Voyer & Sullivan, 2003). Intervention studies, such as one that used an object-completion task to train spatial abilities, corroborated these correlations (Cheng & Mix, 2014). Recent studies further found that preschoolers' mental rotation (Gunderson, Ramirez, Beilock, & Levine, 2012), spatial visualization (Barnes *et al.*, 2011; Zhang *et al.*, 2014), spatial perception (Zhang & Lin, 2015), and spatial assembly (Verdine *et al.*, 2014) abilities correlate or predict mathematical abilities. Consequently, the largest gender difference in state mathematics tests is in the domain requiring spatial understanding (Else-Quest *et al.*, 2010; Harnisch, Steinkamp, Tsai, & Walberg, 1986); controlling for the gender differences in spatial ability eliminates the gender difference in SAT-Math (Burnett, Lane, & Dratt, 1979; Casey *et al.*, 1995; Casey, Nuttall, Pezaris, & Benbow, 1997).

Researchers believe that even basic mathematical abilities (e.g., counting) involve considerable spatial reasoning (Hoshi *et al.*, 2000; Zhang *et al.*, 2014; Zhou *et al.*, 2006), although it is unclear how exactly spatial understanding facilitates mathematical understanding (Mix & Cheng, 2012). Conceivably, spatial representations may facilitate mathematical understanding by helping to develop mental models of number (Mix & Cheng, 2012) and assess numerical magnitude and line length (Dehaene, 2011; de Hevia & Spelke, 2010; Gunderson *et al.*, 2012).

Among all spatial abilities, mental rotation is the most extensively studied in relation to mathematics. The gender difference in mental rotation is one of the largest among spatial abilities, universally present in adults across 53 nations (Lippa, Collaer, & Peters, 2010), and has not decreased over the decades (Masters & Sanders, 1993; Voyer *et al.*, 1995). It also emerges as early as 3 and 5 months of age in a few studies using looking-time measures (Moore & Johnson, 2008; Quinn & Liben, 2008) and around 4–5 years of age in some studies using paper tests (Levine, Huttenlocher, Taylor, & Langrock, 1999; Perrucci, Agnoli, & Albiero, 2003).

Like mental rotation, targeting accuracy, the ability to aim accurately at a target, also shows a consistent male advantage that emerges as early as preschool age, except that the gender difference in targeting accuracy is even larger and more stable across ages (Thomas & French, 1985). Because one rationale to link mathematics with spatial abilities is that both favour males, the space-math link may reasonably be extended to include targeting accuracy. However, whereas other spatial abilities have been studied in relation to mathematics (e.g., Barnes *et al.*, 2011; Casey *et al.*, 1995; Gunderson *et al.*, 2012; Zhang & Lin, 2015; Zhang *et al.*, 2014), targeting accuracy has not. This is surprising considering the consistent gender difference found in targeting accuracy and the importance of this ability, such as in sports and driving. One reason of this lack of research may be that targeting accuracy does not fit readily into traditional categories of spatial abilities (Linn & Peterson, 1985). However, these categories are vague, non-exclusive, and non-exhaustive (Mix & Cheng, 2012; Voyer *et al.*, 1995).

Another possibility is that targeting tasks (e.g., throwing balls at a target) usually involve both motoric coordination and spatial analysis. However, motoric coordination shows no consistent gender difference (Ellis *et al.*, 2013; Moser & Reikeras, 2014) and therefore cannot explain the male advantage in targeting accuracy; neither is there a basis to expect that motor coordination, instead of spatial abilities involved in targeting, would be related to mathematics. In fact, targeting accuracy tasks such as ball throwing have been used widely as measures of spatial ability (e.g., Auyeung *et al.*, 2012; Hines *et al.*, 2003; Jardine & Martin, 1983; Watson & Kimura, 1991).

Evidently, accurate targeting relies heavily on spatial analysis (Kimura, 1993). For example, aiming requires accurate judging of relative distance and velocity of moving objects, and tracking of moving objects (Geary, 1996). Thus, targeting accuracy recruits spatial orientation (perceiving relative positions of objects and viewer, particularly across changes in orientation) and visualization (perceiving complex spatial patterns and comprehend imaginary movements), two of the three major spatial factors identified by factor analyses (Mix & Cheng, 2012). Targeting accuracy can also be conceptualized by a new categorization (Newcombe & Shipley, 2015; Uttal *et al.*, 2013) as an extrinsic (involving spatial relations among objects and between objects and the surrounding space) and dynamic (involving movement and transformation) spatial ability, whereas spatial abilities that have been related to mathematics (e.g., mental rotation) are intrinsic (spatial representations that are intrinsic to objects). Regardless of the typology, some unique spatial processes involved in targeting, such as judging distance in space and projecting trajectory as objects move, are analogous to certain crucial cognitive processes involved in mathematics, such as judging distance on the number line during addition and subtraction. In fact, number estimation is thought to share with space and time estimations the same cognitive intuition within the approximate number system, the cognitive ability to non-verbally represent numerical quantity or magnitude (Dehaene & Brannon, 2010). Moreover, success in science and technology requires both intrinsic and extrinsic spatial abilities (Newcombe & Shipley, 2015). However, the role of extrinsic spatial abilities in mathematical competence is unknown. This knowledge is relevant to understanding the space-math link (Mix & Cheng, 2012) and diversifying intervention strategies.

Gender differences in the space-math link

Although the space-math link is generally robust, some studies found gender specificity. For example, a stronger link in boys has been found in preschool (Klein, Adi-Japha, & Hakak-Beizri, 2010) and middle school (Ganley & Vasilyeva, 2011). Consistent with a stronger link in males, self-reports, reaction time measures, and verbal-distraction studies suggest that females use more verbal strategies and males more spatial strategies when solving visual–spatial problems (Eme & Marquer, 1999; Marquer, 1990; Pezaris & Casey, 1991). Similarly, females use more language-based, and males more spatial-based, strategies when solving mathematical problems (Geary, Saults, Liu, & Hoard, 2000). Also, mental rotation activates the language-related and the spatial-related brain regions more in females and males, respectively (Jordan, Wustenberg, Heinze, Peters, & Jancke, 2002). Even young boys seem to apply more spatial reasoning than girls do in visual–spatial problems (Ratliff, Saunders, & Levine, 2009; Tzuriel & Egozi, 2007, 2010) and mathematical problems (Carr & Jessup, 1997; McGuinness, 1993; Vasilyeva, Casey, Dearing, & Ganley, 2009).

