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by

Eukyung Yhang

Dr. Hojin Kim
Adviser

Institute of Quantitative Theory and Methods

Dr. Hojin Kim

Adviser

Dr. Patricia Bauer

Committee Member

Dr. Scott Lilienfeld

Committee Member

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An abstract of
a thesis submitted to the Faculty of Emory College of Arts and Sciences
of Emory University in partial fulfillment
of the requirements of the degree of
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Abstract

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There is a well-established relation between spatial reasoning abilities and math achievement (Mix & Cheng, 2012). However, research examining the association between mental rotation and math skills is relatively limited. In the current meta-analysis, I quantified the magnitude of the relation between mental rotation and math performance by synthesizing data from 19,870 participants across 59 articles. Furthermore, I examined the developmental trajectory of this association between early childhood and adulthood as well as the role of potential procedural variables (e.g., math task characteristics) in moderating its magnitude across development. The meta-analysis demonstrated that there is a moderate correlation between mental rotation and math performance (r = 0.30) that exhibits developmental continuity between the ages of 4 and 32 years. Additional analyses indicated that type of math task (e.g., geometry, arithmetic) and type of stimuli presented in the math task (i.e., symbolic, non-symbolic) significantly moderated the strength of the association, but moderators related to the mental rotation task (e.g., stimulus dimensionality) did not influence the magnitude of the correlation between mental rotation and math performance. The theoretical and educational implications of present findings are discussed within the context of the spatial development and math cognition literatures.

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A Meta-Analysis of the Relation Between Mental Rotation Ability and Math Achievement

Growing evidence suggests that spatial reasoning abilities are critical to math achievement (for review, see Mix & Cheng, 2012). Numerous cross-sectional studies have reported a relation between spatial ability and math achievement, when measured via various spatial tasks, such as mental rotation (e.g., Delgado & Prieto, 2004), spatial visualization (e.g., Markey, 2010), and visuospatial working memory (e.g., Kyttälä, Aunio, Lehto, Van Luit, & Hautamäki, 2003). Similarly, the relation also has been documented across various math measures, such as arithmetic (e.g., Mix et al., 2016), geometry (e.g., Battista, 1990), and numerical concepts (e.g., Rider, 2003). Providing further support for this relation, longitudinal studies have demonstrated that spatial abilities during adolescence predict later academic and professional success in math-related fields (Kell, Lubinski, Benbow, & Steiger, 2013; Wai, Lubinksi, & Benbow, 2009; Wai, Lubinski, Bebow, & Steiger, 2010; Webb, Lubinski, & Benbow, 2007) and that the predictive relation between spatial reasoning and math achievement emerges during early childhood (Casey et al., 2015; Cheng & Mix, 2014; Gunderson, Ramirez, Beilock, & Levine, 2012; Lauer & Lourenco, 2016). In light of these findings, research examining this relation not only has the potential to contribute insight into the cognitive processes that are integral to quantitative reasoning, but also is of educational relevance.

Mental rotation, which refers to the ability to rotate mental images of objects, is a hallmark of spatial reasoning that has been particularly well studied in relation to math performance. For instance, considerable evidence suggests that mental rotation is correlated with math performance at multiple points in development (for review, see Mix & Cheng, 2012) and for different measures of math proficiency, including arithmetic (e.g., Hawes, Moss, Caswell, & Poliszczuk, 2015) and geometry tasks (e.g., Casey, Nuttall, Pezaris, & Benbow, 1995). However, despite evidence of a link across development and diverse measures of math performance, the magnitude of the correlation is not yet known. Additionally, it is unclear the extent to which it varies across the development and the extent to which procedural factors influence it.

Therefore, in the current study, I explored the relation between mental rotation and math performance via meta-analysis to address open questions regarding its magnitude and consistency across development and across procedural moderators of interest. This meta-analysis was undertaken with three specific aims: 1) to quantify the strength of the association between mental rotation ability and math achievement across development, 2) to characterize the developmental trajectory of this relation between early childhood and adulthood, and 3) to identify demographic (e.g., gender) and procedural moderators (e.g., type of math task) that influence its magnitude. In the following sections, I discuss outstanding questions regarding the association between mental rotation and math performance that have motivated this meta-analysis. I first review the evidence of developmental change of this relation and subsequently consider potential demographic variables (e.g., gender) and task-related variables that may impact the magnitude of the relation across development.

Developmental Change

The relation between mental rotation and math skills have been studied in childhood, adolescence, and adulthood. A number of studies have reported significant relations between mental rotation and geometry skill in middle- and high-school students (Battista, 1990; Delgado & Prieto, 2004; Kyttälä & Lehto, 2008) and between measures of mental rotation and basic numerical processes (e.g., numerical concepts, number line mapping, numerosity comparison) in adults aged 18 to 44 years (Rider, 2003; Thompson, Nuerk, Moeller, & Kadosh, 2013). Similarly, studies have reported a significant correlation between mental rotation and math ability in younger children, when measured both concurrently and longitudinally. For instance, Hawes and colleagues (2015) found a moderate correlation between mental rotation and arithmetic performance in children aged 6 to 8 years (see also, Lauer & Lourenco, 2016). Similarly, Gunderson and colleagues (2012) demonstrated that children's mental rotation ability at five years of age was correlated with their number line knowledge at six years of age as well as their calculation performance at eight years of age. Furthermore, a recent longitudinal study reported that this predictive relation between mental rotation and math ability may emerge even earlier in development (Lauer & Lourenco, 2016). Taken together, these findings suggest that the relation between mental rotation ability and math achievement is present by elementary school and continues to be detectable throughout middle school, high school, and into adulthood.

Although a link between mental rotation and math performance has been documented at multiple points in development, it remains unclear whether age moderates the magnitude of this association. Despite some evidence, the consistency of the relation over time remains an open question, and previous literature puts forth three clear predictions regarding the potential developmental trajectory of the relation between mental rotation and math performance.

The first possibility supported by the literature is that the correlation between mental rotation and math increases with age. One may expect age-related gains in the magnitude of this relation given that the nature of math assessments administered to participants changes considerably across development, becoming more spatially relevant with age. During early childhood, math assessments commonly require math skills that are not overtly spatial, such as counting and simple arithmetic. As children advance in their schooling, math that more overtly relies on spatial concepts, namely geometry, becomes increasingly more prominent. Thus, one may predict that correlation between mental rotation and math performance will emerge early in children and will simultaneously increase across development as math becomes more spatial in nature.

