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Is the spatial/math connection unique? Associations between mental rotation and elementary mathematics and English achievement

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ABSTRACT

It is commonly thought that strong spatial ability enhances mathematics performance and that associations between spatial ability and mathematics may be in part responsible for the gender gap in math performance. We investigated whether this spatial/math link is unique by examining the associations between mental rotation and both math and English/Language Arts (ELA) achievement using three similar samples of upper elementary students and three different measures of mental rotation. In each study, we found that the association between mathematics and mental rotation is no different than the association between ELA and mental rotation. We discuss how additions of prior achievement measures modify these associations and examine gender moderators, for which we find little support.

1. Introduction

There has been considerable focus on spatial ability as foundational for STEM (science, technology, engineering, and mathematics) achievement (AAUW, 2010; Committee on Support for Thinking Spatially, 2006). Unique links between spatial ability and mathematics in particular have long been posited (Geary, 2011; Mix & Cheng, 2012) and have even been used to explain gender differences in mathematics achievement (Casey, Nuttall, & Pezaris, 1997; Geary, Saults, Liu, & Hoard, 2000; Nuttall, Casey, & Pezaris, 2005). These findings have led to a push for spatial interventions, including those with elementary-aged children (Newcombe, 2010; Tzuriel & Egozi, 2010). Although there is evidence to justify the posited spatial/math relation, it remains an open question whether this link is exclusive. The current paper addresses these issues by examining the association between spatial ability and both mathematics and English/Language Arts (ELA) in elementary children and asks whether this association is unique to mathematics and consistent across measures, genders, and samples.

1.1. Spatial ability and mathematics achievement

1.1.1. Concurrent performance

The link between spatial ability and mathematics achievement has been of interest to psychologists and education researchers since the mid-1900s (Bishop, 1980). Prior research has supported this link by reporting associations between student spatial ability and students' concurrent performance on tests of mathematics (e.g., Casey et al., 1997; Casey, Nuttall, Pezaris, & Benbow, 1995; Ganley & Vasilyeva, 2011; Verdine et al., 2014). Verdine et al. (2014) found that spatial ability of preschool children from both high and low socioeconomic statuses was associated with scores on the Number and Operations subset of the Early Mathematics Assessment System measured at the same time. Additionally, for middle school through college students, Casey et al. (1995) found that mental rotation was associated with scores on the SAT-Mathematics.

1.1.2. Long-term performance

Long-term performance in mathematics can also be predicted by spatial ability, be it a year later or over 10 years later (e.g., Casey et al., 2015; Wai, Lubinski, & Benbow, 2009). As an example, Gunderson, Ramirez, Beilock, and Levine (2012) found that spatial skill measured at the beginning of the school year for first and second graders predicted improvement in number line estimation at the end of the school year. They also found that spatial skill of five-year-olds predicted performance on a mathematics task three years later. Similarly, LeFevre et al. (2010) found that spatial ability measured in preschool or kindergarten predicted mathematics skills in first or second grade, independent of language and quantitative skills.

Relatedly, Wai et al. (2009) found that the probability of earning an advanced degree in a STEM field, including those that heavily draw on

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mathematics, was a function of spatial ability. Almost half of their sample with doctorates in a STEM field were in the top 4% of spatial ability measured at least 11 years prior, and < 10% of this high-STEM-achieving sample scored below the top quartile. A quarter of their sample with a bachelor's degree in a STEM field were in the top 4% of spatial ability measured at least 11 years prior. Although their outcome, attainment of advanced STEM degree, is likely a function of more than just long-term mathematics performance (see Eccles & Wigfield, 2002), these results do offer evidence for a longer-term link between spatial ability and STEM, including mathematics achievement.

1.1.3. Spatial ability as a mediator of gender differences in mathematics

Gender differences in mathematics have long been an area of concern, partly due to the finding that men outnumber women in STEM professions that rely heavily on mathematics (e.g., AAUW, 2010). Spatial ability has been found to mediate this gender difference in mathematics performance (Casey, Nuttall, & Pezaris, 2001; Geary et al., 2000; Nuttall et al., 2005). For example, Geary et al. (2000) found that an indirect relation between gender and arithmetical reasoning, mediated by spatial abilities, provided a better fit to the data than did modeling only a direct relation between gender and arithmetical reasoning. Additionally, Nuttall et al. (2005) attained similar results in a variety of populations—college students, low- and high-ability high school students, and talented seventh- to ninth-graders. Even when compared to affective variables, such as mathematics self-confidence and mathematics anxiety, spatial ability has been shown to be a stronger mediator of the gender/mathematics relation (Casey et al., 2001; Nuttall et al., 2005).