However, a stronger space-math link in girls has also been found in college and middle school (Casey *et al.*, 1995; Friedman, 1995), the reason of which is unclear (Casey *et al.*, 1995). Some have suggested that results may depend on age and type of test (Ganley & Vasilyeva, 2011). Because spatial strategies are often more efficient than verbal strategies when solving spatial (Bethel-Fox & Shepard, 1988; Geiser, Lehmann, & Eid, 2006; Moe, Meneghetti, & Cadinu, 2009) and mathematical tasks (Halpern, Wai, & Saw, 2005), it is important to study whether and how the space-math link differs for boys and girls.

Affective factors

Besides cognitive factors such as spatial abilities, affective factors also affect spatial and mathematical learning. Girls experience more negative affect (e.g., spatial anxiety, Ramirez, Gunderson, Levine, & Beilock, 2012; mathematics anxiety, Ma & Cartwright, 2003; Tocci & Engelhard, 1991), especially as they grow older (Hyde *et al.*, 1990). Stress (Beilock & Carr, 2005), fear of mathematics (Ashcraft & Kirk, 2001), and stereotype threat (Steele & Aronson, 1995) affect mathematical performance. Similarly, affective factors such as confidence (Estes & Felker, 2012) and stereotype threat (cf. Doyle & Voyer, 2016; Flore & Wicherts, 2015) affect spatial performance. High spatial anxiety may also discourage the application of spatial strategies. For example, spatial anxiety is negatively correlated with spatial strategy use in way-finding (Kallai, Karadi, & Kovacs, 2000; Lawton, 1994). Therefore, the space-math link may be weaker at higher anxiety levels. However, this possibility has rarely been tested.

Overview

This study explored the early link between two spatial abilities (one intrinsic, one extrinsic) and counting ability, and the moderation effects by gender and spatial anxiety. Mental transformation, targeting accuracy, counting ability, and spatial anxiety were measured in Hong Kong preschoolers. Counting is a major pre-mathematical ability at preschool age and strongly predicts mathematics achievement in primary school (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004; Aunola, Leskinen, & Nurmi, 2006). Although the magnitude of gender differences varies across cultures, like many countries, male advantages in mathematical performance and affect (Else-Quest *et al.*, 2010) and spatial abilities (Lippa *et al.*, 2010) have been found in older Hong Kong samples. A Hong Kong-based study also reported the expected space-math link in preschoolers (Zhang & Lin, 2015). Thus, findings in Hong Kong and elsewhere are mutually relevant.

The hypotheses tested were that first, boys would score higher on mental transformation (H1a) and targeting accuracy (H1b), and either higher than or similarly as girls on counting (H1c), and lower on spatial anxiety (H1d). Second, mental transformation (H2a) and targeting accuracy (H2b) would correlate positively with counting. Because prior findings have been mixed, this study also explored whether the correlations were stronger in boys or girls. Third, male advantages in spatial abilities would mediate any potential gender difference in counting (H3). Finally, the space-math link would be weaker at high spatial anxiety levels (H4). Major results were supplemented with bootstrap confidence intervals or p-values based on 5,000 bootstrap samples for more accurate estimates and less reliance on normality (Hayes, 2013).

Method

Participants and procedures

Participants were 182 K3 children (99 boys and 83 girls) from 10 kindergartens in Hong Kong. Based on income per household member and the number of households living in poverty per district (Hong Kong Census Department, Government of the Hong Kong Special Administrative Region, 2013), four kindergartens, five kindergartens, and one kindergarten were from relatively low (poorest one-third), middle, and high (wealthiest one-third) socio-economic districts, respectively. Among the boys, 24%, 71%, and 5% were from low, middle, and high socio-economic districts, respectively; among the girls, these percentages were 29%, 67%, and 4%. Boys and girls did not differ in family income or parental education, ps $> .05$. Chinese was the major ethnicity (99%; 1% mixed). Ethical approval was obtained from the Human Research Ethics Committee at a local university.

Participants took part in a larger study on spatial and social abilities. Parental consent and student assent were obtained before testing. For this study, participants completed the mental transformation measure, followed by the counting task, and then the targeting accuracy task, and finally the spatial anxiety interview. They were tested individually in a quiet room in their preschool and received a HKD50 cash coupon for compensation.

Mental transformation

Levine's Mental Transformation Task (MT) (Levine *et al.*, 1999) assessed mental rotation (MT-rotation) and mental translation (MT-translation: transformation not requiring rotation). It has been shown to be sensitive to the male advantage in children as young as 4.5 years old (Ehrlich, Levine, & Goldin-Meadow, 2006; Levine *et al.*, 1999). There were four practice items and 32 test items (16 rotational, 16 translational), each requiring the child to choose one of four whole shapes that can be formed by two given halves. The final score (MT-total) was the number of correct answers (0–32). The Cronbach's alpha was .76. The total score was above chance level (8) for boys, $t(98) = 22.84$, $p < .001$, bootstrap mean difference = 11.70, 95%CI [10.69, 12.69] and girls, $t(82) = 18.00$, $p < .001$, bootstrap mean difference = 10.81, 95%CI [9.63, 11.95].

Targeting accuracy

The adapted targeting task (Auyeung *et al.*, 2012; Hines *et al.*, 2003) required participants to throw Velcro balls at the centre of a 1 m $\times$ 1 m Velcro board mounted vertically 1.2 m away using their dominant hand. There were four practice trials and 10 test trials. Sticker markers recorded the position of the ball after each test throw. The distance (millimetres) from the centre was averaged. Shorter distance indicates higher accuracy.

Counting

The Diagnostic Tests for Metacognitions and Mathematics (Salonen *et al.*, 1994) assessed counting ability. One item asked participants to count from 1 to 50. One point was given for correct counting without errors. Eight items required participants to count forward (four items), or backward (four items), from a given number. One point was given for correctly counting at least four numbers. Another four items asked participants what number s/he would reach by making a certain count starting from a given number. One point was given for each correct answer. The total score was the sum of correct answers (0–13). The Cronbach's alpha was .80.

Spatial anxiety

The adapted eight-item Child Spatial Anxiety Questionnaire (CSAQ) (Ramirez *et al.*, 2012) asked about spatial activities that might make children nervous (e.g., 'How do you feel being asked to say which direction is right or left?'). Items were translated and back-translated into Chinese by the author and assistants proficient in Chinese and English. Participants responded by pointing to smileys representing a 5-point scale (0 = not anxious at all; 4 = very, very anxious). The researcher first explained the scale. Children were asked whether they understood what it meant by being anxious, to give examples of anxious situations, and to familiarize with the scale (e.g., by pointing to the smiley representing a certain anxiety level). Interview started after the child confirmed s/he understood the scale. All children indicated that they understood the scale. Four items referring to blocks, maps, shapes, and mazes were supplemented with picture stimuli used in Ramirez *et al.* (2012), except that a Hong Kong map replaced the U.S. map. Scores were averaged. The Cronbach's alpha was .66, which was higher than that reported in the original study (Ramirez *et al.*, 2012). However, both alphas can be considered good for short measures of children's attitudes (Ramirez *et al.*, 2012).