An alternative prediction furnished by previous research is that the association between mental rotation and math will diminish with age. It has been argued that spatial abilities may be particularly useful in learning mathematical and scientific concepts, but that they are less crucial to performance once foundational concepts are acquired (Uttal & Cohen, 2012). On this view, spatial abilities may serve primarily as a gateway to math success, becoming less central to math performance after a certain level of proficiency is obtained. Thus, one may predict that the correlation between mental rotation and math performance will decrease with age, particularly within a given domain of mathematical reasoning. For example, spatial skills may be highly related to children's arithmetic performance because young children rely on spatial mental models to acquire a foundational understanding of numbers and their transformations. However, as children's knowledge of numbers and basic operations solidifies, they may successfully solve arithmetic problems without recruiting spatial processes. Therefore, it is plausible that the importance of spatial skills in math performance declines with age, particularly within a given domain of mathematics.

A final possibility is that the relation between mental rotation and math performance is developmentally continuous, exhibiting consistency in its magnitude across the lifespan. Evidence that early mental rotation skills scaffold numerical development, which in turn facilitates later math performance supports this possibility. For instance, Gunderson and colleagues (2012) documented a predictive relation between children's mental rotation skills at five years of age and their number line knowledge at six years of age, the latter of which predicted children's performance on a calculation task at eight years of age. The authors argued that early spatial skills may assist children in mapping symbolic numbers onto spatial concepts such as the number line, supporting the development of early numerical knowledge and computation skills. If mental rotation indeed facilitates the acquisition of basic numerical concepts, such as number line knowledge, we may expect that the correlation between mental rotation and math would emerge early in life and be maintained throughout development.

Considering the variability in findings of the extant literature, the developmental trajectory of the mental rotation-math association remains unclear. Previous longitudinal studies have examined this association over the course of less than five years and were thus limited to address the question of its developmental trajectory. Furthermore, the developmental change cannot be characterized by comparing studies because too few have examined multiple age groups. Thus, for a more comprehensive understanding of the mental rotation-math link across development, the current meta-analysis examined the effect of mean sample age on reported correlations between mental rotation ability and math achievement.

Gender Differences

One of the reasons that the association between spatial and mathematical reasoning has garnered substantial attention in the scientific literature is that a male advantage in performance is present within both domains by adulthood (Linn & Petersen, 1985; Voyer, Voyer, & Bryden, 1995; Maccoby & Jacklin, 1974). In addition to gender differences in spatial and math performance, there is evidence that the relation between spatial and math performance differs for women and men. More specifically, some studies have reported that the correlation between mental rotation and math performance is stronger for males than females (e.g., Klein, Adi-Japha, & Hakak-Beizri, 2010; Ganley & Vasilyeva, 2011). These findings are particularly interesting as some researchers have contended that males are more likely to employ spatial strategies during mathematical problem-solving than are females, who may be relatively more likely to employ verbal strategies (Gallagher et al., 2000; Geary, Saults, Liu, & Hoard, 2000). Although this is an interesting possibility, there is conflicting evidence of this gender difference within the literature, with some researchers even reporting larger correlations between spatial and math performance among female participants (Casey et al., 1995; Friedman, 1995). Consequently, I sought to characterize the role of gender in the relation between mental rotation and math performance in the present meta-analysis by considering gender as a moderator of reported effect sizes.

Task-level Variables

In addition to age and gender, the literature suggests that a number of task-related variables may moderate the relation between mental rotation and math performance. In the present meta-analysis, I considered four procedural variables as potential moderators. Two of the task-level moderators of interest pertained to the math measure: 1) type of math task, such as arithmetic, basic numerical processes, and geometry, and 2) type of math stimulus, namely symbolic or non-symbolic. The remaining two moderators pertained to the mental rotation measure: 1) type of mental rotation task, namely object completion and object discrimination, and 2) stimulus dimensionality, namely two-dimensional and three-dimensional. These procedural moderators are discussed in detail below.

Math task. Previous studies have largely administered tasks that test three types of math skills: arithmetic, basic numerical processes (e.g., numerical concepts, number line mapping, numerosity comparison), and geometry. The literature suggests that spatial processing in mental rotation may facilitate performance in overtly spatial math measures (e.g., geometry) because they require reasoning about spatial features (e.g., form, angle) and spatial relations (for a review, see Mix & Cheng, 2012). However, significant relations between mental rotation and math performance have been detected with math measures that are overtly spatial (e.g., Battista, 1990; Delgado & Prieto, 2004) as well as with those that are less overtly spatial (e.g., arithmetic; Carr, Steiner, Kyser, & Biddlecomb, 2008; Weckbacher & Okamoto, 2014), suggesting that mental rotation may be related to math performance in less ostensible ways.

Why might spatial abilities be related to performance on less overtly spatial math abilities, such as arithmetic or basic numerical processing? Evidence from various sources have led researchers to speculate that spatial concepts serve as a metaphor for mathematical concepts (for review, see Mix & Cheng, 2012). For instance, individuals exhibit faster response to small numbers with their left hand and to large numbers with their right hand, a phenomenon termed the SNARC effect (i.e., Spatial Numerical Association of Response Codes effect; Dehaene, Bossini, & Giraux, 1993). This effect illustrates that the individuals are representing numbers in space using a mental number line, and thus biased to associate small numbers with the left side and the large numbers with the right side. This association between space and number appears to be also neurally instantiated, as overlapping regions of parietal cortex are recruited during both spatial and numerical processing (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999). Both behavioral and neuroimaging findings point to a predisposition to associate space with number. However, there is evidence that these space-number mappings may not necessarily relate to math performance (Cipora & Nuerk, 2013). Thus, it remains unclear whether one would expect individual differences in spatial abilities to relate to individual differences in performance on measures of basic numerical processing such as number line knowledge.

