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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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ABSTRACT

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.

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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.

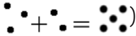
First, many aspects of mathematics are inherently spatial (e.g., [9]). For example, geometry, linear and area measurement, and algebra – to name but a few strands – are based on spatial relationships and representations. Furthermore, for any given mathematics task, a combination of spatial skills might 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

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[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].

shared recruitment of visual–spatial processes, including visual–spatial working memory. The missing term test was included as an attempt to replicate the previously mentioned training study by Cheng and Mix [8].

2. Method

2.1. Participants and procedure

Sixty-one children aged 6 to 8 years participated ($M_{\text{age}}=7.2$ years, $SD=0.55$ years). Children were recruited from a single elementary school in Toronto, Canada, with ethics approval from the University of Toronto and the district school board committee. Prior to student recruitment, two 1st grade and two 2nd grade teachers provided written consent to participate in the project. Teachers agreed to implement and monitor scheduled game play in their classrooms, as well as complete a detailed log of the frequency and duration of game play throughout the intervention. Information letters and consent forms went home to all students; 86% of parents agreed to have their child participate. It is worth mentioning that this particular public school was approached to participate in the study due to its known leadership in the school board for its use of technology in the classroom. As such, children were familiar with iPad devices and routinely used them as part of classroom instruction. In terms of school demographics, the school serves students from a middle-to-high SES neighborhood, with a generally high percentage of English Language Learners (at the time of this study, 55%), and routinely performs at or around the provincial standard in mathematics and literacy.

2.2. Study design

A randomized, controlled pre-post study design was utilized. Participants were randomly assigned to either the spatial training condition or the literacy training condition (see Table 1). All participants took part in identical pre- and post-test measures the week before and after the 6-week training intervention. Test administrators were trained research assistants who were blind to the group assignment at all times. The teachers were blind to the specific purposes of the study and were told in advance that both the training conditions were of potential benefit to student learning.

2.3. Description of training procedure and intervention games

Children in both groups played their games on personally assigned iPad devices three times a week at 15–20 min per session (approximately 4.5 h in total). In all classrooms, teachers managed game play by having one group engage in a self-directed or teacher-led learning activity (e.g., writing centre) while the other group engaged in their 15–20 min of game play. For the spatial game play intervention, children began each session at the highest level achieved during the previous session. This same adaptive approach was not possible with the literacy games, as they were not leveled. To assist teachers with the scheduling of game play, a detailed 6-week schedule was provided that specified the name of the games to be played and the order in which they should be played.

2.4. Mental rotation training

Mental rotation training involved playing three separate games that were all housed within a single application (see Fig. 1 for a screen shot and brief description of each game). Two of the three games, referred to hereafter as Games 1 and 2 respectively, involved the identification and matching of 2D shapes under time limitations. A central objective of both Games 1 and 2 was the avoidance of selecting mirror images. The third game, hereafter referred to as Game 3, was a puzzle activity in which children had to compose a given image (i.e., an outlined shape) by dragging and rotating selected pieces. All three games were adaptive in that they involved 'unlocking' levels upon reaching a certain level of play (i.e., completing a certain number of matches or completing the puzzle). Children spent 1.75 h playing Game 1, 2 h playing Game 2, and 45 min playing Game 3. Our rationale for having children spend more time playing games 1 and 2 was twofold: First, we felt that these games explicitly targeted mental rotation and better reflected the cognitive skills required to complete our selected measures of spatial learning. Second, a pilot study revealed that children were capable of completing all levels of Game 3 in a relatively short period of time (i.e., between 40 and 60 min). Thus to sustain motivation and to more explicitly target mental rotation skills, Games 1 and 2 were given priority.