Results

H1 Gender differences in spatial abilities, counting, and spatial anxiety

Gender differences were tested using planned independent *t*-tests. Contrary to hypotheses, there were no significant gender differences in MT-total, $t(180) = 1.14, p = .258$, or spatial anxiety, $t(180) = -0.30, p = .767$. However, counting showed a male advantage, $t(180) = 2.63$, $p = .009$, as did targeting accuracy, $t(180) = 2.86$, $p = .005$. Table 1 shows scores on each variable.

H2 Correlation between spatial abilities and counting

The unique correlations of MT-total and targeting with counting were tested using a multiple regression on counting using mental transformation, targeting, and their interaction with gender as predictors. Family income and parental education were entered as covariates. Gender, family income, and parental education were entered in the first block. MT-total and targeting were added to the second block. Two interaction terms (gender × MT-total and gender × targeting) were added to the final block. MT-total and targeting each correlated uniquely with counting even after controlling for gender and socio-economic status. The interactions were not significant, indicating that the correlation of counting with MT-total and targeting did not vary across gender. Although targeting did not correlate with counting in the third model, the R^2 change of the third

Table 1. Boys' and girls' performance

	Boys (n = 99)		Girls (n = 83)				
	M	*SD*	*M*	*SD*	*d*	Bootstrap mean difference	95% CI
MT-total	19.70	5.10	18.81	5.47	0.17	0.89	−0.66, 2.46
Targeting	158.68	49.91	180.02	50.59	−0.42	21.34	−36.05, −6.89
Counting	10.25	2.43	9.27	2.62	0.39	0.99	0.22, 1.72
Spatial anxiety	1.83	0.86	1.86	0.83	−0.04	−0.04	−0.28, 0.21

Note. A positive *d* for all the variables but targeting indicates a male advantage.

model was not significant, meaning that interpretation should be based on the second model. Additionally, the interaction terms had tolerance of <.10 and variance impact factors >10, suggesting that they are redundant. Table 2 shows that boys', but not girls', targeting correlated moderately with MT. Table 3 shows results from the multiple regression.

H3 Types of spatial abilities as mediators of gender differences in counting

The potential role of MT-total and targeting accuracy as mediators between gender and counting, controlling for family income and parental education, was tested in PROCESS (Hayes, 2013). Unlike Baron and Kenny's causal steps approach, modern mediation analysis does not depend on the showing of significant correlations in each step of the mediation model. Rather, the analysis directly tested the indirect effects (i.e., mediation), with significance indicated by bootstrap confidence intervals. The results reported here focus on the indirect effect by MT-total and targeting accuracy. The model was significant, R^2 = .293, F(5, 176) = 14.619, p < .001. The indirect effect of targeting was significant, B = −0.14, bootstrap SE = 0.09, bootstrap 95% CI [−0.39, −0.02], but the indirect effect of mental transformation was not, B = −0.11, bootstrap SE = 0.11, bootstrap 95%CI [−0.36, 0.08]. The direct effect of gender (i.e., effect of gender after accounting for the mediation) was not significant, B = −0.63, SE = 0.33, t(176) = −1.873, p = .063, 95%CI [−1.28, 0.03].

H4 The space-math link across levels of spatial anxiety

Finally, H4 was tested with a regression-based moderation analyses employing the Johnson–Neyman (JN) technique (Hayes, 2013), using spatial anxiety as the moderator for the effect of each spatial ability on counting. The JN technique identifies value(s) of a continuous moderator that cut(s) off significant and non-significant regions. This test of moderation differs from pick-a-point methods (e.g., traditionally used in ANOVAs and regressions) in that no arbitrary cut-off points based on percentiles or means/*SDs* are needed (Hayes, 2013). Using this method, an interaction is indicated by cut-off values that are identified, and the identification of these values (or of no values) replaces the reliance on arbitrary values. The JN technique was run by PROCESS (Hayes, 2013) and allowed one moderator at a time, and was thus conducted separately for boys and girls and for each spatial ability. To complement H4, simple correlations between spatial anxiety and spatial ability and counting were also tested.

Table 2. Intercorrelations

	1. MT-total	2. Targeting	3. Counting	4. Anxiety
1. MT-total	–	−**.27 (.006) [−0.45, −0.10]**	**.51 (<.001) [0.35, 0.65]**	.02 (.853) [−0.20, 0.22]
2. Targeting	.00 (.984) [−0.22, 0.22]	–	−**.28 (.005) [−0.45, −0.10]**	−.03 (.794) [−0.24, 0.20]
3. Counting	**.31 (.004) [0.11, 0.52]**	−.17 (.130) [−0.36, 0.03]	–	.11 (.293) [−0.13, 0.33]
4. Anxiety	−.14 (.198) [−0.38, 0.11]	.14 (.201) [−0.10, 0.36]	−.13 (.226) [−0.37, 0.12]	–

Note. Correlation statistics are *r* (*p*-value) [bootstrap 95% CI]. Above the diagonal: boys (n = 99). Below the diagonal: girls (n = 83). Significant correlations are in bold.

Table 3. Multiple regression on counting

Model		B	SE	β	t	p-Value	Bootstrap p-value
1	(Constant)	8.036	0.866		9.282	<.001	<.001
	Gender	−0.876	0.348	−.171	−2.517	.013	.012
	Family income	1.009	0.278	.299	3.637	<.001	.001
	Parental education	0.257	0.161	.132	1.601	.111	.104
	R^2 = .189, adjusted R^2 = .175, $F(3, 178)$ = 13.838, p < .001						
2	(Constant)	6.802	1.154		5.894	<.001	<.001
	Gender	−.625	0.334	−.122	−1.873	.063	.062
	Family income	0.627	0.272	.186	2.301	.023	.011
	Parental education	0.232	0.152	.119	1.528	.128	.124
	MT-total	0.146	0.033	.301	4.425	<.001	<.001
	Targeting	−0.007	0.003	−.136	−2.059	.041	.045
	R^2 = .293, adjusted R^2 = .273, R^2 change = .104, p < .001, $F(5, 176)$ = 14.619, p < .001						
3	(Constant)	6.254	2.976		2.102	.037	.047
	Gender	−0.266	1.833	−.052	−0.145	.885	.878
	Family income	0.621	0.278	.184	2.236	.027	.011
	Parental education	0.226	0.153	.116	1.479	.141	.135
	MT-total	0.161	0.048	.331	3.328	.001	<.001
	Targeting	−0.007	0.005	−.144	−1.547	.124	.147
	Gender × MT-total[a]	−0.030	0.064	−.117	−0.461	.645	.668
	Gender × Targeting[a]	0.001	0.007	.045	0.180	.857	.853
	R^2 = .295, adjusted R^2 = .266, R^2 change = .001, p = .871, $F(7, 174)$ = 10.380, p < .001						

Note. [a]Tolerance statistic of these predictors suggested that they were redundant.

