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Research Article

Effects of mental rotation training on children's spatial and mathematics performance: A randomized controlled study

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A B S T R A C T

The purpose of the current study was to (i) investigate the malleability of children's spatial thinking, and (ii) the extent to which training-related gains in spatial thinking generalize to mathematics performance. Sixty-one 6- to 8-year-olds were randomly assigned to either computerized mental rotation training or literacy training. Training took place on iPad devices over a 6-week period as part of regular classroom activity. Results revealed that in comparison to the control group, children who received spatial training demonstrated significant gains on two measures of mental rotation and marginally significant improvements on an untrained mental transformation task; a finding that suggests that training may have had a general effect on children's spatial ability. However, contrary to theoretical claims and prior empirical findings, there was no evidence that spatial training transferred to mathematics performance.

1. Introduction

Spatial thinking is a fundamental aspect of human cognition. Broadly defined as the ability to generate, retrieve, maintain, and manipulate visual–spatial information [27], spatial thinking plays a critical role throughout education [41,44]. For example, spatial skills have been linked to performance in music [19],visual arts [15], physical education [35], geography [34], science [44], and perhaps most notably, mathematics [28]. In higher education, spatial thinking performance is not only related to but acts as a gatekeeper to entrance and success in STEM disciplines (Science, Technology, Engineering, Mathematics; [23,32]). Moreover, from a historical perspective, spatial thinking has played an important role in scientific breakthroughs such as the invention of the induction motor, the discovery of the structure of DNA, and Einstein's theory of relativity [32,43]. Taken together, evidence points to spatial thinking as a strong contributor to both learning processes and learning outcomes.

Yet, spatial thinking remains a neglected aspect of educational practice [9,30,36]. According to the National Research Council [30], spatial thinking represents a "major blind spot" in the current educational system and that without explicit attention and curricular focus "spatial thinking will remain locked in a curious educational twilight zone: extensively relied on across the K–12 curriculum but not explicitly and systematically instructed in any part of the curriculum" (p. 6). What explains the lack of spatial instruction? One possibility has to do with the common perception that spatial ability is a fixed intellectual trait – 'either you have it or you don't' – and for this reason is viewed as "unteachable" [41]. Yet, recent research findings indicate that spatial thinking is not as immutable as many people may have been led to believe.

Drawing on 206 spatial training studies conducted over a 25-year period (1984–2009), Uttal and colleagues [38] performed a meta-analysis and found evidence to suggest spatial thinking is malleable. The findings indicated that spatial thinking can be improved in people of all ages and through a wide assortment of interventions (e.g., video games, course training, spatial task training). Relative to a control, the average effect size of training was large and approached half a standard deviation (0.47). To put this effect into context, Uttal et al. [38,39] explained that an improvement of this magnitude would approximately double the number of people with the spatial skills associated with being an engineer. Indeed, the educational implications of improving spatial thinking skills are significant and potentially far-reaching. It has recently been argued that one way to effectively meet the growing demand for STEM participation and success is to increase the education and development of spatial thinking [32,39]. To date, few studies have empirically investigated whether spatial training results in improved STEM performance.

A good place to begin examining this question is within the discipline of mathematics. For over a century now, psychologists have identified a strong link between spatial thinking and mathematics (e.g., see [12,14]). In general, people with strong spatial skills tend to do well in mathematics [28]. The relationship between

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spatial thinking and mathematics is so well established, in fact, that Mix and Cheng [28] suggest that it no longer makes sense to ask whether, but rather why and how, the two are related. In what follows is a brief review of three ways in which spatial thinking and mathematics are linked. These links provide the necessary theoretical grounds on which to reason that spatial training might and/or should result in improved mathematics performance.

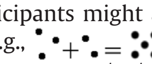
First, many aspects of mathematics are inherently spatial (e.g., [9]). For example, geometry, linear and area measurement, and algebra – to name but a few strands – are based on spatial relationships and representations. Furthermore, for any given mathematics task, a combination of spatial skills might be called upon. For example, when comparing the area of two different polygons, one might approach the task through spatial strategies that include, composition/decomposition, mental rotation/visualization, mental iterations, and unitization. Second, decades of research in cognitive science and neuroscience reveal the human tendency to represent numbers spatially (see [12]). For instance, individuals automatically associate smaller numbers (e.g., 1,2,3) with the left side of space and larger numbers (e.g., 7,8,9) with the right side of space, a finding that has been coined the SNARC effect (Spatial Numerical Association of Response Codes; [10]). Moreover, spatial skills, such as 2D mental rotation, have been linked to the precision of an individual's ability to map numbers to space [42,16]. That is, people with superior spatial skills appear to possess a more accurate 'mental number line'—a useful metaphor to describe numerical–spatial associations [20]. Findings from brain imaging studies corroborate behavioral evidence and indicate that basic numerical and visual–spatial tasks activate neighboring and overlapping regions in the intraparietal sulcus [11,20,47]. Finally, spatial thinking and mathematics performance both appear to rely heavily on visual–spatial working memory [25,28]. Visual–spatial memory provides a 'mental blackboard' in which mathematics problems can be organized and worked out according to the visual and spatial relationships involved [1].