2.5. Literacy training

Literacy training involved playing three games targeting early literacy skills. Game 1 involved five separate literacy challenges each to be completed within a set time limit (e.g., 30 s). Challenges included identifying properly spelled words amongst alternatives (e.g., focus, focis, foccus), recalling the names of objects briefly presented, reading a sentence and selecting the appropriate corresponding image, selecting the proper letter to complete a given word (ap_le), and identifying verbs from nouns. If the child achieved three or more correct items for each challenge, he/she was offered the opportunity to play the game again but with a stricter time limit and new and/or rearranged stimuli. Game 2 included a two-in-one application. One of the games involved selecting nouns and adjectives to form novel sentences. The other game involved completing crossword puzzles of increasing difficulty. Game 3 included two separate interactive reading books that required children to select rhyming words and alliterations to complete different songs and tongue twisters. Children played each game once a week for a total of 1.5 h per game.

2.6. Pre- and post-test measures

Participants took part in identical pre- and post-tests before and after the intervention. Three of the measures were administered over a 20-min period to each participating class. These measures included the 2D and 3D mental rotation tests (animal-pictures, letters, and cube-figure stimuli); administered in this order at both time points. The remaining measures were all conducted on a one-to-one basis by

Table 1
Participant information by group.

	Participants	1st Grade	2nd Grade	Mean age in years (standard deviation)	Females:Males	Hours of training (standard deviation)
Spatial training	32	17	15	7.2 (0.6)	12:20	4.6 (0.29)
Literacy training	29	16	13	7.2 (0.49)	12:17	4.5 (0.14)

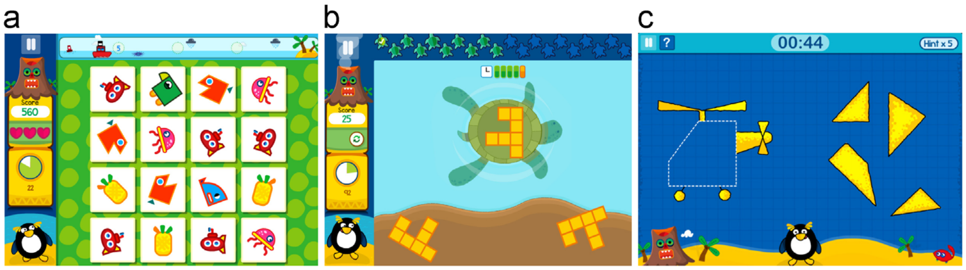

Fig. 1. Screen shots of the three spatial training games. In Game 1 (Fig. 1a) children are presented with a grid arrangement of 'playing cards' that depict matching and mismatching images. Children have a limited time to select matching 2D images, being careful not to select 'distracting' mirror images. As children progress, the angles of rotation and the size of the grid both increase. In Game 2 (Fig. 1b), children are presented with streams of turtles that pass by from left to right. Each turtle momentarily stops and offers the child the opportunity to identify and drag one of two polyominoes onto the corresponding polyomino on the turtle's back. Children are awarded points for correct matches. As children progress, children have less time to select the correct match. In Game 3 (Fig. 1c), children use the provided shapes to construct the given image on the left (i.e., in this example, the helicopter image). Shapes must be rotated manually and dragged into their appropriate location. As children progress, the puzzles increase in difficulty.

one of five trained research assistants. This testing took place in quiet and private rooms and lasted between 20- and 25-min. The tests were administered in the following order at both pre and post: Nonverbal Exact Arithmetic, Children's Mental Transformation Task, Visual–Spatial Puzzle Task, and Missing Term Problems.

Due to interruptions during testing and/or absenteeism, along with two instances of experimenter error, data were incomplete for several children. Data were missing at pre-test for one child in the control group on all but two measures, Children's Mental Transformation Task and the Missing Term problems. Data were missing for one child in the spatial training group on the Visual–Spatial Puzzle Task at post. Data were missing for two children from the control group on the following post-test measures: Children's Mental Transformation Task, Visual–Spatial Puzzle Task, Nonverbal Exact Arithmetic Task, and Missing Term Problems. In addition, data were missing for one child in the control group on all post-test measures. Missing data were not included in any of the subsequent analyses.