Results suggested a gender-specific moderating role of anxiety. For boys, spatial abilities correlated with counting except when anxiety was *high*. MT-total correlated with counting, $B = 0.33$, $t(93) = 3.43$, $p < .001$, but not if anxiety was above 2.85 ($n = 9$ in the non-significant region). Targeting correlated with counting, $B = -0.02$, $t(93) = -2.07$, $p = .041$, but, again, not if anxiety was above 2.37 ($n = 32$ in the non-significant region).

For girls, spatial abilities either correlated with counting if anxiety was *not low*, or the space-math link *did not* depend on anxiety. Specifically, MT-total did not correlate with counting, $B = 0.00$, $t(77) = 0.03$, $p = .967$, but this was true only when anxiety was below 1.60 ($n = 31$). Targeting did not correlate with counting, $B = 0.01$, $t(7) = -0.42$, $p = .678$, and there were no cut-off values.

Results from the JN analyses are illustrated in Figure 1. The horizontal line on the y-axis indicates when the effect of spatial ability on counting is 0 (position in each graph differs depending on the observed range of correlation coefficients and the confidence intervals). Positive values on the y-axis indicate positive correlations between spatial abilities and counting, and vice versa for negative values. Regions in which the 95% upper and lower limit Confidence Intervals cover 0 are the regions in which the space-math link is non-significant. Table 2 shows that spatial anxiety did not correlate directly with spatial abilities or counting.

Discussion

Results add to growing evidence linking preschoolers' spatial abilities to mathematical abilities (Barnes *et al.*, 2011; Gunderson *et al.*, 2012; Verdine *et al.*, 2014; Zhang & Lin,

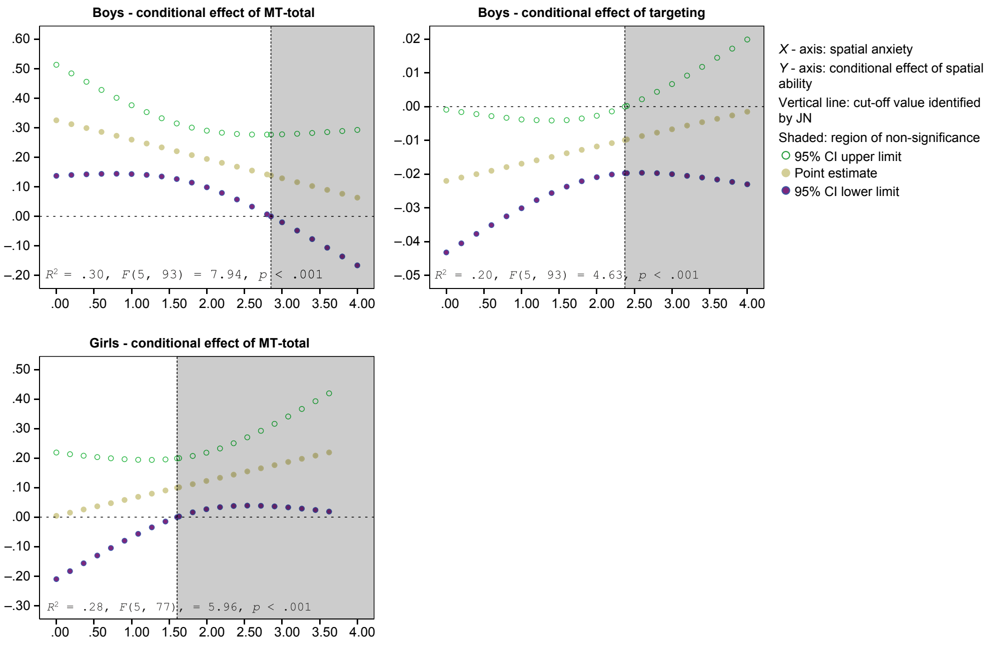

Figure 1. Results from JN analyses, showing conditional effect of spatial abilities on counting as a function of spatial anxiety. The graph of girls' targeting is not shown because there were no cut-off values. The horizontal line on the *y*-axis indicates when the correlation between spatial ability and counting is 0. Regions in which the 95% upper and lower limit confidence intervals cover zero are the regions of non-significance (the shaded areas). A positive correlation between mental transformation and counting means that higher mental transformation ability correlates with better counting, but a negative correlation between targeting and counting means that higher targeting accuracy correlates with better counting.

2015; Zhang *et al.*, 2014). They extend the evidence base of the space-math link to include an extrinsic, dynamic spatial ability (targeting accuracy) and have implications for spatial and mathematics intervention.

Gender differences in spatial abilities, counting, and spatial anxiety (H1)

Counting and targeting accuracy showed male advantages, while spatial anxiety and mental transformation showed no gender differences. The gender differences in spatial abilities and spatial anxiety appeared to be smaller in this preschool sample than Western samples (e.g., Miller & Halpern, 2014; Ramirez *et al.*, 2012; Voyer *et al.*, 1995). The male advantage in counting is consistent with some studies and inconsistent with others, as prior studies have found mixed results (Ellis *et al.*, 2013). It is possible that the gender differences would grow larger with age. By adolescence, Hong Kong students show significant male advantages in mathematical and spatial abilities (Else-Quest *et al.*, 2010; Lippa *et al.*, 2010) and also show the largest gender difference in mathematics self-confidence across countries (Else-Quest *et al.*, 2010).

The majority of studies on gender differences have been conducted in North America and Europe and in older samples. No study using the current measures in comparable samples is available for comparison. However, some other studies have also found no gender difference on the Levine's Mental Transformation Task (e.g., Hawes, Lefevre, Xu, & Bruce, 2015). Additionally, the small gender differences in this study may not be surprising considering its cultural context. Gender differences in spatial and mathematical abilities and attitudes in older samples vary across cultures (e.g., Else-Quest *et al.*, 2010; Lippa *et al.*, 2010). The smaller gender differences in spatial abilities likely reflect cultural-specific influences. For example, writing Chinese serves as spatial training and improves spatial abilities (Li, Nuttall, & Zhu, 1999), and spatial training has been found to diminish gender differences (Uttal *et al.*, 2013). However, despite cultural differences in levels of performance and sizes of gender differences, the cognitive mechanisms underlying mathematical learning are similar across cultures (Zhang & Lin, 2015), so the current findings are relevant to understanding mathematical learning elsewhere.