Spatial abilities may be linked with performance on arithmetic measures via their role in the construction of mental models. In their training study, Cheng and Mix (2014) reported that training children to solve mental rotation tasks through the transformation of mental imagery led to a significant improvement in their calculation performance, particularly on missing-term calculation problems (e.g., 2 + __ = 7). The authors argued that children may be solving these problems by engaging in mental rotation to transform the location of the numbers in "mental space" (e.g., __ = 7 – 2), and that the mental rotation training may have facilitated the underlying process of mental transformation (Cheng & Mix, 2014). This finding suggests that mental rotation and arithmetic may share cognitive processes and that mental rotation ability may be just as important to arithmetic performance as it is to performance in more overtly spatial math such as geometry.

Although there is a wealth of research on the relation between spatial abilities and math performance, conclusions about the role of mental rotation ability in different subdomains of math have been unclear as existing studies have rarely administered different types of math tasks and often used composite measures of math performance (e.g., SAT-Math). Moreover, the type of math task administered is confounded with age as studies have often administered arithmetic, basic numerical processes, and geometry tasks to children, adolescents, and adults, respectively. Thus, our understanding of how age and math task uniquely relate to the magnitude of the correlation has been further hindered. Therefore, to address these issues the present meta-analysis separated the confounds between age and math task by observing age-related change within each type of math task, in addition to assessing the effect of type of math task on the magnitude of the relation by analyzing the types of mathematical tasks administered.

Type of stimuli in math task. As noted earlier, humans have a tendency to associate numbers with space and to use a spatial-mathematical metaphors like the mental number line (Gunderson et al., 2012; Mix & Cheng, 2012). Therefore, on this view that space provides a metaphor for symbolic numerical concepts (e.g., digits), one can divide the type of stimuli in math tasks into two categories: symbolic (e.g., digits) and non-symbolic (e.g., sets of dots). Furthermore, one may expect to find a greater relation between mental rotation and math performance with symbolic math stimuli than with non-symbolic stimuli, because symbolic stimuli recruits the use of spatial metaphors. To examine this possibility, the present meta-analysis assessed the effect of type of stimuli in math task on reported correlations between mental rotation and math performance.

Mental rotation task. As with math tasks, mental rotation tasks vary in their use across development. In adolescence and adulthood, mental rotation ability is generally assessed via tasks that require participants to discriminate between rotated mirrored figures, such as the Vandenberg-Kuse Mental Rotation Test (VMRT; Vandenberg & Kuse, 1978; see Figure 1), which require active dynamic visualization and rotation of objects. In childhood, mental rotation ability is more often assessed using object completion tasks that require children to construct a shape using the mental alignment of its component parts, such as the Children's Mental Transformation Task (CMTT; Levine, Huttenlocher, Taylor, & Langrock., 1999; see Figure 1A) and the Primary Mental Abilities-Space Relations subtest (PMA-SR; Thurstone & Thurstone, 1943; see Figure 1B). An important difference between these types of mental rotation tasks is the degree to which they necessitate the use of mental rotation processes for successful task completion. For instance, object completion tasks may be solved by mentally rotating component shapes or may alternatively be solved by attending to shape features (e.g., angles, edges) that are unique to the component shapes. In contrast, object discrimination tasks are difficult to solve without employing mental rotation strategies. As object discrimination tasks may be more likely to rely on dynamic visualization and mental rotation, it is possible that the correlation between mental rotation and math performance will be particularly pronounced for these types of mental rotation tasks. Therefore, the present study assessed the effect of type of mental rotation task on the magnitude of the mental rotation-math relation by categorizing mental rotation tasks into two groups: object completion (e.g., CMTT, PMA-SR) and object discrimination (e.g., VMRT) tasks.

Dimensionality of mental rotation task stimuli. The rigor of mental rotation assessments can be influenced by the dimensionality of their stimuli. Three-dimensional (3D) stimuli are often more complex than two-dimensional (2D) stimuli, potentially placing greater demands on visuospatial working memory (Peters et al., 1995). Because both mental rotation and math performance are closely linked to visuospatial working memory (Kaufman, 2007; Kyttlälä & Lehto, 2008), one may expect to see larger correlations between mental rotation and math performance when 3D stimuli are used to assess mental rotation ability. To investigate this possibility, this meta-analysis examined the effect of stimulus dimensionality on the magnitude of the correlation between mental rotation ability and math achievement.

Current Research

As detailed above, there are numerous outstanding questions regarding the relation between mental rotation and math performance and its variation across sample-level and task-level variables. Given the diversity of samples and procedures, these questions about age-related change, gender difference, and procedural variation cannot be addressed without synthesizing findings across studies. Therefore, the current research adopted a meta-analytic approach to examine the relation between mental rotation and math performance and its variation across moderators.

Method

Inclusion Criteria

Studies had to meet the following criteria for inclusion in the meta-analysis.

1. *Mental rotation measure.* The study must have included a behavioral measure of mental rotation ability and reported response accuracy data obtained from that measure.
2. *Math measure.* The study must have reported data on math performance, as measured by response accuracy or by achievement scores (e.g., course grades, standardized test scores).
3. *Population of interest.* The study must have obtained data from healthy, typically developing individuals and reported that data separately from any data obtained from individuals with physical, neuropsychiatric, or learning differences (e.g., dyscalculia).
4. *Sufficient statistics.* The study must have reported a Pearson's correlation coefficient (*r*) for the relation between mental rotation and math performance.

Literature Search

Searches of the PsycInfo, ERIC, PubMed databases were conducted in May of 2017, using the following search terms: (math* OR arithmetic) AND ("mental rotation" OR "mental transformation" OR "spatial transformation" OR "spatial rotation"). Search terms produced 344 records (PsycInfo: 209, ERIC: 64, PubMed: 71), consisting of 256 unique articles. To obtain unpublished research, I also conducted a search of the ProQuest Dissertations and Theses database with the same search terms, acquiring 150 student theses for consideration. After removing the duplicates, 405 records remained for consideration (see Figure 2). I identified an additional 15 articles for consideration from the reference list of a previous meta-analysis on mental rotation (Lauer, Yhang, & Lourenco, under revision). An additional 21 articles were obtained through Google Scholar searches, and an additional 3 articles were later acquired through Internet searches. In total, 444 articles remained for consideration.