2.7. *Assessing near transfer*

Near transfer measures included two paper-and-pencil psychometric tests of 2D mental rotation adopted with permission from Neuburger and colleagues [31]. The two tests varied only in the type of stimuli presented; animal pictures vs. letters (see Fig. 2). Similar in format to the classic mental rotation test of Vandenberg and Kuse ([40]), participants were presented with a target image on the left side of the page and four comparison stimuli on the right. Two of the four comparisons were rotated versions of the target and two were mirror images of the target. Participants were awarded one point for crossing out both of the rotated versions of the target. Rotations included angles that differed from the target by 45°, 90°, and 135° clockwise and counterclockwise. Test administration occurred in the children's regular classroom and was facilitated by the lead author and a research assistant. To introduce each task, children were provided with instructions and two sample items to complete. For each test, participants were given two minutes to complete as many of the 16 items as possible. For each item, one point was awarded for correctly identifying the two figures that matched the target. Prior research has indicated good internal consistency (Chronbach's alpha) for both the animal-picture version (.92) and the letters version (.90).

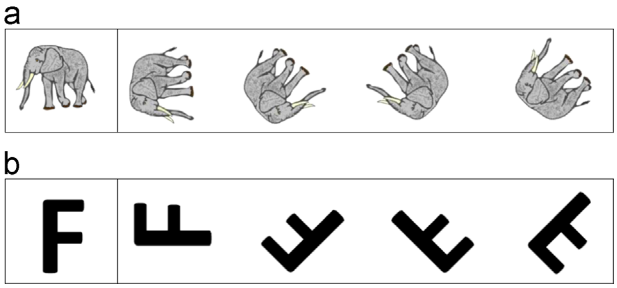

Fig. 2. Examples of 2D mental rotation test items. Fig. 2a is an example of the animal-picture stimuli and Fig. 2b is an example of the letter stimuli. Permission to use the test and share the above two items was granted by Claudia Quaiser–Pohl (see [31] for more test details).

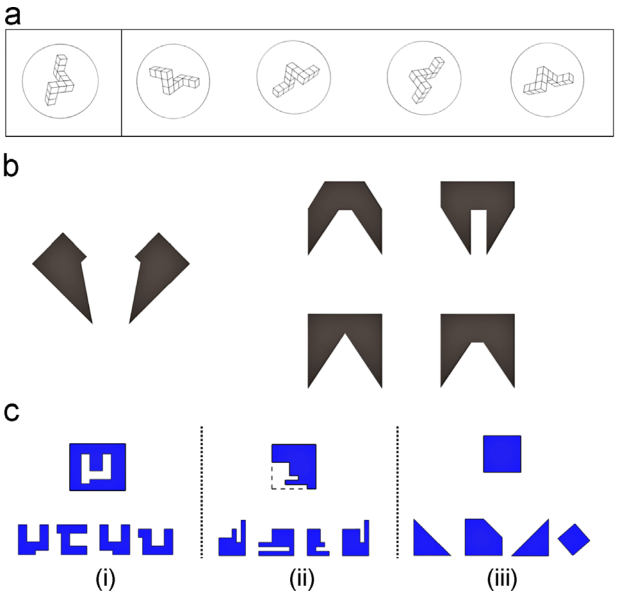

Fig. 3. Examples of items used to assess intermediate transfer effects. Fig. 3a is an example of the 3D Mental Rotation Task [31], Fig. 3b is an example of the Children's Mental Transformation Task [26], and Fig. 3c is an example of the Visual–Spatial Puzzle Task. The types of questions depicted in (i) and (ii) required participants to identify the 'missing piece,' whereas (iii) required participants to indicate the two shapes that could be put together to make the image centered above.