Correlation between spatial abilities and counting (H2)

More importantly, this is the first study to relate targeting accuracy to mathematics. Although rarely studied as an antecedent to other outcomes, targeting accuracy is important for various daily activities, such as sports and driving. How targeting accuracy relates to other spatial abilities is unclear (cf. Hines *et al.*, 2003; Watson & Kimura, 1991). Here, mental transformation and targeting accuracy were dissociated in girls, and only correlated moderately in boys, suggesting that these are overlapping but different spatial abilities (also see Saucier & Kimura, 1998).

As hypothesized, mental transformation and targeting accuracy both correlated uniquely with counting (H2). This suggested that, besides blocks and puzzle training (Cheng & Mix, 2014), extra-personal, dynamic spatial training (e.g., sports involving targeting) may effectively improve mathematics performance. For example, a unique spatial process involved in targeting, judging distance in space, is analogous to a crucial process involved in mathematics, judging distance on the number line. Both processes may share their root in the approximate number system (Dehaene & Brannon, 2010). Practice in one process therefore likely improves the other. Moreover, as in previous studies (Thomas & French, 1985; Voyer *et al.*, 1995), targeting accuracy showed a larger male advantage than mental transformation. There is thus value to consider diverse types of spatial abilities, such as targeting accuracy, in studying the space-math link (Mix & Cheng, 2012).

There was no gender difference in the space-math link, but significant male advantages in counting and targeting accuracy, suggesting that the root of later male advantages in spatial abilities and mathematics may not initially lie in the differential application of spatial abilities, but in male advantages in spatial and mathematical abilities *per se*. The finding of a similar space-math link in boys and girls contradicts the finding of a stronger space-math link in young boys (Klein *et al.*, 2010) and findings that showed a higher tendency for males to apply spatial reasoning (e.g., Geary *et al.*, 2000; Pezaris & Casey, 1991; Tzuriel & Egozi, 2007, 2010). However, the space-math link may show a gender difference at older ages in the current sample if, for example, girls slowly lose motivation to apply spatial abilities because they have poorer spatial abilities. Spatial abilities become increasingly crucial in more advanced mathematics (Halpern *et al.*, 2007; Hyde *et al.*, 1990; Miller & Halpern, 2014), so it would also be important to test how early disadvantages in spatial abilities in girls intensify gender gaps in mathematics later.

Types of spatial abilities as mediators of gender differences in counting (H3)

Prior studies in the West found that mental rotation mediated the gender difference in college entrance test scores, both of which showed a male advantage in high school (Casey *et al.*, 1997; Casey *et al.*, 1995). Incidentally, boys in this study were better at counting and targeting accuracy, although not mental transformation, than girls. Consistent with hypothesis, targeting accuracy mediated the gender difference in counting (H3). The mediation analysis showed that targeting accuracy, but not mental transformation, mediated the male advantage in counting. This finding gives further support to the hypothesis that male advantages in mathematical ability can be explained in part by spatial abilities that also show male advantages (Mix & Cheng, 2012).

The space-math link across levels of spatial anxiety (H4)

Interestingly, spatial anxiety moderated the space-math link, but differently for boys and girls, offering partial support to the hypothesis that the space-math link would be weaker at high anxiety levels (H4).

Although some studies have reported correlations between anxiety and mathematical achievement in older samples (Ma & Cartwright, 2003; Miller & Bichsel, 2004), spatial anxiety did not correlate with spatial abilities or counting in the preschoolers. Rather, results were consistent with Ramirez *et al.* (2012) who found no direct role of spatial anxiety in young children's spatial ability, but a moderating role of spatial anxiety in the effect of working memory on spatial ability. The current results also found a moderating role of spatial anxiety, such that it seemed to relate to whether spatial abilities correlated with counting.

For boys, the space-math link consistently disappeared at high anxiety levels. For girls, the link with targeting was consistent across anxiety levels (therefore not shown in Fig. 1), and the link with MT-total disappeared at low anxiety levels. The moderation involving boys' MT-total should be interpreted with caution because the sample size in the non-significant region was small (n = 9), and small samples are more likely to yield non-significant results. However, similar results were found even for boys' targeting accuracy, in which the sample size in the non-significant region was not small (n = 32). This lends credibility to the finding that the space-math link in boys was weaker at high anxiety levels. Also, sample size considerations cannot explain why, for a given analysis, the non-significant region appeared at one end of anxiety level and not the other.

The finding in boys resonates with the finding that spatial anxiety correlated negatively with spatial strategy use (Kallai *et al.*, 2000; Lawton, 1994). The finding in girls, that the space-math link tended to disappear at low anxiety level, is less intuitive. It could be that a minimum level of spatial anxiety is needed to drive girls to use spatial abilities. Perhaps girls with low spatial anxiety also have low general anxiety; these girls may feel they can rely on some slow, non-spatial strategies. However, the CSAQ correlated uniquely with spatial performance and not reading achievement (Ramirez *et al.*, 2012), suggesting that it is not a proxy for general anxiety. It is also possible that for the girls, the anxiety level was a manifestation instead of determinant of their strategy use. Experimental research and research using other samples and related forms of anxiety (e.g., math anxiety) will be needed to evaluate these possibilities.

The utilization of spatial abilities benefits spatial and mathematical performance (Ganley & Vasilyeva, 2011; Halpern *et al.*, 2007; Mix & Cheng, 2012; Moe *et al.*, 2009). Therefore, formal teaching of spatial abilities and their application have been encouraged (Casey *et al.*, 2008). Results suggested that for both boys and girls, from preschool, affective factors should also be considered to optimize training outcomes. In particular, although it is unclear how anxiety relates to girls' application of spatial abilities, reducing anxiety levels may encourage boys to apply spatial abilities.

Limitations

The Child Spatial Anxiety scale (Ramirez *et al.*, 2012) is a trait measure. Findings may differ when using a state anxiety measure. However, if traits reflect reliable predisposed tendencies to behave in a certain way across situations (Matthews, Deary, & Whiteman, 2003), then the CSA should generally reflect state anxiety.

Although the targeting accuracy task has been used as a measure of spatial ability (e.g., Auyeung *et al.*, 2012; Hines *et al.*, 2003; Jardine & Martin, 1983; Watson & Kimura, 1991) and motoric coordination shows no consistent gender difference (Ellis *et al.*, 2013; Moser & Reikeras, 2014), it is still possible that gender difference on the targeting task was affected by motor competence and throwing experience. Future studies may utilize non-motoric targeting tasks (Falter, Arroyo, & Davis, 2006) to single out the spatial element of targeting accuracy.