Screening process. From the sample of 444 articles, studies were identified for inclusion in the meta-analysis in two steps, as described below.

Step 1. Abstracts of all articles identified during the search process were reviewed. I excluded studies that did not meet the four eligibility criteria outlined above, and additionally excluded studies that were not written in English. Following abstract review, 285 articles remained for consideration in Step 2.

Step 2. I next conducted full-text reviews to determine whether articles met the four inclusion criteria detailed above. Full-text versions of 28 of the articles from Step 1 were unobtainable or not published in English; thus, full-text reviews were completed for 257 articles. Of these articles, 142 were excluded because they did not include the necessary behavioral measures (i.e., a mental rotation task and a math task), one article was excluded because it did not include data obtained from typically developing individuals, five articles were excluded because they did not contain original data, and 50 articles were excluded because they did not report sufficient statistics (e.g., r). Therefore, 59 articles were retained for inclusion in the meta-analysis.

Data Extraction

For the 59 articles included in the meta-analysis, I coded a number of study-level, sample-level, and task-level variables that allowed us to characterize our meta-analytic sample and assess potential moderators of the relation between mental rotation and math performance. Specifically, study-level variables were publication year and publication status; sample-level variables were sample size, gender ratio, and mean age of participants; and task-level variables were math task, type of stimuli used in the math task, mental rotation task, dimensionality of mental rotation task stimuli, and the time elapsed between completion of the mental rotation task and completion of the math task. In addition, I extracted the sample size and the effect size for the correlation between mental rotation ability and math achievement (measured via Pearson's *r*). Ultimately, the meta-analysis included 59 studies reporting 169 effect sizes derived from 19,870 unique participants.

Study-level moderators. I coded the publication year of each article included in the meta-analysis as a continuous variable. All 59 articles were published between 1978 and 2017, with 49% published since 2010 (see Table 1). I also coded the publication status of each article as a dichotomous variable (i.e., published or unpublished). Articles were classified as published if they were published in a peer-reviewed journal, in published conference proceedings, or as original research articles in books; articles were classified as unpublished if they consisted of student theses or papers presented at conferences. About 70% of the articles were classified as published; the remaining 30% were unpublished (see Table 1).

Sample-level moderators. For each sample included in the meta-analysis, I coded the mean sample age as a continuous variable. Mean sample age ranged from 4.33 to 32.00 years (M = 12.53 years, SD = 5.78). Three studies on college students provided no specific age statistics, so these studies were excluded from analyses including age as a predictor. In addition to age, I also coded the ratio of female to male participants in each sample as a continuous variable (M = 0.54, SD = 0.27). The majority of samples (57%) were between 40 and 60% female; 17 samples contained only female participants, and 14 samples contained only male participants.

Task-level moderators. I coded the type of math task (e.g., arithmetic, geometry), and the type of stimuli comprising the math task (i.e., symbolic, non-symbolic). Three types of math task were found to be used in 10 or more studies: arithmetic, basic numerical processes (i.e., numerical concepts, number line, and number discrimination tasks), and geometry. For type of stimuli in math tasks, I examined the effect of math stimuli in only in arithmetic and basic numerical processes tasks, because geometry task did not include symbolic or non-symbolic stimuli. In case that the effect of math stimuli might be tempered by task differences, I only analyzed the tasks that could be characterized by differences in stimuli type.

Next I coded the task used to assess mental rotation and the dimensionality of the stimuli comprising the mental rotation task (i.e., 2D, 3D). Given the diversity of experimenter-designed mental rotation tasks employed in the collected studies, I combined mental rotation tasks into three groups: (1) tasks requiring object completion through the mental rotation of component shapes, including the Children's Mental Transformation Task (Levine et al., 1999) and the Primary Mental Abilities-Space Relations (Thurstone & Thurstone, 1943); (2) tasks requiring same-different discrimination of rotated objects, including the Card Rotation Test (French, Ekstron, & Price, 1963) and the Vandenberg Mental Rotation Test (Vandenberg & Kuse, 1978); and (3) tasks consisting of rotational analogies, such as the Purdue Spatial Visualization Test-Rotations (Bodner & Guay, 1997). Fewer than ten studies ($m < 10$) administered rotational analogy tasks, so this task group was excluded from moderator analyses examining task effects.

Lastly, the amount of time between completion of the mental rotation measure and completion of the math measure was coded as an ordinal variable (e.g., 0-1 year, 1-2 years). I coded this variable to ensure that any longitudinal studies included in the current study did not have an undue influence on the meta-analytic results. Examination of this variable indicated that the mental rotation and math tasks were administered within the same year for majority of the effect sizes (81%, $k = 139$) and within two years for nearly all effect sizes (4%, $k =7$). Removing the effect sizes that were collected with more than 2 years in between the testing sessions had no effect on the significance of any analyses. Thus, all effect sizes were retained in the analyses reported in the Results section.

Statistical Analysis

To accomplish the three objectives of this meta-analysis, I first estimated the magnitude of the correlation between mental rotation abilities and math achievement by performing a meta-analysis of all effect sizes collected from the literature. Then, I conducted meta-regression analyses to characterize the extent to which the relation between mental rotation and math performance exhibits developmental change within the age range assessed (i.e., 4 to 32 years). Lastly, I examined the effects of other demographic and procedural moderators of interest, hypothesized to influence the magnitude of the association between mental rotation and math. Effect sizes were converted to the Fisher's *z* scale for all analyses and were transformed back into correlation coefficients for reporting results.

Meta-analytic approach. Many articles included in the meta-analysis reported multiple effect sizes, derived from different samples and/or using different measures. Obtaining multiple effect sizes from the same article led to interdependence in the effect size distribution. To address dependencies among effect size estimates, I conducted all meta-analyses using the robust variance estimation (RVE) method developed by Hedges and colleagues (2010a, 2010b). Meta-regression analyses were performed in R using the "robumeta" package (*v*. 2.0; Fisher, Tipton, & Zhipeng, 2017; Tanner-Smith et al., 2016). I implemented the correlated effects weighting method following the suggestion of Tanner-Smith and Tipton (2014), as studies in this meta-analytic sample more often reported multiple effect sizes obtained from the same sample of participants than multiple effect sizes obtained from different samples of participants. I tested the significance of continuous moderators via robust *t*-tests and the significance of categorical moderators via robust F-tests on k -1 dummy-coded predictors, using the "clubSandwich" package (*v.* 0.3.0; Pustejovsky, 2017).

