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Supporting mathematics learning: a review of spatial abilities from research to practice

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This review examines the relationship between spatial abilities and students' mathematics achievements and the neurobiological substrates underlying their association. Both cross-sectional and longitudinal studies suggested a positive association between spatial and math skills, while the relationship may vary depending on the participants' age or grade. Although numerous researchers claimed that in-class or out-of-class spatial training programmes enhance students' mathematics achievements over the past decade, few studies could reveal the mechanisms for the transfer effects. Based on neuroimaging evidence, the intraparietal sulcus is one of the most robust brain regions related to both spatial and math skills, indicating that the two skills may share some mental processes. These neural and cognitive results provide grounds for educational interventions. Further studies employing complex math skills will provide opportunities to guide classroom teaching practices.

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Introduction

An increasing number of studies have explored the relationship between spatial skills and mathematical abilities, which were partially driven by the findings that indicate spatial ability was a significant predictor of achievements in science, technology, engineering, and mathematics [1,2]. Both cognitive psychologists and math educators endeavoured to further their understanding of spatial–math relations. However, existing discordances in the terminology and topology of spatial skills have stymied progress in both fields. Several topological frameworks of spatial ability have been proposed to overcome these inconsistencies. One of the frameworks suggested spatial ability could be separated into three categories, namely spatial perception, mental rotation, and spatial visualisation [3]. Another theorised spatial ability derived from two dimensions, intrinsic–extrinsic and static–dynamic, which also incorporated the former three categories [2]. Some researchers have defined other skills as complements to the above-mentioned frameworks, such as visual–spatial working memory [3]. Moreover, cognitive psychologists mainly investigated the correlation between spatial and math skills and the associated mechanisms, while mathematics educators were more concerned about whether spatial learning could be harnessed to promote more efficient mathematical education [4,5]. It remains unclear how the findings from psychological and brain imaging researches could meet the demands of educational practices [6].

This paper employs the previously mentioned frameworks and aims to review recent evidence on 1) associations among spatial and mathematical skills, 2) the neurobiological substrates underlying the spatial–math relationships and 3) the effect of spatial skills training on mathematics learning outcomes. Ultimately, this mini-review could provide systematic information on spatial–math relations in the hope that it could bring research closer to improving mathematical education.

Associations between spatial and math skills

While the association between spatial and math skills has been well established over decades of research [7–9], recent studies have advanced the knowledge of spatial–math relations by employing several approaches: utilising longitudinal design, incorporating new types of mathematical skills and discussing moderators, such as age and gender [3,10–12].

A number of studies have longitudinally explored the associations between spatial abilities and mathematical skills. Some were particularly focused on the period from preschool to early elementary school [13–20]. Frick et al. (2019) found that spatial abilities are already predictive of mathematical skills at the beginning of schooling [13]. Reciprocal relations between spatial skills and mathematical achievements have been examined in several studies using cross-lagged models. Fung et al. (2020)

found that spatial perception in kindergarten could predict math learning outcomes one year later in Grade 1 [14]. A similar unidirectional relationship has also been reported between spatial visualisation/mental rotation and mathematical abilities from Grade 1 to Grade 2 [15]. Kahl et al. (2022) further observed that spatial visualisation between ages six and seven could predict mathematical skills three years later, which indicated a long-lasting unidirectional effect of early spatial skills on math performance [16]. Most previous studies were conducted in western countries [14,21], Yang et al. (2021) tested children's spatial perception/visualisation and arithmetic skills in Hong Kong among kindergarten students in three waves and 6-month intervals. They found that spatial visualisation at age five (wave one) could predict arithmetic performance (wave three) through basic number knowledge (wave two) [19]. Meanwhile, spatial–math associations in school-age children were analogous to students with higher grades between Grade 5 and Grade 7. This suggests that older students who were better at spatial skills also showed greater gains in learning mathematics [22,23].

Other than traditional theory-based math abilities, some researchers have explored the association between spatial abilities and application-based math problem solving. In a large sample (more than 1000) of 15-year-old teens, math problem-solving performance based on the Programme for International Student Assessment testing was found to be significantly correlated with spatial skills [24]. Students were divided into different samples, including high-performing Asian countries[1] and G7+ countries.[2] Cultural differences were reported, indicating that students from some Asian countries regularly performed better than students from G7+ countries on spatial skill assessments [24]. Wang et al. (2022) also found that spatial visualisation and spatial working memory were related to open math problem solving in Chinese children. Furthermore, different subdomains of spatial skills were related to the difficulties of open math problem solving. For example, spatial working memory was typically correlated with easy open math problems, whereas spatial visualisation was more often correlated with difficult open math problems [25].