This study controlled for socio-economic variables that may confound the relationships between spatial ability and counting. However, other types of non-spatial abilities were not included, so general intelligence was not ruled out as a possible confounding factor.

This study and some others inferred the use of spatial strategies in mathematics if the spatial abilities and mathematics performance were correlated. Future studies can assess strategy use more closely by examining participants' descriptions of how they solved the problems. Besides, longitudinal and experimental research controlling for general intelligence in addition to socio-economic status can help test the hypothesized causal effects.

Conclusion

This study extends recent research showing an early space-math link. Both extrinsic and intrinsic spatial abilities are related to mathematical ability in young children. Although the space-math link was not stronger in boys, boys outperformed girls in targeting accuracy and counting. Targeting accuracy also mediated the gender difference in counting. These findings suggest that in preschoolers, gender differences in spatial abilities, more than gender differences in the application of spatial abilities, relate to gender differences in mathematical ability. Although the space-math link was similar for boys and girls, its relation to spatial anxiety was gender specific. Findings contribute to the understanding and intervention of spatial and mathematical learning. Future studies may test other types of spatial abilities, differentiate the mechanisms through which anxiety affects the space-math link, and explore how and when gender differences in the space-math link develop.

References

Ashcraft, M. H., & Kirk, E. P. (2001). The relationships among working memory, math anxiety, and performance. *Journal of Experimental Psychology: General*, *130*, 224–237. doi:10.1037//0096-3445.130.2.224

Aunola, K., Leskinen, E., Lerkkanen, M. K., & Nurmi, J. E. (2004). Developmental dynamics of math performance from preschool to Grade 2. *Journal of Educational Psychology*, *96*, 699–713. doi:10.1037/0022-0663.96.4.699

Aunola, K., Leskinen, E., & Nurmi, J. E. (2006). Developmental dynamics between mathematical performance, task motivation, and teachers' goals during the transition to primary school. *British Journal of Educational Psychology*, *76*, 21–40. doi:10.1348/000709905X51608

Auyeung, B., Knickmeyer, R., Ashwin, E., Kevin, T., Hackett, G., & Baron-Cohen, S. (2012). Effects of fetal testosterone on visuospatial ability. *Archives of Sexual Behavior*, *41*, 571–581. doi:10.1007/s10508-011-9864-8

Barnes, M. A., Stubbs, A., Raghubar, K. P., Agostino, A., Taylor, H., Landry, S., . . . Smith-Chant, B. (2011). Mathematical abilities in 3- and 5-year-olds with spina bifida and their typically developing peers: A longitudinal approach. *Journal of the International Neuropsychological Society*, *17*, 431–444. doi:10.1017/S1355617711000233

Beilock, S. L., & Carr, T. H. (2005). When high-powered people fail: Working memory and "choking under pressure" in math. *Psychological Science*, *16*, 101–105. doi:10.1111/j.0956-7976.2005.00789.x

Benbow, C. P. (1988). Sex differences in mathematical reasoning ability in intellectually talented preadolescence: Their nature, effects, and possible causes. *Behavioral and Brain Sciences*, *11*, 169–183. doi:10.1017/S0140525X00049244

Bethel-Fox, C. E., & Shepard, R. N. (1988). Mental rotation: Effects of stimulus complexity and familiarity. *Journal of Experimental Psychology: Human Perception and Performance*, *14*, 12–23. doi:10.1037/0096-1523.14.1.12

Burnett, S. A., Lane, D. M., & Dratt, L. M. (1979). Spatial visualization and sex differences in quantitative ability. *Intelligence*, *3*, 345–354. doi:10.1016/0160-2896(79)90003-5

Carr, M., & Jessup, D. L. (1997). Gender differences in first-grade mathematics strategy use: Social and metacognitive influences. *Journal of Educational Psychology*, *89*, 318–328. doi:10.1037/0022-0663.89.2.318

Casey, M. B., Andrews, N., Schindler, H., Kersh, J., Samper, A., & Copley, J. (2008). The development of spatial abilities through interventions involving block-building activities. *Cognition and Instruction*, *26*, 269–309. doi:10.1080/07370000802177177

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

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

Ceci, S. J., & Williams, W. M. (2007). *Why aren't more women in science? Top researchers debate the evidence*. Washington, DC: American Psychological Association.

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

de Hevia, M. D., & Spelke, E. S. (2010). Number–space mapping in human infants. *Psychological Science*, *21*, 653–660. doi:10.1177/0956797610366091

Dehaene, S. (2011). *The number sense: How the mind creates mathematics* (2nd ed.). New York, NY: Oxford University Press.

Dehaene, S., & Brannon, E. M. (2010). Space, time, and number: A Kantian research program. *Trends in Cognitive Sciences*, *14*, 517–519. doi:10.1016/j.tics.2010.09.009

Doyle, R. A., & Voyer, D. (2016). Stereotype manipulation effects on math and spatial test performance: A meta-analysis. *Learning and Individual Differences*, *47*, 103–116. doi:10.1016/j.lindif.2015.12.018

Ehrlich, S. B., Levine, S. C., & Goldin-Meadow, S. (2006). The importance of gesture in children's spatial reasoning. *Developmental Psychology*, *42*, 1259–1268. doi:10.1037/0012-1649.42.6.1259

Ellis, L., Hershberger, S., Field, E., Wersinger, S., Pellis, S., Geary, D., . . . Karadi, L. (2013). *Sex differences: Summarizing more than a century of scientific research*. New York, NY: Psychology Press.

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

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*, 89–108. doi:10.1007/BF03173113

Estes, Z., & Felker, S. (2012). Confidence mediates the sex differences in mental rotation performance. *Archives of Sexual Behavior*, *41*, 557–570. doi:10.1007/s10508-011-9875-5

Falter, C. M., Arroyo, M., & Davis, G. J. (2006). Testosterone: Activation or organization of spatial cognition?. *Biological Psychology*, *73*, 132–140. doi:10.1016/j.biopsycho.2006.01.011

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

Friedman, L. (1995). The space factor in mathematics: Gender differences. *Review of Educational Research*, *65*, 22–50. doi:10.3102/00346543065001022

Ganley, C. M., & Vasilyeva, M. (2011). Sex differences in the relation between math performance, spatial abilities, and attitudes. *Journal of Applied Developmental Psychology*, *32*, 235–242. doi:10.1016/j.appdev.2011.04.001

Geary, D. C. (1996). Sexual selection and sex differences in mathematical abilities. *Behavioral and Brain Sciences*, *19*, 229–284. doi:10.1017/S0140525X00042400

Geary, D. C., Saults, S. J., Liu, F., & Hoard, M. K. (2000). Sex differences in spatial cognition, computational fluency, and arithmetic reasoning. *Journal of Experimental Child Psychology*, *77*, 337–358. doi:10.1006/jecp.2000.2594

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*, 261–293. doi:10.1006/jecp.2000.2594

Gunderson, E. A., Ramirez, G., Beilock, S. L., & Levine, S. C. (2012). The relation between spatial ability and early number knowledge: The role of the linear number line. *Developmental Psychology*, *48*, 1229–1241. doi:10.1037/a0027433

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

Halpern, D. F., Wai, J., & Saw, A. (2005). A psychobiosocial model: Why females are sometimes greater than and sometimes less than males in math achievement. In A. M. Gallagher & J. C. Kaufman (Eds.), *Gender differences in mathematics: An integrative psychological approach* (pp. 48–72). Cambridge, UK: Cambridge University Press.