Publication bias. I investigated the possibility of publication bias in the literature in two ways. First, I assessed the moderating role of publication status on reported effect sizes. Then, I examined the distribution of reported effect sizes by constructing a funnel plot and conducting Egger's regression test (Egger, Smith, Schneider, & Minder, 1997) via the "metafor" package in R (Viechtbauer, 2010).

Results

Across the 59 studies (k = 169) included in the meta-analysis, the weighted mean correlation coefficient equaled 0.30 (95% CI [0.27, 0.34], $p < 0.001$), demonstrating that the relation between mental rotation and math performance is moderate in magnitude. There was also substantial heterogeneity among effect size estimates ($I^2 = 81.55\%$; Higgins et al., 2003). Consequently, moderator analyses were conducted to determine whether sample- and task-level characteristics accounted for variability among effect sizes.

Moderator Analyses

Age. Meta-regression revealed that age did not significantly moderate the relation between mental rotation and math performance ($\beta < .001$, $SE_\beta = .004$, $p = 0.932$; Figure 2). There were six outliers for mean sample age (i.e., greater than 22 years old). When these outliers were removed, age remained a non-significant predictor of effect size. Together, these results suggest that the relation between mental rotation and math abilities is developmentally continuous between early childhood and adulthood.

Gender ratio. Gender ratio did not significantly moderate the magnitude of reported effect sizes ($\beta = 0.10$, $SE_\beta = 0.06$, $p = 0.103$). Effect sizes obtained from samples containing only female participants (r = 0.30, SE = 0.05, m = 14, k = 29) did not differ significantly from those obtaining only male participants (r = 0.26, SE = 0.06, m = 12, k = 19); F = 1.46, df = 13.1, p = 0.249. These findings do not provide evidence for a relation between gender and the association between mental rotation and math performance.

Math task. The robust F-test indicated that the effect of math task on reported effect size was trending towards significance (F = 3.03, df = 18.20, p = 0.073). Follow-up examination of confidence intervals revealed that effect sizes obtained using arithmetic math tasks (r = 0.25, SE = 0.03, p < 0.001, m = 14, k = 27) and basic numerical processing tasks (r = 0.24, SE = 0.03, p < 0.001, m = 15, k = 36) were both significantly smaller than effect sizes obtained using geometry math tasks (r = 0.36, SE = 0.04, p < 0.001, m = 11, k = 19). Thus, although mental rotation ability significantly relates to performance on all three types of math tasks, the relation between mental rotation and math performance is particularly strong for geometry.

Given the larger mean estimated correlation for geometry measures and the confound between age and math task, I next examined whether there was any effect of age on the relation between mental rotation and math performance when considering each type of math task individually. There was no evidence of a relation between age and the mental rotation-math relation when math was measured via arithmetic (β < .001, SE_β = 0.01, p = 0.849), basic numerical processes (β < .001, SE_β = 0.01, p = 0.758), or geometry tasks (β = -0.01, SE_β = 0.20, p = 0.662). These results are consistent with the previous findings of developmentally continuous in the mental rotation-math relation across different types of math tasks.

Type of stimuli in math task. There was a significant difference between effect sizes obtained using symbolic math stimuli (r = 0.26, SE = 0.03, m = 21, k = 49) and those obtained using non-symbolic math stimuli (r = 0.18, SE = 0.03, m = 7, k = 11), F = 7.36, df = 7.19, p =

0.029. These findings support the contention that mental rotation ability is more strongly related to performance on math tasks involving symbolic math stimuli, which are often spatially represented.

Mental rotation task. Effect sizes derived from object-completion tasks (r = 0.33, SE = 0.03, m = 10, k = 26) did not differ significantly from those derived using object discrimination tasks (r = 0.29, SE = 0.03, m = 29, k = 60), F = 1.50, df = 11.30, p = 0.245. This finding indicates that the type of mental rotation task may not statistically predict the relation between mental rotation and math abilities.

Dimensionality of mental rotation task stimuli. Effect sizes obtained via 2D mental rotation tasks (r = 0.33, SE = 0.03, m = 17, k = 43) did not differ significantly from those obtained via 3D mental rotation task (r = 0.29, SE = 0.02, m = 45, k = 116), F = 2.63, df = 21.30, p = 0.120. These findings do not provide evidence of moderating effects of stimulus dimensionality, suggesting that the correlation between mental rotation ability and math achievement may not arise solely from their shared relations with visuospatial working memory.

Publication Bias

The relation between mental rotation and math performance was similar in magnitude for published studies (r = 0.31, SE = 0.02, m = 41, k = 126) and unpublished studies (r = 0.30, SE = 0.03, m = 18, k = 43); F = 0.05, df = 26.4, p = 0.831. This result provides no evidence for publication bias. Examination of the funnel plot (see Figure 3) also provides no evidence of publication bias in the meta-analytic sample, as reported effect sizes were symmetrically distributed around the mean (Egger's Test of Asymmetry: z = 0.67, p = 0.503).

Discussion

There are a number of open questions about the relation between mental rotation ability and math achievement, including its strength, developmental trajectory, and task-related moderators. To address these questions, I conducted a meta-analysis of 169 effect sizes to quantify the correlation between mental rotation ability and math achievement and to investigate study-level, sample-level, and measure-level characteristics that may moderate its magnitude. The meta-analytic results indicate that there is a moderate, positive relation between mental rotation and math performance (r = 0.30), and that the relation is developmentally continuous between early childhood and adulthood. Moreover, procedural variables pertaining to math task, namely, the type of math task administered and the type of stimuli presented during the task, significantly moderated the magnitude of the observed correlation across the age range assessed.