2.8. *Assessing intermediate transfer*

Intermediate transfer measures included three separate spatial tasks. The *3D Mental Rotation Task* (see Fig. 3a) was adopted from Neuburger et al. [31] and was administered immediately following the 2D mental rotation tests described above. Participants were presented with one target cube-figure. (i.e., 2D representation of a 3D figure) and four response cube-figures, two of which could be rotated to match the target and two that were mirror images. Response stimuli were rotated in a single plane and differed from the target by 45°, 90°, and 135° clockwise and counterclockwise. Participants were given four minutes to complete as many of the 16 items as possible. For each item, one point was awarded for correctly identifying the two cube-figures that matched the target. Cronbach's alpha of internal consistency was previously identified as satisfactory (.65). This measure was included as an intermediate measure of transfer due to the high cognitive demands of the task [31] and previous research findings suggesting that 2D and 3D mental rotation, although related, are separable and require different processes [22,29].

The *Children's Mental Transformation Task* was adopted from Levine and colleagues ([26]; see Fig. 3b). The original task contains 32 items that require either mental translations or mental rotations and translations. For this study, we used only those items that required both mental rotation and translation skills. Participants were presented with two halves of an irregular symmetrical shape and then asked to indicate the image that results when the two halves are joined through a 60° rotation and translation. The test consisted of 16 items. This task was selected to determine whether the effects of mental rotation training were limited to gains in mirror discrimination. Cronbach's alpha of internal consistency was previously identified as satisfactory (.70: [17]).

The *Visual–Spatial Puzzle Task* was created for the purposes of this study, as a means of assessing mental rotation skills that do not involve mirror discrimination (see Fig. 3c). The task included 12 questions that required students to engage in visual–spatial reasoning through 'puzzle-like' challenges. The task was further broken up into three types of questions: missing centre problems, missing border problems, and 2D shape composition problems. In each case, the child had to identify amongst alternatives the piece (s) of the puzzle that completed a given image; a task that required rotating the pieces into place.

2.9. *Assessing far transfer*

Far transfer was assessed using two separate measures of calculation skills. The *Nonverbal Exact Arithmetic Task* was modeled after Butterworth, Reeve, Reynolds, and Lloyd [6] and Butterworth, Reeve, and Reynolds [5]. Participants were first provided with a shallow bowl containing 18 counting chips and an A4 sized piece of cardstock. Similarly, the experimenter prepared a bowl of 20–26 counting chips, an A4 sized piece of cardstock, and a large place mat. The experimenter sat to the right of the child. The child was first told the 'rules of the game' followed by three practice trials. The task worked by showing the child a given number of counting chips (e.g., 3 counters) for 4 s. The experimenter then covered the chips with the place mat and performed one of the following operations to the hidden set: added chips, subtracted chips, added and then subtracted chips, or subtracted and then added chips. The child was then asked to use his/her own counting chips to show how many chips were under the experimenter's mat. Points were awarded only if the child was able to demonstrate the exact number of chips. The task consisted of 20 items; 5 trials of each type of operation performed. Cronbach's alpha inter-item reliability coefficient for this test was .78.

Table 2
Correlations between age, gender, and performance on pre-test measures.

	1	2	3	4	5	6	7	8
1. Age	–							
2. Gender	.20	–						
3. 2D MR: Animals	.22	.01	–					
4. 2D MR: Letters	.28*	.02	.78**	–				
5. 3D MR: Cubes	.00	−.17	.33**	.38**	–			
6. CMTT	.36**	.01	.21	.35**	.19	–		
7. Visual–spatial puzzles	.41**	.15	.43**	.40**	.27*	.34**	–	
8. Nonverbal arithmetic	.58**	.13	.40**	.45**	.15	.30*	.49**	–
9. Missing term problems	.55**	.19	.50**	.63**	.18	.34**	.47**	.78**

Note. MR=Mental Rotation, CMTT=Children's Mental Transformation Task.

* $p < .05$.

** $p < .01$.

The *Missing Term Problems* were modeled after those described in Cheng and Mix [8]. To familiarize participants to the task, a standard set of instructions were offered along with 4 guided practice questions. Participants were then given 5 min to complete as many of the 18 problems as possible. Problems were balanced according to number of addition vs. subtraction problems, single digit vs. double-digit numbers, and position of the missing term ($\_\_+3=5$ vs. $3+\_\_=5$ vs. $5=3+\_\_$). Participants were assigned a point for each correct solution.