Harnisch, D. L., Steinkamp, M. W., Tsai, S. L., & Walberg, H. J. (1986). Cross-national differences in mathematics attitude and achievement among seventeen-year-olds. *International Journal of Educational Development*, *6*, 233–244. doi:10.1016/0738-0593(86)90027-1

Hawes, Z., Lefevre, J., Xu, C., & Bruce, C. (2015). Mental rotation with tangible three-dimensional objects: A new measure sensitive to developmental differences in 4- to 8-year-old children. *Mind, Brain and Education*, *9*, 10–18. doi:10.1111/mbe.12051

Hayes, A. F. (2013). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach*. New York, NY: The Guilford Press.

Hines, M., Fane, B. A., Pasterski, V. L., Mathews, G. A., Conway, G. S., & Brook, C. (2003). Spatial abilities following prenatal androgen abnormality: Targeting and mental rotations performance in individuals with congenital adrenal hyperplasia. *Psychoneuroendocrinology*, *28*, 1010–1026. doi:10.1016/S0306-4530(02)00121-X

Hong Kong Census Department, Government of the Hong Kong Special Administrative Region. (2013). *Hong Kong poverty situation report 2012*. Retrieved from http://www.povertyrelief.gov.hk/pdf/2012_Poverty_Situation_Eng.pdf

Hoshi, Y., Oda, I., Wada, Y., Ito, Y., Yamashita, Y., Oda, M., . . . Tamura, M. (2000). Visuospatial imagery is a fruitful strategy for the digit span backward task: A study with near-infrared optical tomography. *Cognitive Brain Research*, *9*, 339–342. doi:10.1016/S0926-6410(00)00006-9

Hyde, J. S., Fennema, E., & Lamon, S. J. (1990). Gender differences in mathematics performance: A meta-analysis. *Psychological Bulletin*, *107*, 139–155. doi:10.1037/0033-2909.107.2.139

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

Jardine, R., & Martin, N. S. (1983). Spatial ability and throwing accuracy. *Behavior Genetics*, *13*, 331–340. doi:10.1007/BF01065771

Jordan, K., Wustenberg, T., Heinze, H. J., Peters, M., & Jancke, L. (2002). Women and men exhibit different cortical activation patterns during mental rotation tasks. *Neuropsychologia*, *40*, 2397–2408. doi:10.1016/S0028-3932(02)00076-3

Kallai, J., Karadi, K., & Kovacs, B. (2000). Influences of fear and anxiety on organization of way-finding and spatial orientation. *Review of Psychology*, *7*, 27–35.

Kimura, D. (1993). *Neuromotor mechanisms in human communication*. New York, NY: Oxford University Press.

Klein, P. S., Adi-Japha, E., & Hakak-Beizri, S. (2010). Mathematical thinking of kindergarten boys and girls: Similar achievement, different contributing processes. *Educational Studies in Mathematics*, *73*, 233–236. doi:10.1007/s10649-009-9216-y

Lawton, C. A. (1994). Gender differences in way-finding strategies: Relationship to spatial ability and spatial anxiety. *Sex Roles*, *30*, 765–779. doi:10.1007/BF01544230

Levine, S. C., Huttenlocher, J., Taylor, A., & Langrock, A. (1999). Early sex differences in spatial ability. *Developmental Psychology*, *35*, 940–949. doi:10.1007/BF01065974

Li, C., Nuttall, R. L., & Zhu, W. (1999). Writing Chinese characters and success on mental rotation test. *Perceptual and Motor Skills*, *88*, 1261–1270. doi:10.2466/PMS.88.3.1261-1270

Linn, M. C., & Peterson, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development*, *56*, 1479–1498. doi:10.2307/1130467

Lippa, R. A., Collaer, M. L., & Peters, M. (2010). Sex differences in mental rotation and line angle judgments are positively associated with gender equality and economic development across 53 nations. *Archives of Sexual Behavior*, *39*, 990–997. doi:10.1007/s10508-008-9460-8

Ma, X., & Cartwright, F. (2003). A longitudinal analysis of gender differences in affective outcomes in mathematics during middle and high school. *School Effectiveness and School Improvement*, *14*, 413–439. doi:10.1076/sesi.14.4.413.17155

Marquer, J. (1990). Reaction times and verbal reports in the study of strategies: A reply to Evans. *Quarterly Journal of Experimental Psychology*, *42*, 171–172. doi:10.1080/14640749008401214

Masters, M. S., & Sanders, B. (1993). Is the gender difference in mental rotation disappearing? *Behavioral Genetics*, *23*, 337–341. doi:10.1007/BF01067434

Matthews, G., Deary, I. J., & Whiteman, M. C. (2003). *Personality traits*. Cambridge, UK: Cambridge University Press.

McGuinness, D. (1993). Gender differences in cognitive style: Implications for mathematics performance and achievement. In L. A. Penner, G. M. Batsche, H. M. Knoff & D. L. Nelson (Eds.), *The challenge of mathematics and science education: Psychology's response* (pp. 251–274). Washington, DC: American Psychological Association.

Miller, H., & Bichsel, J. (2004). Anxiety, working memory, gender, and math performance. *Personality and Individual Differences*, *37*, 591–606. doi:10.1016/j.paid.2003.09.029

Miller, D. I., & Halpern, D. F. (2014). The new science of cognitive sex differences. *Trends in Cognitive Sciences*, *18*, 37–45. doi:10.1016/j.tics.2013.10.011

Mills, C. J., Ablard, K. E., & Stumpf, H. (1993). Gender differences in academically talented young students' mathematical reasoning: Patterns across age and subskills. *Journal of Educational Psychology*, *85*, 340–346. doi:10.1037/0022-0663.85.2.340

Mix, K. S., & Cheng, Y. L. (2012). The relation between space and math: Developmental and educational implications. In J. B. Benson (Ed.), *Advances in child development and behavior* (Vol. 42, pp. 197–243). Burlington, MA: Academic Press.