Spatial and math associations seemed to vary depending on development. Gilligan et al. (2019) noticed that intrinsic dynamic skills could only predict mathematics at age six and age seven but not at age eight, which indicated that there might be a transition period for the contribution of spatial ability to math [26]. Results from a three-wave longitudinal study also demonstrated that spatial visualisation/mental rotation in Grade 1 could predict math performance in Grade 2, yet the effect disappeared between Grade 2 and Grade 3 [15]. Another study recruited 1754 subjects with a larger age range from 5 to 20 years old and reported that the associations of spatial and mathematical abilities were stronger in adolescents (age > 16.77 years) than in children (age < 12.33 years) [27]. However, a recent meta-analysis demonstrated that the relationship between spatial ability and mathematical ability was not moderated by age or by the subdomains of spatial skills (e.g. intrinsic-dynamic spatial ability versus extrinsic-static spatial ability) [3].

Cognitive and neurobiological mechanisms underlying spatial and math relations

Although relations between spatial and math skills have long been established, the nexus of spatial skills and mathematics remains unclear [28,29]. Studies have been devoted to exploring the potential mechanisms underlying the association between spatial and mathematical abilities at the cognitive and neurobiological levels [8].

At the cognitive level, the mental number line, a left-to-right continuum that is formed internally and extended horizontally with increasing magnitude, was thought to play a crucial role in space and number association [30]. Several studies explored the potential mediation effect of the mental number line underlying spatial and mathematics relations [19,31–33], which had yielded mixed results. Tam et al. (2019) recruited 109 students in Grade 2 and modelled a variety of spatial and mathematical skills with cross-sectional structural equation models [33]. They found that the spatial ability represented by both mental rotation and spatial orientation skills predicted calculation and word problem solving through mental number line performance [33]. Hawes et al. (2019) reported that numerical skills partially mediated the association between spatial skills and mathematics, including both numeration and geometry subdomains. This finding supports the hypothesis that the same mental number line system might not only allow people to map and conceptualise numbers, but also other abstract mathematical relationships [32]. However, using a longitudinal design, Yang, Huo and Zhang (2021) assessed 104 Hong Kong kindergarteners three times in 6-month intervals and failed to find that the mental number line measured at time two was able to serve as a mediator between the visual perceptual skills (time one) and arithmetic (time three) [19].

At the neural level, evidence from neuroimaging studies supported the idea that the sense of numerical magnitude was deeply spatial [34] and supported the shared processing account for spatial and math relations [8]. The most consistent findings of neural regions on which

[1] High-performing Asian countries refer to China, Singapore, and Korea.

[2] G7+ countries refer to UK, USA, Canada, Germany, France, Italy, Japan, Ireland, Australia, and New Zealand.

spatial and math skills relied were the intraparietal sulcus (IPS) and its surrounding area [8,35]. While research on spatial skills and mathematics interprets the function of IPS differently [36–38], evidence from both fields demonstrates the potential interaction of spatial and math skills in IPS and its adjacent regions. Neuroimaging studies on mathematics skills, such as number perception and arithmetic, were associated with the function of IPS [36,39]. From a spatial perspective, with the adoption of tasks such as mental rotation, visual–spatial construction and line bisection [35,40–44], researchers found that mental rotation broadly activated a large swath of the parietal lobe bilaterally, the precentral gyrus, inferior and middle frontal gyrus, the supplementary motor area, and the visual cortex [43,44]. Two studies using a complex visual–spatial construction task revealed similarly activated areas located in the bilateral superior and inferior parietal lobes in both adults [42] and children [40]. However, few studies have explored spatial and math skills simultaneously. Only one meta-analysis recently linked spatial and math skills by investigating the neurobiological substrates that supported symbolic numbers, arithmetic, and mental rotation processing [43]. Specifically, the analysis found that all three measures activated bilateral IPS and nearby parietal regions [43]. The findings were in concert with the neuronal recycling hypothesis [45] that a brain area inherently engaged in interaction with tools, objects and locations in space was re-used for numerical processing, symbols and mathematics concepts [8,46].

To summarise, recent evidence from cognitive and neurobiological studies suggests that the mental number line and shared neural substrates might be potential mechanisms that underpinned spatial and mathematical relations. Other than the spatial representation of numbers account and shared neural processing account, there were also other explanations for spatial and math associations, such as the spatial modelling account and the working memory account [8]. It should be noted that different accounts were not mutually exclusive. Rather, they could work in concert with each other [8].