Even though there is substantial change in the types of tasks that are used across development, the results demonstrate that the relation between mental rotation ability and math achievement emerges early in development and exhibits continuity between early childhood and adulthood. Moreover, no age-related change was observed within any subdomain of math examined in this study (i.e., arithmetic, basic numerical processing, and geometry), which indicates that the mental rotation-math link does not diminish with growing proficiency within a given domain of mathematics. Together, these meta-analytic findings suggest that mental rotation may facilitate math performance across diverse domains of math and across development. One possible explanation for the developmental continuity is that mental rotation may scaffold math development by positively influencing foundational math concepts. This interpretation is consistent with recent evidence which demonstrated that early spatial skill predicted number line knowledge, which in turn mediated the relation between spatial skill and later computational skill (Gunderson et al., 2012). Alternatively, the observed continuity in the mental rotation-math relation may be due to extraneous factors not central to the current meta-analysis. It is possible that both mental rotation and math performance are affected by a third variable such as general intelligence or visuospatial working memory capacity and display a continuous relation across development. The present meta-analysis only included zero-order correlations, and could not examine this claim. Therefore, future meta-analytic effort to control for these possible third variables by using partial correlations may be valuable.

When comparing all-female samples and all-male samples, gender was not found to moderate the magnitude of reported effect sizes. This result does not provide support for a gender difference in the relation between mental rotation ability and math achievement, calling into question whether males are indeed more likely to employ spatial strategies during mathematical problem-solving. Alternatively, considering that it has been argued that females are more likely to recruit verbal/analytical strategies for mental rotation (Bryden, 1979) and mathematical problem-solving (Gallagher et al., 2000; Geary et al., 2000), it is possible that females may be recruiting verbal strategies for both mental rotation and mathematical tasks and performing just as successfully as males who may be using spatial strategies, thereby producing a consistency across gender. Future research will be necessary to ascertain whether there are gender differences in the recruitment of spatial strategies during mathematical problem-solving, and if so, the extent to which these differing strategies influence math performance.

The correlation between mental rotation and math was significant for all three types of math tasks, namely arithmetic, basic numerical processes, and geometry, but the correlation for geometry task was significantly greater. Therefore, the results are consistent with previous findings of associations between mental rotation and these types of math tasks (for a review, see Mix & Cheng, 2012), and provide evidence that mental rotation may be particularly critical for geometry, which is plausible considering geometry and spatial reasoning are highly interrelated (Clements & Battista, 1992). The results also add support to the contention that spatial cognition is important to math that are less ostensibly spatial in nature (e.g., arithmetic, basic numerical processing) as well as those that are overtly spatial (e.g., geometry). The significant relation between mental rotation and arithmetic performance could indicate that arithmetic indeed engages the use of mental models in which mental images of numbers are manipulated in "mental space" (Cheng & Mix, 2014). Similarly, the significant relation between mental rotation and basic numerical processing could indicate that understanding of numbers and quantities is also a largely a spatial experience due to the use of spatial metaphors like the mental number line (Dehaene et al., 1993; Siegler & Opfer, 2003). While the results of the meta-analysis offer provide some evidence that different math abilities may be uniquely related to mental rotation, further research will be necessary to fully understand the nature of these relations.

The present meta-analysis indicated that the type of stimuli presented during the math task was a significant moderator of the mental rotation-math correlation, and that effect sizes were greater for math tasks that employed symbolic stimuli (e.g., digits) than those that employed non-symbolic stimuli (e.g., sets of dots). Individuals often represent symbolic stimuli such as numbers in space (e.g., mental number line; Dehaene et al., 1993), and it has been proposed that higher level math skills are built on similar uses of spatial-mathematical metaphors (for a review, see Mix & Cheng, 2012). Therefore, the larger correlation for symbolic stimuli may reflect the possibility that spatial abilities that support the grounding of abstract number concepts may overlap with those relevant to mental rotation. Alternatively, stronger mental rotation-math association for symbolic stimuli could be attributed to the fact that math tasks that used symbolic stimuli (e.g., arithmetic) generally required more spatial transformation and manipulation. Because their spatial demands were more similar to those of mental rotation tasks than those of math tasks that used non-symbolic stimuli, it is possible that this difference in the nature of the task obscured the effect of math stimuli. The results do not conclusively demonstrate either argument and suggest that future research endeavoring to better separate the effect of math stimuli from the effect of math task from may be meaningful.

The type of mental rotation task administered did not significantly moderate the magnitude of the mental rotation-math correlation, as performance on object completion mental rotation tasks and object discrimination mental rotation tasks did not differentially correlate with math achievement. Because object completion tasks can be easily solved by means other than mental rotation but object discrimination tasks require mental rotation skill for high performance, the results suggest that broader spatial abilities that are equally beneficial for solving these two types of mental rotation tasks may be at play. For example, it is possible that more general spatial ability, like sensitivity to interspatial relations of objects or attention to spatial features, is important for math achievement rather than the visualization of rotation specifically. If so, it is possible that the moderate correlation between mental rotation and math skills was found in the analysis because general spatial abilities are highly related to mental rotation skills. To address this possibility in the future, it may be beneficial to conduct a meta-analysis that includes all spatial abilities (e.g., mental rotation, spatial visualization, perspective taking) and examines if different spatial abilities moderate the correlation between spatial ability and math achievement.

Mental rotation tasks that used 2D stimuli did not produce a significantly different mental rotation-math correlation relative to those that used 3D stimuli. This finding is surprising given that visuospatial working memory, the differentiating factor between 2D mental rotation tasks and 3D mental rotation tasks (Peters et al., 1995), has been previously related to both mental rotation and mathematical ability (Kaufman, 2007; Kyttlälä & Lehto, 2008; Reuhkala, 2001). However, the visuospatial working memory may not be the sole or central factor in the relation between mental rotation and mathematical performance. For example, a spatial ability more specific than visuospatial working memory could be influencing both mental rotation and math performance. While this conjecture competes with the previous one which stated the possible role of more general spatial ability in math achievement, the two conjectures converge on the conclusion that future meta-analysis that considers types of spatial abilities as a moderator will be necessary.

Limitations

The diversity and skewed distribution of levels within procedural variables led to exclusion of multiple levels with small sample sizes, decreasing the statistical power and the ability to detect procedural effects. Future meta-analyses may subdivide the variables into fewer levels, although doing so may call for other possible limitations such as the need for subjective interpretation when coding or the possibility of overlooking important task differences.