1.2. Causal evidence for the link between spatial ability and mathematics

There is limited experimental evidence investigating a causal link between spatial ability and mathematics. However, this is not because spatial ability cannot be changed. Uttal et al. (2013) conducted a meta-analysis of 217 spatial training studies to determine if spatial ability is malleable. They found an average Hedge's g effect size of 0.47 on various spatial ability outcomes when comparing the trained group to controls. Therefore, theoretically, because spatial training can improve spatial ability, there should be an indirect effect of spatial training on mathematics ability. We see some evidence for this positive indirect effect in the few studies that have experimentally evaluated the causal link between spatial ability and mathematics (e.g., Cheng & Mix, 2014; Sorby, Casey, Veurink, & Dulaney, 2013). Cheng and Mix (2014) used a spatial training program on first and second graders and found that those who received the training performed statistically significantly better on a math test based on Michigan Grade Level Content Expectations. However, improvements were only seen in a certain type of problem (missing term problems; Cheng & Mix, 2014). Additionally, Sorby et al. (2013) found that their mental rotation training improved spatial and calculus performance in undergraduate students. Both these studies demonstrate that improvements in spatial ability have potential consequences for math outcomes; however, the authors did not include theoretically less related outcomes, such as language, to confirm divergent validity. In this way, the studies demonstrate a causal link between spatial ability and mathematics, but not a unique link.

Another way to explore potential causal relationship is through longitudinal studies of how changes in spatial ability relate to changes in mathematics. This is helpful because it may not always be possible or desirable to conduct experiments, especially with children in the realm of academic achievement. However, research examining how growth in spatial ability predicts growth in mathematics achievement is scarce. There is research examining how a prior measure of spatial ability predicts growth in achievement (e.g., Bull, Espy, & Wiebe, 2008; Geary, 2011; Zhang et al., 2014). For example, Bull et al. (2008) found that initial visual-spatial short-term memory predicted mathematics but not reading growth; however, these results did not appear consistent across all grades when a concurrent measure of reading achievement was entered for math analyses and vice-versa. Bull et al. (2008) did not control for a measure of achievement prior to their spatial measure, nor did they examine growth in spatial ability, leaving open the possibility for omitted variable bias and making causal conclusions more difficult. Geary (2011) found that visuospatial working memory measured at first grade predicted the growth in mathematics achievement from first to fifth grade. Similarly, Zhang et al. (2014) found that spatial visualization measured in kindergarten predicted both mathematics achievement and growth in mathematics achievement from kindergarten to third grade. It should also be noted that a number of these longitudinal studies focus on spatial working memory—it remains an open question whether other spatial abilities, such as mental rotation, have similar relations with long-term achievement.

1.3. Measurement of spatial ability

What constitutes spatial ability and how it is best measured is an area of extant debate. As part of this debate, there is disagreement over the number of facets of spatial ability, with some studies saying there are as few as three and others saying there are at least 10 (cf Carroll, 1993; Linn & Petersen, 1985; Lohman, 1979; Lohman, Pellegrino, Alderton, & Regian, 1987). The characterization and measurement of spatial ability have implications for the relation of this construct with both gender and mathematics achievement. Meta-analyses conducted by Linn and Petersen (1985), as well as Voyer, Voyer, and Bryden (1995), found gender differences varied between specific tests. They both found that spatial visualization showed the smallest gender difference ($d = 0.13$, Linn & Petersen, 1985; $d = 0.19$, Voyer et al., 1995), whereas mental rotation showed the largest ($d = 0.73$, Linn & Petersen, 1985; $d = 0.56$, Voyer et al., 1995). Additionally, a meta-synthesis of 106 meta-analyses found that mental rotation displayed the second largest gender difference (in favor of males) with a Cohen's d of 0.57 (other differences included masculine versus feminine traits, peer attachment, and aggression; Zell, Krizan, & Teeter, 2015). For this reason, measures of spatial relations, more specifically mental rotation, are often used when investigating the relationship between gender, spatial ability, and mathematics (e.g., Casey et al., 1997; Casey et al., 2001; Ganley & Vasilyeva, 2011; Geary et al., 2000; Laski et al., 2011; Nuttall et al., 2005). Within tests of mental rotation, factors such as working memory load, time constraints, and figure format (two vs. three-dimensional) impact gender differences in accuracy and speed of reaction time (Jansen-Osmann & Heil, 2007; Kaufman, 2007; Maeda & Yoon, 2013). Given the link between mental rotation, gender differences, and mathematics (Casey et al., 1997; Geary et al., 2000; Nuttall et al., 2005), these differences in measures may also induce variance in the links between mathematics and mental rotation.

1.4. Is the spatial-mathematics relationship unique?

1.4.1. Isolating the spatial-mathematics relationship from confounds

Although the relationship between spatial and mathematics abilities has been frequently found and may even be commonly accepted, there is conflicting evidence as to whether this association is unique (e.g., Lemos, Abad, Almeida, & Colom, 2013). Prior researchers have pushed for relevant control variables in order to best examine unbiased links between spatial ability and mathematics (Floyd, Evans, & McGrew, 2003; Friedman, 1995; Linn & Petersen, 1986; Voyer & Sullivan, 2003). Without the appropriate controls, the supposed unique relation between spatial and mathematics ability may be inflated because of the relationships between spatial ability, mathematics, and other abilities, such as verbal ability (e.g., Casey, Dearing, Vasilyeva, Ganley, & Tine, 2011; Floyd et al., 2003; Friedman, 1995; Linn & Petersen, 1986).

The possibility of biased estimates is apparent when comparing zero-order correlations to regression-adjusted estimates. For example, LeFevre et al. (2010) looked at the relationship between spatial ability