

Individual Differences in Spatial and Mathematics Skills: Implications for Educational and Clinical Psychology

Alexander P. Burgoyne^{1*},
Tessa Johnson²,
Kelly S. Mix²,
Susan C. Levine³ and
Christopher J. Young⁴

Abstract

In a recent empirical article published in *Cognition*, we examined the relationships between spatial and mathematics skills in a cross-sectional sample of 1,592 children that included kindergarteners, third graders, and sixth graders. We tested whether individual differences in math and spatial skills could be explained by factors such as socioeconomic status or sex (i.e., boys vs. girls), and furthermore, whether the relationships between spatial and math skills were moderated by these factors or by developmental stage. This brief article serves as a summary and extension of our recent work, with a discussion of implications that may be relevant to educational and clinical psychologists. We encourage readers to reference our empirical article for a more thorough presentation of the issues discussed in the present review.

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Introduction

Against a backdrop of calls to make Science, Technology, Engineering and Mathematics (STEM) education a national priority [1,2], understanding individual differences in spatial and mathematics skills has become increasingly important. For example, longitudinal research has shown that adolescents with stronger spatial skills achieve more advanced educational credentials and occupations in STEM fields [3]. Others have found reciprocal relations between spatial and mathematics skills in childhood [4,5], and at times suggestions of a causal relation between the two constructs. For instance, Mix, et al. [6] found that spatial training led to an increase in mathematics performance in a sample of first and sixth grade students [7]. On balance, the evidence suggests that children with better spatial skills have an advantage in mathematics, with consequences for subsequent academic achievement [8].

That said, spatial skill is not the only significant predictor of childhood mathematics outcomes. Other factors such as Socioeconomic Status (SES) are also related to students' mathematics skill [9,10], raising the concern that individual differences in STEM achievement or academic achievement more broadly may be driven in part by environmental inequality.

Indeed, SES has moderate effects on both spatial and mathematics skill, such that students from more affluent backgrounds tend to outperform students from lower-SES backgrounds. For spatial skill, the effect of SES holds even after controlling for verbal skill [9], suggesting that SES-linked performance differences are not merely driven by a general effect on overall cognitive functioning. For mathematics skill, SES effects become more pronounced as a function of age, although small differences between high and low-SES students can be detected early on [11]. The upshot is that material advantages (or disadvantages) may have compounding effects on academic achievement over time.

Complicating matters further, sex differences are also associated with individual differences in spatial skill. On average, boys tend to outperform girls on spatial tests, with the mean difference between groups increasing slightly with age [12]. Interestingly,

¹School of Psychology, Georgia Institute of Technology, Atlanta, Georgia, USA

²Department of Human Development and Quantitative Methodology, University of Maryland, Maryland, USA

³Department of Psychology, University of Chicago, Chicago, Illinois, USA

⁴National Opinion Research Center, University of Chicago, Chicago, Illinois, USA

***Corresponding author:** Burgoyne PA

School of Psychology, Georgia Institute of Technology, Atlanta, Georgia, USA,

E-mail: burgoyne4@gmail.com

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some of these differences may be attributable to strategy use; boys appear to use more holistic strategies when solving spatial problems than girls do. For instance, in a wayfinding task, boys may be more likely to construct and visualize a mental map to aid navigation, whereas girls tend to use part-by-part strategies such as using landmarks. Similarly, girls are more likely to use relations between salient features during mental rotation tasks, rather than holistically rotating a stimulus about its axis as boys tend to do [13]. Although individuals can still differ within groups (i.e., these trends reflect group averages), a mediation analysis by Wang and Carr [13] suggested that strategy use partially explained the relation between sex and spatial skill. Furthermore, their work indicated that boys and girls may select particular strategies that play to their unique strengths or skill profiles.

With respect to mathematics, the evidence for differences between boys and girls is mixed. Girls tend to earn higher mathematics grades in school and demonstrate greater proficiency on well-practiced math skills such as counting and computation, whereas there may be a slight male advantage when tests include novel problems and among adolescents or top-performing students on standardized tests [14-16]. Thus, rather than a general trend of one group outperforming another, observed differences between boys and girls on mathematics tests may reflect differences in the specific type of test they are administered.

Literature Review

The preceding review suggests that age, SES and sex all contribute to individual differences in math and spatial skills. However, it is unknown whether these factors interact or are largely independent during child development, and furthermore, whether they influence the relations between math and spatial skills. Previous research established that math and spatial skills are “separate but correlated” across this age range [17]. Specifically, factor analysis revealed that measures of mathematical and spatial skills cohered on two unitary but correlated latent factors, indicating that they shared considerable variance but ultimately reflected different cognitive skills. Prior to Johnson, et al. [1], an open question was whether this pattern of “separate but correlated” math and spatial skills would hold across subgroups defined by age, sex, or SES.

To address these questions, we [1] conducted a secondary analysis of a cross-sectional dataset collected as part of a larger research effort [17,18]. The dataset included 1,592 children, divided evenly among kindergarteners, third graders, and sixth graders who completed a series of age-appropriate tests of math and spatial skills as the focal measures of interest, as well as a vocabulary test as a proxy for general cognitive skill. Participating families also provided an estimate of their annual household income, which was used as an approximation of SES. Our analyses revealed five major findings, described below:

1. Children from higher-SES families performed better on the spatial and mathematics tests relative to children from lower-SES families. Factor-analytic models revealed that the effect of income on mathematics skill increased across

grade levels, whereas the effect of income on spatial skill was relatively constant from kindergarten through sixth grade.