3. Results

3.1. *Preliminary analyses*

Bivariate correlations were carried out to determine the strength of the relationships between age, gender, and the seven pre-test measures (see Table 2). Performance on the 3D Mental Rotation Task revealed low correlations with the other measures ($rs < .38$). This was due to floor effects. Only a small number of participants performed above chance, replicating previous research suggesting that children struggle with mental rotation of 2D representations of 3D cube-figures [21]. Moderately strong correlations were observed between the near transfer measures and the far transfer mathematics tasks (r range=.40 –.63). Mental rotation performance with the animal-picture and letter stimuli shared 25% and 40% of the variance on the missing term problems, respectively. Thus, there is preliminary, albeit inconclusive, evidence in support of the hypothesis – and previous finding of Cheng and Mix [8] – that mental rotation and calculation skills, especially on missing term problems, might recruit shared cognitive mechanisms.

To test for group differences prior to the intervention, a MANOVA was conducted. Results revealed no significant group differences on any of the seven-pretest measures: 2D Mental Rotation: Animal Stimuli, $F(1,58)=.003$, $p=.959$, $\eta_p^2 = < .001$, 2D Mental Rotation: Letter Stimuli, $F(1,58)=.003$, $p=.954$, $\eta_p^2 < .001$, 3D Mental Rotation: Cube Stimuli, $F(1,58)=.33$, $p=.566$, $\eta_p^2=.006$, Children's Mental Transformation Task, $F(1,58)=.02$, $p=.883$, $\eta_p^2 < .001$, Visual–Spatial Puzzle Task, $F(1,58)=.14$, $p=.710$, $\eta_p^2=.002$, Nonverbal Exact Arithmetic, $F(1,58)=.32$, $p=.572$, $\eta_p^2=.006$, Missing Term Problems, $F(1,58)=2.48$, $p=.121$, $\eta_p^2=.04$. All data were screened for potential outliers defined as three standard deviations above or below the mean. No outliers were identified.

3.2. *Intervention effects*

Training effects were assessed using a series of repeated measures ANOVAs with time (pre vs. post) as the within-subjects variable and group (spatial vs. literacy) as the between-subjects variable. Fig. 4 provides a summary of the main findings.

3.3. *Near transfer*

Analyses of performance on the 2D mental rotation task with animal-picture stimuli showed a main effect of time, $F(1,57)=35.37$, $p < .001$, $\eta_p^2=.38$. Results further revealed a significant interaction between time and group, $F(1,57)=4.15$, $p=.046$, $\eta_p^2=.07$. Pairwise comparisons with Bonferonni correction indicated significant gains by the spatial group compared to the literacy group. Analyses on 2D mental rotation performance with letter stimuli revealed a main effect of time, $F(1,57)=19.73$, $p < .001$, $\eta_p^2=.26$, and a significant interaction between time and group, $F(1,57)=6.71$, $p=.012$, $\eta_p^2=.11$. Pairwise comparisons with Bonferonni correction indicated significant gains by the spatial group compared to the literacy group. Overall, the results