The procedural variables like type of math task or mental rotation task were considerably confounded with age and thus provided further challenge to the analysis when controlling for it. Therefore, future work examining the procedural effect within the same sample by administering multiple types of tasks will be needed to clarify the moderating effect of procedural variables.

The results of the meta-analysis do not indicate the temporal or causal direction of the relation between mental rotation ability and math achievement. Although the relation between spatial reasoning ability and math achievement is typically discussed in ways that set spatial ability as the facilitator of math, there is likely reciprocity. It is possible that math benefits spatial reasoning as much as spatial reasoning benefits math (Mix & Cheng, 2012). Therefore, to establish the causal direction of this relation, future studies that consider the bidirectional effect of the relation between mental rotation and math ability in a longitudinal way, such that the direction of the relation can be examined in an alternating order (e.g., mental rotation ability at time 1, math ability at time 2, mental rotation ability at time 3), will be needed. Another way to address the directionality problem is through further training studies. Of the few training studies currently in the literature, a small number of them have reported that mental rotation training improved math performance (Cheng & Mix, 2014; Lowrie, Logan, & Ramful, 2017), suggesting that there may be a causal link between spatial cognition and mathematics. However, not all training studies have found such effect (Hawes et al., 2015). Although there is some evidence, there need to be more studies regarding the causal direction of this relation, especially in light of the potential educational implications of the work.

Conclusion

The present meta-analysis synthesized the findings from various studies on the relation between mental rotation ability and math performance and contributed to the extant literature by characterizing the moderate strength, the developmental continuity, and the moderators of the relation. The results corroborate the well-established connection between spatial reasoning ability and math, and provide evidence that the relation may be continuous across development and influenced by characteristics of the math measures, namely type of task and stimuli. Taken together, these findings suggest both directions for future research previously outlined and possible benefits of incorporating spatial training into educational curricula.

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Table 1

Number of Effect Sizes (n), Number of Studies (k), Mean Weighted Effect size (r) and Its 95% CI, of Study-Level Characteristics

	m	*k*	*r*	95% CI of *r*
Publication year				
Before 1980	1	1	N/A	N/A
1980s	3	7	0.41	[0.30, 0.50]
1990s	13	38	0.33	[0.24, 0.42]
2000s	13	23	0.27	[0.19, 0.34]
2010s	29	100	0.30	[0.25, 0.35]
Publication status				
Published	41	126	0.31	[0.26, 0.35]
Unpublished	18	43	0.29	[0.23, 0.36]
Gender				
All-female	14	29	0.30	[0.21, 0.39]
All-male	12	19	0.26	[0.13, 0.38]
Combined	45	121	0.31	[0.26, 0.35]

Table 2

Number of Effect Sizes (n), Number of Studies (k), Mean Weighted Effect size (r) and Its 95% CI, of Task-Level Characteristics

	m	*k*	*r*	95% CI of *r*
Type of math task				
Arithmetic	14	27	0.25	[0.18, 0.31]
Basic numerical processes	15	36	0.24	[0.17, 0.30]
Geometry	11	19	0.36	[0.28, 0.44]
Type of math stimuli				
Symbolic	21	49	0.26	[0.20, 0.31]
Non-symbolic	7	11	0.18	[0.11, 0.25]
Type of mental rotation task				
Object completion	10	26	0.33	[0.25, 0.39]
Same-different discrimination	29	60	0.29	[0.23, 0.34]
Rotational analogy	5	11	0.40	[0.26, 0.52]
Type of mental rotation stimuli				
Two-dimensional	17	43	0.33	[0.27, 0.38]
Three-dimensional	45	116	0.29	[0.25, 0.33]

A
B
C

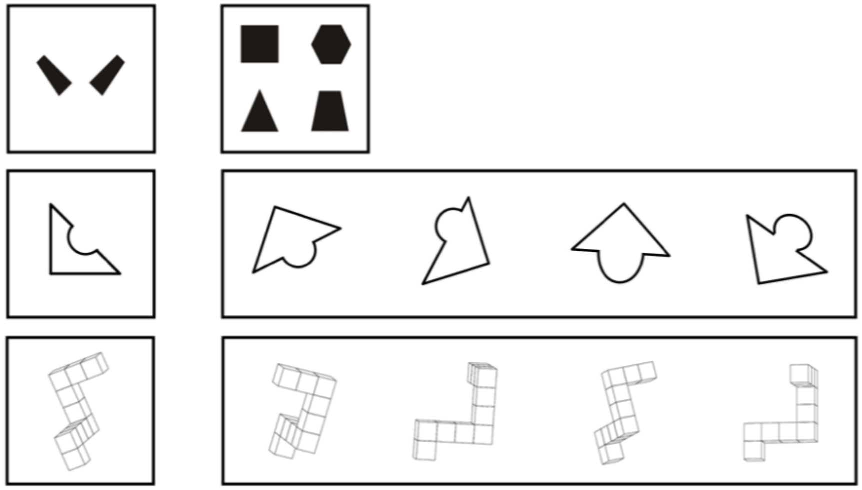

Figure 1. Examples of mental rotation task items from: (**A**) the Children's Mental Transformation Task (CMTT; Levine et al., 1999), (**B**) the Primary Mental Abilities-Space Relations task (PMA-SR; Thurstone & Thurstone, 1943), and (**C**) the Vandenberg-Kuse Mental Rotation Test (VMRT; Vandenberg & Kuse, 1978). Reprinted from "The Development of Gender Differences in Spatial Reasoning: A Meta-Analytic Review," by J. E. Lauer, E. Yhang, & S. F. Lourenco (under revision). Reprinted with permission from authors.