Moe, A., Meneghetti, C., & Cadinu, M. (2009). Women and mental rotation: Incremental theory and spatial strategy use enhance performance. *Personality and Individual Differences*, *46*, 187–191. doi:10.1016/j.paid.2008.09.030

Moore, D. S., & Johnson, S. P. (2008). Mental rotation in human infants: A sex difference. *Psychological Science*, *19*, 1063–1066. doi:10.1111/j.1467-9280.2008.02200.x

Moser, T., & Reikeras, E. (2014). Motor-life-skills of toddlers: A comparative study of Norwegian and British boys and girls applying the Early Years Movement Skills Checklist. *European Early Childhood Education Research Journal*, *24*, 115–135. doi:10.1080/1350293X.2014.895560

Newcombe, N. S., & Shipley, T. F. (2015). Thinking about spatial thinking: New typology, new assessments. In J. S. Gero (Ed.), *Studying visual and spatial reasoning for design creativity* (pp. 179–192). New York, NY: Springer.

Penner, A. M., & Paret, M. (2008). Gender differences in mathematics achievement: Exploring the early grades and the extremes. *Social Science Research*, *37*, 239–253. doi:10.1016/j.ssresearch.2007.06.012

Perrucci, V., Agnoli, F., & Albiero, P. (2003, April). *Stimulus type, age and gender effects on mental rotation*. Poster presented at the Biennial Meeting of the Society for Research in Child Development, Tampa, FL.

Pezaris, E., & Casey, M. B. (1991). Girls who use "masculine" problem-solving strategies on a spatial task: Proposed genetic and environmental factors. *Brain and Cognition*, *17*, 1–22. doi:10.1016/0278-2626(91)90062-D

Quinn, P. C., & Liben, L. S. (2008). A sex difference in mental rotation in young infants. *Psychological Science*, *19*, 1067–1070. doi:10.1111/j.1467-9280.2008.02201.x

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. *The Quarterly Journal of Experimental Psychology*, *65*, 474–487. doi:10.1080/17470218.2011.616214

Rathbun, A., West, J., & Hausken, E. G. (2004). *From kindergarten through third grade: Children's beginning school experiences*. NCES Publication No. 2004-2007, Washington, DC: United States Department of Education, National Center for Education Statistics.

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

Salonen, P., Lepola, J., Vauras, M., Rauhanummi, T., Lehtinen, E., & Kinnunen, R. (1994). *Diagnostiset testit 3. Motivaatio, Metakognitio ja Matematiikka [Diagnostic Tests 3: Motivation, metacognition and mathematics]*. Turku, Finland: Center for Learning Research, University of Turku.

Saucier, D., & Kimura, D. (1998). Intrapersonal motor, but not extra-personal targeting skill is enhanced during the midluteal phase of the menstrual cycle. *Developmental Neuropsychology*, *14*, 385–398. doi:10.1080/87565649809540717

Steele, C. M., & Aronson, J. (1995). Stereotype threat and the intellectual test performance of African Americans. *Journal of Personality and Social Psychology*, *69*, 797–811. doi:10.1037/0022-3514.69.5.797

Thomas, J. R., & French, K. E. (1985). Gender differences across age in motor performance: A meta-analysis. *Psychological Bulletin*, *98*, 260–282. doi:10.1037//0033-2909.98.2.260

Tocci, C. M., & Engelhard, G. (1991). Achievement, parental support, and gender differences in attitudes toward mathematics. *Journal of Educational Research*, *84*, 280–286. doi:10.1080/00220671.1991.10886028

Tzuriel, D., & Egozi, G. (2007). Dynamic assessment of young children's spatial abilities. *Journal of Cognitive Education and Psychology*, *6*, 218–247. doi:10.1891/194589507787382160

Tzuriel, D., & Egozi, G. (2010). Gender differences in spatial ability of young children: The effects of training and processing strategies. *Child Development*, *81*, 1417–1430. doi:10.1111/j.1467-8624.2010.01482.x

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

van Garderen, D. (2006). Spatial visualization, visual imagery, and mathematical problem solving of students with varying abilities. *Journal of Learning Disabilities*, *39*, 496–506. doi:10.1177/00222194060390060201

Vasilyeva, M., Casey, B. M., Dearing, E., & Ganley, C. M. (2009). Measurement skills in low-income elementary school students: Exploring the nature of gender differences. *Cognition and Instruction*, *27*, 401–428. doi:10.1080/07370000903221809

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., Newcombe, N. S., Filipowicz, A. T., & Chang, A. (2014). Deconstructing building blocks: Preschoolers' spatial assembly performance relates to early mathematics skills. *Child Development*, *85*, 1062–1076. doi:10.1111/cdev.12165

Voyer, D., & Sullivan, A. (2003). The relation between spatial and mathematical abilities: Potential factors underlying suppression. *International Journal of Psychology*, *38*, 11–23. doi:10.1080/00207590244000241

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin*, *117*, 250–270.

Wai, J., Cacchio, M., Putallaz, M., & Makel, M. C. (2010). Sex differences in the right tail of cognitive abilities: A 30 year examination. *Intelligence*, *38*, 412–423. doi:10.1016/j.intell.2010.04.006

Watson, N. V., & Kimura, D. (1991). Nontrivial sex differences in throwing and intercepting: Relation to psychometrically-defined spatial functions. *Personality and Individual Differences*, *12*, 375–385. doi:10.1016/0191-8869(91)90053-E

Zhang, X., Koponen, T., Rasanen, P., Aunola, K., Lerkkanen, M. K., & Nurmi, J. E. (2014). Linguistic and spatial abilities predict early arithmetic development via counting sequence knowledge. *Child Development*, *85*, 1091–1107. doi:10.1111/cdev.12173

Zhang, X., & Lin, D. (2015). Pathways to arithmetic: The role of visual-spatial and language skills in written arithmetic, arithmetic word problems, and nonsymbolic arithmetic. *Contemporary Educational Psychology*, *41*, 188–197. doi:10.1016/j.cedpsych.2015.01.005

Zhou, X., Chen, C., Zhang, H., Xue, G., Dong, Q., Jin, Z., . . . Chen, C. (2006). Neural substrates for forward and backward recitation of numbers and the alphabet: A close examination of the role of intraparietal sulcus and perisylvian areas. *Brain Research*, *1099*, 109–120. doi:10.1016/j.brainres.2006.01.133

Received 22 May 2016; revised version received 20 September 2016