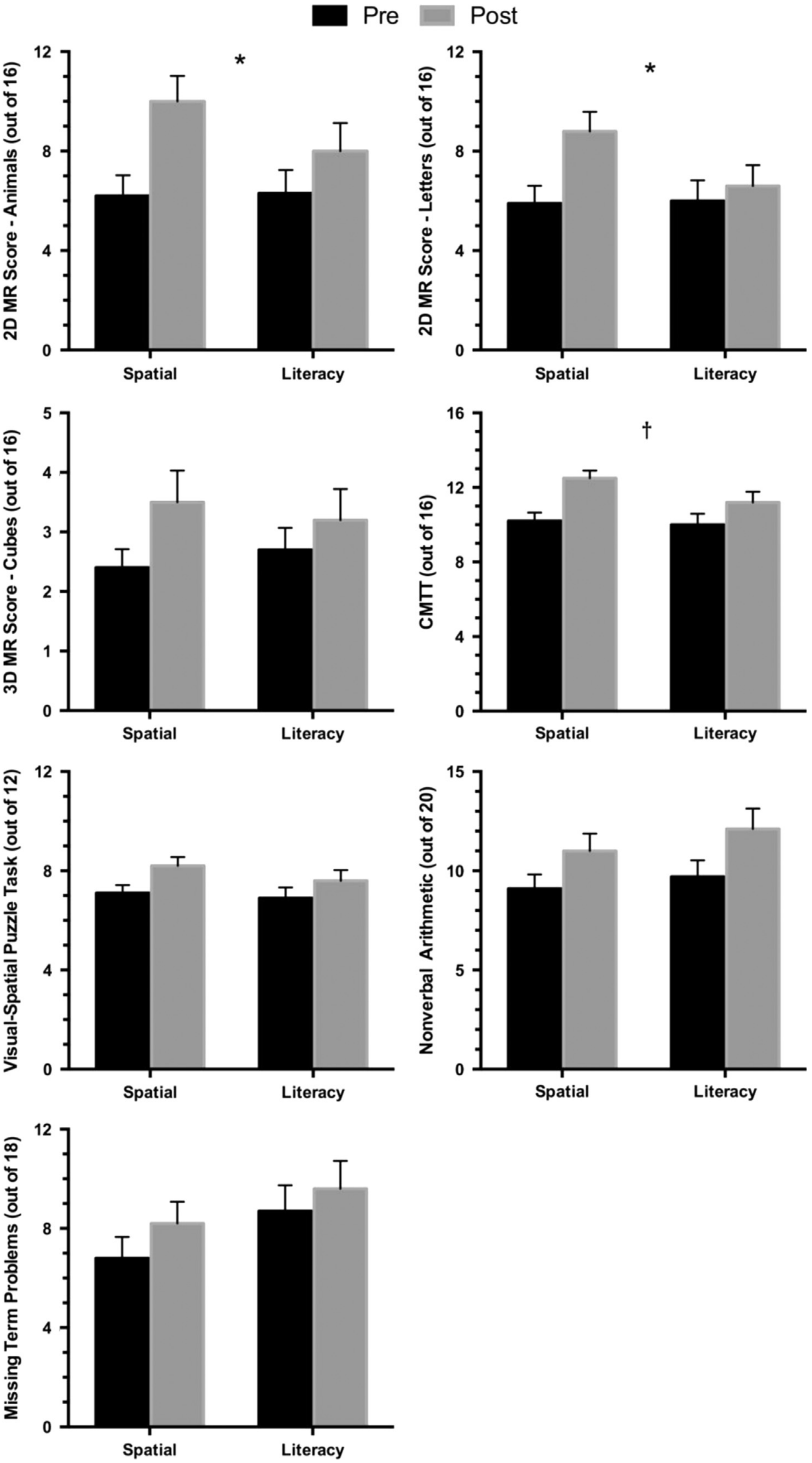

Fig. 4. Comparisons between spatial and literacy training groups at pre- and post-test on all seven measures. Note. MR=Mental Rotation. CMTT=Children's Mental Transformation Task. * denotes a significant group (spatial vs. literacy) by time (pre vs. post) interaction, $p < .05$, while † denotes a marginally significant interaction, $p = .056$. Error bars represent standard error of the mean.

supported the hypothesis that mental rotation training would result in near transfer effects.