The transfer effect of training spatial skills on mathematical performance

The close relationship between spatial abilities and mathematics has led to conjecture regarding the malleability of spatial skills and their subsequent training effect on mathematical abilities [2,4]. Many studies have been concerned about the effects of spatial abilities training on mathematical performance, and the types of intervention programmes could be categorised as *in-class settings* [5,47–52] and *out-of-class settings* [53–59].

One recent research endeavour is to embed spatial training with mathematics classroom teaching [5,47–52]. Lowrie et al. (2015) conducted a series of class-based intervention programmes within a specific pedagogical framework — Experience-Language-Pictorial-Symbolic-Application (ELPSA) [60]. This type of in-class spatial training improved students' mathematical performance across a wide age range of 9–13 years old (Grades 3–8) [5,48–50]. The improvements appeared to be greater than those in instruction based on the standard geometry curriculum [49]. Moreover, this training could transfer to the improvement of mathematical abilities despite the differences in total training time (6, 12 and 20 hours) spread over three or 10 weeks [5,48,50]. While the training effects seem to be moderated by the types of mathematical abilities, the spatial training enhanced students' performance in geometry and word problems but not on nongeometry graphics tasks [50]. However, null results were also reported for in-class training. Using the Modelling-Representing-Visualising-Generalising-Sustaining pedagogical model, which is very similar to the ELPSA framework but is more concentrated on visual memory, Mulligan et al. (2020) carried out an intensive intervention programme that extended over two or four terms for Grade 3 and Grade 4 students, respectively. They failed to find any transfer from spatial training to mathematical skills [51].

As for the out-of-class settings of the spatial training programme, several studies found successful transfers to mathematical abilities [53,55,56,58,59,61], while others did not [54,57]. The magnitude of the training effects seemed to be moderated by the socioeconomic status (SES) of the participants. Low-SES preschoolers benefited more from the intervention programme [59,61]. Moreover, a few researchers have argued that training in different subcomponents of spatial abilities showed different contributions to mathematics gains. For example, Judd et al. (2021) recruited 17 648 students aged six to eight and conducted an intervention programme lasting seven weeks (the amount of training was at least 12 hours). They reported that interventions on visual-spatial working memory and nonverbal reasoning were more effective than mental rotation on mathematical learning [56]. Nevertheless, Mix et al. (2021) did not find any differences in training effects regarding on the types of spatial skills [58].

In summary, both out-of-class and in-class training programmes are likely to be effective. However, most programmes were initiated based on evidence that spatial and mathematical abilities were associated instead of being based on specific theories. More importantly, few studies have been designed to uncover the influence of training strategies and processes that support math problem solving [4]. Additional studies are necessary to further the understanding of the mechanisms underlying the intervention effect of spatial training on math skills [4,21].

Conclusions

The converging evidence in the literature that sought to examine the association between spatial and math abilities is that children who are better at spatial tasks are likely to have higher math achievement concurrently and longitudinally, whereas this relationship might change depending on the developmental stages of children. Meanwhile, both lab-based and classroom-based intervention research suggests that mathematical learning could benefit from spatial training programmes. Regarding the potential mechanisms for the associations and transfer of training, the mental number line could possibly be a mediator between spatial and math skills at the cognitive level, while other paths should also be examined in future studies. At the neural level, one of the robust brain regions related to both spatial and math skills was the IPS, which indicates that the two skills may share some mental processes, such as spatial–numerical mappings. However, few studies have investigated the neural substrates of spatial and math skills at the same time, which might be because the mental processes involved in tasks that measure those two skills are extremely complex. More delicate experimental designs and multivariate analysis approaches could uncover the brain mechanisms of spatial–math associations.

Although the findings were far from what was expected, we should hold the promise that there might be something special about spatial–math associations [40,44]. Consistent efforts should be made to evaluate the potential paths that enable the effective transfer from spatial training to mathematical gains, especially based on the existing successful training designs. It would be even more compelling to employ particularly complex math skills in psychological research, which offers opportunities to move lab-based findings towards actual classroom teaching activities.

Conflict of interest statement

The authors declare that they have no conflict of interests.

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Based on the framework of intrinsic–extrinsic and static–dynamic [2], additionally with visual–spatial memory, the meta-analysis included 73 studies with 263 effect sizes and found that spatial abilities were more related to logical reasoning rather than numerical or arithmetic skills. The spatial–math associations were not moderated by ages or the status of developmental disabilities.

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