Of the various spatial skills identified, mental rotation ability appears to play an especially important role in mathematics learning and achievement [4,7]. Defined as the ability to rotate mental representations of 2D and 3D objects in one's mind, mental rotation skills have been linked to performance across a wide variety of mathematical tasks, including geometry [2,13], algebra [37], mental arithmetic [24,25] word problems [18], and advanced mathematics (e.g., function theory, mathematical logic, computational mathematics; [45]). Furthermore, mental rotation skills have been shown to be strong predictors of later mathematics performance, including one's scores on the Mathematics Scholastic Aptitude Test (SAT-M; [7]). Most recently, it has been discovered that mental rotation is one of the spatial skills that plays a fundamental role in determining which students enjoy, enter, and succeed in STEM [44]. These findings suggest that mental rotation is a potentially important skill to target in spatial training programs.

The idea that spatial training will benefit mathematics performance is not new (e.g., see [3]), but, to date, has garnered little empirical support. There is one notable exception, however. In the first and only study to causally examine the effects of spatial training on mathematics, Cheng and Mix [8] randomly assigned 6- to 8-year-olds to either a mental rotation condition or an active control group (i.e., crossword puzzle condition). Both groups participated in identical pre- and post-tests that assessed both spatial and mathematics skills. The mental rotation condition consisted of a single 40-min one-on-one training session that involved solving 2D mental rotation task items (see [26]). Participants first performed the task mentally and then were provided with the opportunity to (dis)confirm the accuracy of their response through physically manipulating cardboard cutouts of the test stimuli. Children in the mental rotation group, but not the crossword condition, demonstrated significant improvements on the trained mental rotation task as well on the calculation test. Improvements were most evident on missing term problems (e.g., 2+____=8). This finding was attributed to the possibility that spatial training primed children to approach the problems through spatially reorganizing the problems (e.g., 2+____=8 becomes ____=8–2). This is an important finding and one that provides preliminary evidence for the claim that spatial instruction is likely to have a "two-for-one" effect, yielding benefits in both spatial thinking and mathematics [41]. However, caution should be warranted as this is but one study to demonstrate such a finding. More research is needed to test the generalizability of spatial training.

The purpose of the current study was to twofold: First, we sought to examine whether participation in an in-class computerized 2D mental rotation training program would result in improved spatial thinking in 6- to 8-year-olds. Second, we were interested in determining the extent to which spatial training generalized to children's calculation performance. In an attempt to replicate[1] the findings of Cheng and Mix [8], we included a measure of missing term problems along with a nonverbal exact arithmetic task.

With respect to the first objective, it was expected that training would result in near transfer effects. This prediction was based on previous research indicating that computerized mental rotation training is an effective means for improving mental rotation test performance [33,46]. More specifically, we reasoned that the 2D mental rotation training would transfer to tests of 2D mental rotation due to the shared need to differentiate between 'mirror images.' Previous research has shown that many children struggle with mental rotation tasks, at least partly attributable to difficulties with mirror images [17]. With adaptive and distributed practice, we hypothesized that children would become more efficient at identifying and differentiating mirror images—a key obstacle to successful 2D mental rotation performance. We were less certain that the training would transfer to other tests of spatial thinking that do not include mirror images. To test for intermediate transfer, we included two spatial tests that lend themselves to mental rotation strategies but importantly do not require mirror discrimination. The inclusion of these tests provided an opportunity to examine whether the training was responsible for more general changes in spatial cognition or whether the training was specific to near transfer tests that require mirror image discrimination.

To determine whether spatial training transferred to mathematics performance, two separate tests of calculation were administered. A nonverbal exact arithmetic test was selected due to its potentially shared mechanisms with visual–spatial processes. For example, Dehaene and colleagues [11,20] have demonstrated that nonverbal approximate arithmetic activates brain regions that overlap with visual–spatial processing. Although the current measure required exact arithmetic, it was hypothesized that children would use an approximate strategy when the exact solution was unknown. Furthermore, previous research by Butterworth and colleagues has revealed that nonverbal exact arithmetic tasks can be approached through strategies that rely on visual–spatial memory. For example, instead of attaching the number names to the objects being operated on (e.g., "there are two objects under the mat, and now three more are being added, so that makes a total of five"), participants might also approach the task through mental imagery (e.g., ). Given that the intent of the mental rotation games was to train the ability to form, maintain, and manipulate visual images (i.e., spatial visualization), we had reason to believe that spatial training might enhance nonverbal exact arithmetic performance through the

[1] We use the term 'replicate' loosely here and throughout the rest of the paper, as our study design and training method did not fully align with those employed by Cheng and Mix [28].