2. Boys demonstrated greater spatial skill than girls at all three grade levels. For mathematics skill, boys only had a significant advantage in kindergarten. This latter result is somewhat at odds with previous studies reporting a male advantage on mathematics problems that emerges late (i.e., in adolescence). That said, it is possible that the kinds of math problems that were administered to the kindergarteners were novel to them, and thus required non-routine operations to solve them. If so, extant research suggests that boys may have a slight advantage under these problem-solving circumstances [16].
3. Collapsing across grades, spatial skill partially mediated the effect of SES on math skill, even after controlling for general cognitive skill. That is, income had a significant effect on spatial skill, which in turn had a significant effect on math skill. The indirect path capturing the product of these relations was statistically significant. This finding suggests that one reason SES relates to math skill is because of its effect on spatial skill. Conversely, we also found that math skill partially mediated the effect of SES on spatial skill. This pattern of results speaks to the entwined nature of math and spatial abilities in children, and highlights the challenge of disentangling the direction of potentially causal effects in cross-sectional research.
4. Among kindergarteners, spatial skill fully mediated the effect of sex on math skill after controlling for general cognitive skill. In particular, after accounting for the effect of sex on spatial skill and the effect of spatial skill on math skill, the direct path from sex to math skill was no longer statistically significant. This finding suggests that one reason why male and female kindergarteners differed in math performance may be attributable to differences in spatial skills. For comparison, math skill did not mediate the effect of sex on spatial skill.
5. Finally, multigroup confirmatory factor analysis revealed that the “separate but correlated” two factor structure of spatial and math skill was replicated across subgroups defined by grade, sex, and level of SES. Although mean performance may have differed across the subgroups, the same general pattern of relations between math and spatial skills emerged. The robustness of this finding is particularly important given its consequences for our understanding of the link between spatial and mathematical skills in child development.

Discussion

The major finding of Johnson, et al. [1] was that despite mean differences in performance, spatial and mathematics skills formed two “separate but correlated” latent factors across subgroups defined by age, sex, and level of SES. This evidence suggests that

there may be a common cognitive architecture underpinning the relations between performance in these domains that is robust to environmental, developmental, and sex effects. As our sample consisted of kindergarteners, third graders, and sixth graders attending schools in the United States, we can only speculate as to whether these results would hold across the full range of the developmental cycle (i.e., through adolescence, adulthood, and old age), in different countries with different educational practices, or at the extreme tails of the skill distribution (e.g., students with impaired cognitive functioning, or highly gifted students).

Nevertheless, there are important implications of our findings for educational psychologists. First, the observation that spatial skill fully mediated the effect of sex on math skill in kindergarteners, and that spatial skill partially mediated the effect of income on math skill across age groups, suggests that kindergarten boys and children from higher-income families may draw on spatial skills to help solve novel or challenging math problems. This possibility is consistent with a theory proposed by Mix [19] that spatial skills may facilitate mathematical reasoning by way of grounding mathematics symbols and operations. For instance, spatial processing might play a role in interpreting the relations between terms in an equation when students are first introduced to algebra, or in helping them understand the notation for numerators and denominators in a fraction when they first encounter it.

From this perspective, spatial training may be critical for developing skills and strategies useful for solving novel math problems, especially because spatial exercises are rarely implemented in the K-12 curriculum [20,21]. For young children, Newcombe [20] advocates for the use of spatial language in the classroom (e.g., “outside”, “middle”, “corner”, etc.), implementing visualization activities (e.g., “visualize where you think this pencil will go if I roll it off the desk”), and incorporating map reading into geography lessons, to name a few examples. These types of spatial training activities not only stand to benefit the development of spatial skills, but, as Hawes, et al. [8] determined in their meta-analysis of the extant spatial training literature, could lead to tangible gains in mathematics skill. Our results also suggested an increasing effect of SES (i.e., family income) on mathematics performance across age groups, with more pronounced effects for older students. Given that spatial skills partially mediated the effect of SES on mathematics performance, it may be prudent to encourage the development of spatial skills early on, before achievement gaps begin to widen.

From a clinical perspective, there has been much work on the cognitive factors underlying Math Learning Disabilities (MLD). Not surprisingly, various types of math learning disabilities have been identified given the complexity of mathematics and the various skills involved in different kinds of math tasks [22]. Although there has not been much work on the role of spatial skills in MLD, there is evidence suggesting that spatial processing could be involved in some forms of MLD. For example, [23] found that injury to the right parietal lobe not only resulted in

deficits in spatial orientation but also deficits in number line representations. Further, there is some indication that deficits in visuo-spatial working memory are associated with MLD e.g., [24-26]. For example, Szucs, et al. [26] examined the dominant hypothesis that MLD (termed developmental dyscalculia in their study) is linked to deficits in magnitude representation, a function that involves the intraparietal sulcus. They tested this hypothesis against the hypothesis that other intraparietal sulcus functions underlie this deficit in 9 to 10 year-old children with dyscalculia. Their findings indicate that deficits in visuo-spatial working memory, visuo-spatial short-term memory, and inhibitory control rather than deficits in magnitude representation are present in children with developmental dyscalculia. The spatial skill deficit most commonly associated with MLD is visuo spatial working memory [27]. These findings, together with findings showing that visuospatial skills are related to a wide range of mathematics skills [17,28,29] highlight the need to assess the role of spatial functioning in MLD, and to consider interventions that support the development of these skills and/or provide students with alternative strategies that reduce reliance on skills such as visuospatial working memory.

Conclusion

In conclusion, the “separate but correlated” factor structure of spatial and mathematics skills appears robust to the effects of grade level, sex and socioeconomic status, at least in the sample of kindergarteners, third graders, and sixth graders were tested. As the relationship between spatial and math skills has important implications for STEM achievement, future work should continue to investigate how spatial skills contribute to mathematical reasoning.

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