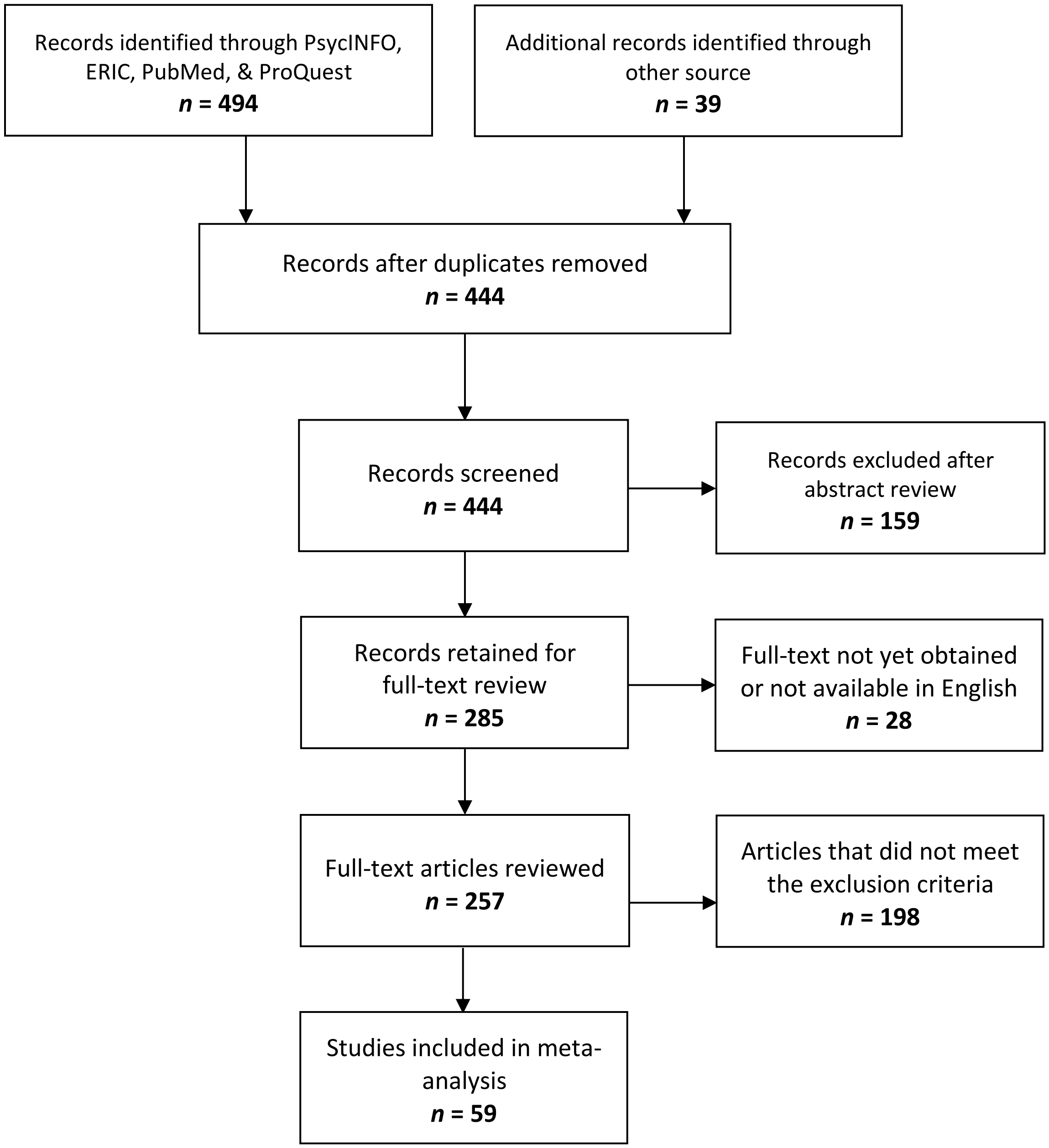

Figure 2. Schematic illustrating the process used to identify articles for inclusion in the meta-analysis and the number of records (*n*) reviewed at each stage.

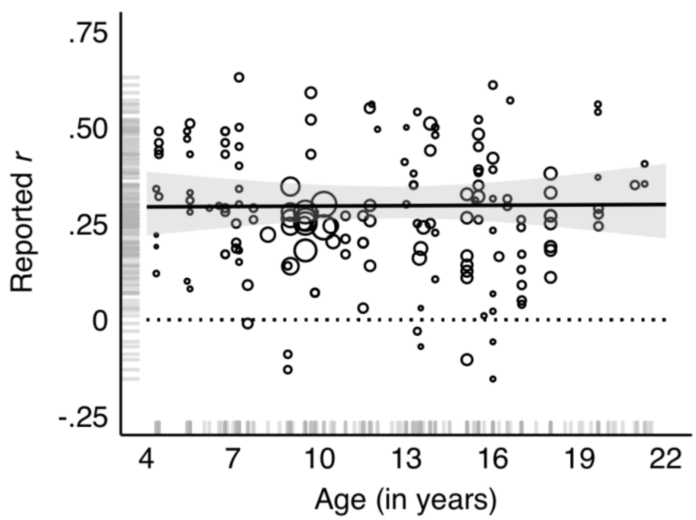

Figure 3. Bubble plot displaying the relation between mental rotation and math performance as a function of mean sample age. Bubbles represent reported effect sizes (*r*), and the bubble size corresponds to the weight of the effect size in the meta-analysis. The solid line represents the meta-regression line obtained from a meta-regression model with age as the only predictor; the shaded region illustrates its 95% confidence interval.

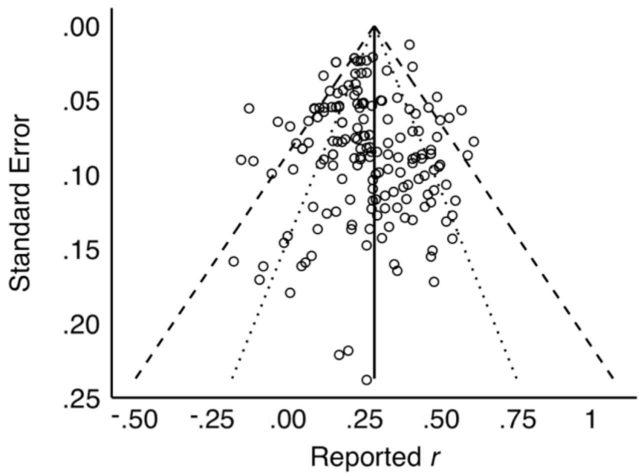

Figure 4. Funnel plot of reported effect sizes as a function of their standard error. The solid line indicates the mean estimated effect size (r = 0.30). The dashed and the dotted diagonal lines represent the 99% and the 95% random-effects confidence intervals, respectively.