3.4. *Intermediate transfer*

Analyses of performance on the 3D mental rotation task revealed a marginally significant effect of time, $F(1,57)=3.88$, $p=.054$, $\eta_p^2=.06$, but no interaction effect between time and group, $F(1,57)\ =.35$, $p=.557$, $\eta_p^2=.006$. Analyses of performance on the mental transformation task showed a significant effect of time, $F(1,56)=22.76$, $p<.001$, $\eta_p^2=.29$, as well as a marginally significant interaction between group and time, $F(1,56)=3.82$, $p=.056$, $\eta_p^2=.06$. Bonferonni corrected comparisons indicated significant gains by the spatial group in comparison to the literacy group. Analyses of performance on the visual–spatial puzzle task showed an effect of time $F(1,54)=9.71$, $p=.003$, $\eta_p^2=.15$, but no interaction between time and group, $F(1,54)=.70$, $p=.407$, $\eta_p^2=.013$. Overall, there is some evidence of intermediate transfer to untrained spatial tasks as indicated by the marginally significant interaction effect on the mental transformation task.

3.5. *Far transfer*

Analyses of performance on the nonverbal exact arithmetic task showed an effect of time $F(1,55)=20.49$, $p<.001$, $\eta_p^2=.27$, but no interaction between group and time, $F(1,55)=.13$, $p=.721$, $\eta_p^2=.002$. Similarly, analyses of performance on missing term problems revealed an effect of time $F(1,56)=8.62$, $p=.005$, $\eta_p^2=.13$, but no significant interaction between group and time, $F(1,56)=1.15$, $p=288$, $\eta_p^2=.02$. Overall, there was no evidence to suggest spatial training transferred to children's calculation skills.

4. Discussion

The current study sought to determine the effects of mental rotation training on children's spatial and mathematics performance. Relative to an active control group, children who received mental rotation training demonstrated significant improvements on two separate measures of 2D mental rotation. Furthermore, more general improvements in spatial thinking were revealed on an untrained spatial task. Thus, there was some evidence to suggest that training generalized beyond the specific task requirements of training (e.g., mirror discrimination). However, contrary to strong theoretical claims and recent empirical findings, there was no evidence that spatial training resulted in improved calculation skills.

4.1. *Near and intermediate transfer effects*

A common concern raised in the spatial training literature regards the extent to which training-induced improvements reflect genuine change in spatial cognition [46]. The present study attempted to partially rectify the issue by including five different mental rotation tests that differentially related to the training tasks. Significant gains were achieved on three of the five measures, suggesting a fairly robust effect of training on children's spatial thinking. A closer look at the training program and the measures employed provides an explanation for these findings as well insight into the more important question regarding the breadth of change.

Central to both the spatial training games and the two near transfer measures was the need to quickly and accurately discriminate mirror images. Indeed, previous research has shown that the majority of 4- to 8-year-olds struggle to differentiate mirror images [17]. It was with this in mind that two of the three games (see Fig. 1a and b) were explicitly designed to provide children with multiple and adaptive experiences discriminating mirror images under time restrictions and varying stimuli (polyominoes vs. animated objects). Thus, it is possible that the gains achieved in 2D mental rotation were attributable to highly task-specific training. That is, learning to quickly and accurately identify and discriminate between mirror images of 2D objects. However, it is also possible that the improvements in mental rotation were a result of more general effects of training.

Support for this possibility comes from the finding of gains made on the children's mental transformation task. Importantly, this task was not explicitly practiced during training and did not require mirror image discrimination. Although task items can be solved through a mental rotation strategy, other approaches include a decomposition strategy and/or the identification of shared perceptual features between the target and response items. As children's strategies were not taken into account during performance, it remains unclear how the training may have resulted in improvements on this task. It is possible that the improvements were a result of playing the puzzle game (see Fig. 1c). This game required selecting and rotating various 2D puzzle pieces to compose a unified whole. Similarly, one approach to solving the children's mental rotation task is through the mental rotation and translation of two shapes to compose a whole. Given that the focus of the three training games varied in the spatial skills they targeted, future research efforts are needed to study the isolated and combinatorial effects of the games.

Nevertheless, the overall findings suggest that training generalized to novel tasks and stimuli, providing evidence that changes in spatial thinking went beyond task-specific characteristics of training. This finding adds further support to the results of Uttal et al. [38] meta-analysis that concluded spatial training brings about significant and transferable improvements in spatial skills.

4.2. *Far transfer effects*

Although the relationship between spatial and mathematical ability is deeply established [28], surprisingly little is known about whether the two share a causal-relationship. Understanding whether and how spatial thinking and mathematics influence the development of one another is of critical importance for the design and implementation of future educational interventions. In the current study, we tested the idea that spatial training is likely to yield benefits in mathematics performance (see [3,41]).

Critically, in order to expect such a result, two prior assumptions should be met. First, it should be established that the training program is effective at bringing about near transfer improvements, thus providing confidence in the efficacy of the training program. Second, it should be shown that the training tasks are related to and explain a significant portion of variance in the far transfer outcome measures. We met both of these assumptions. As indicated above, the training program led to significant improvements on a number of different spatial tasks. It was also found that pre-test performance on the near transfer measures (i.e., a proxy for training), shared a significant portion of the variance with the far transfer measures. Thus, we had reason to believe that spatial training might indeed influence children's calculation performance.

Despite meeting both criteria, we found no evidence that mental rotation training resulted in improved calculation skills. Children in both the spatial and literacy condition demonstrated similar improvements on nonverbal exact arithmetic and missing term problems. Thus, we failed to support the finding reported by Cheng and Mix [28] of improved calculation performance following mental rotation training. The two studies were similar in that they both involved training 6- to 8-year-olds' mental rotation skills and tested for far transfer using missing term problems. However, the studies also differed in important ways. Cheng and Mix's [28] training involved practice on the children's mental transformation task and thus did not require mirror discrimination. Interestingly, the children in our study demonstrated gains on this very measure, presumably raising the likelihood of achieving far transfer. Potentially, the most important difference, however, was in the timing of administering the post-tests. Whereas we tested children 3-6 days following training, Cheng and Mix tested the children immediately following the 40-min training. Therefore, it is possible that the evidence of transfer resulted from a priming effect and was not necessarily driven by changes in spatial thinking per say. As such, participants may have been prompted to endorse a qualitatively different approach to solving missing term problems; an approach hypothesized by Cheng and Mix [28] to involve spatial rearrangements of the problem (e.g., $2+\_\_\_\_=8$ becomes $\_\_\_\_=8–2$). In short, our failure to observe transfer may be due to a lack of priming effects as a consequence of delayed post-testing. Future research efforts are needed to better understand and disentangle the effects of priming from more general change in spatial cognition following training.

4.3. Limitations

The current study had several limitations. First, we did not track children's motivation and engagement with the training tasks. According to the teachers, children in the spatial group appeared slightly more engaged than children in the literacy group. Interestingly, the teachers also reported that while some students' engagement increased over the course of training, others decreased. A second limitation was our failure to track children's progress throughout training. Thus, we were unable to assess how gains in training correlated to gains on the pre-post measures. Finally, another limitation concerned the differences in how the games adapted to individual users. Whereas the spatial games allowed the user to return to the highest level accomplished during their previous training session, this was not possible with the literacy games. Taken together, these are important limitations of the current study and future research should look to include measures of engagement and motivation, data on the progress of game play, and the inclusion of an adaptive control training condition.

4.4. Concluding words and future directions

Our findings suggest that gains in children's spatial thinking can be achieved after a relatively short (4.5 h) computerized intervention. Whereas the majority of previous training studies have been carried out in laboratory settings, this study was implemented within a regular classroom setting, under the leadership of classroom teachers. Thus, it appears as though computerized interventions are at least one ecologically valid approach of providing children with engaging, challenging, and effective spatial curricula. A promising area of future work is studying the effects of computerized interventions in combination with teacher-facilitated instruction (i.e., human-to-human interactions). Although we found no evidence that spatial training led to gains in children's calculation skills, the current study was short in duration and narrow in the spatial skills trained (i.e., mental rotation). More comprehensive and sustainable intervention approaches are recommended to better take advantage of the historically tight relationship between spatial thinking and mathematics.

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