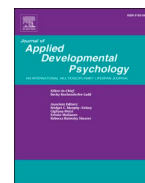




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Using books to improve mental rotation skills with 4- and 5-year-old children

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ABSTRACT

Mental rotation skills predict later achievement in STEM, and prior research shows that children's mental rotation skills improve after training. However, most studies have used dynamic stimuli where children see objects rotating. We hypothesized that reading books that practice mental rotation with only static images could improve children's mental rotation skills. We preregistered a pretest-training-posttest design with 4- and 5-year-olds ($N = 79$). Children completed a mental rotation assessment at pretest, four to six reading days with an experimenter over two weeks in one of two randomly-assigned conditions (Mental Rotation Book Condition versus Control Book Condition), and a mental rotation assessment at posttest. The Mental Rotation Books involved mental rotation practice while the Control Books did not. Consistent with our hypothesis, condition was a significant predictor of posttest mental rotation accuracy, controlling for age, verbal ability, and pretest mental rotation accuracy. Children in the Mental Rotation Book condition significantly improved in mental rotation accuracy from pretest to posttest, while the control group did not. However, condition was not a significant predictor of transfer to posttest mental transformation skills, math achievement, or spatial vocabulary, controlling for age, verbal ability, and respective pretest scores. These results show that book-reading can be an effective method for improving mental rotation skills in early childhood and warrants further investigation to understand the scalability of these effects in home and school settings.

Early spatial skills are strong predictors of later math achievement (Gunderson, Ramirez, Beilock, & Levine, 2012; Lauer & Lourenco, 2016; Mix et al., 2016; Verdine, Irwin, Golinkoff, & Hirsh-Pasek, 2014), success in science (Casey, Nuttall, Pezaris, & Benbow, 1995), and achievement and pursuit of careers in science, technology, engineering, and mathematics (STEM) (Wai, Lubinski, & Benbow, 2009). Spatial skills are thought to enhance STEM achievement by helping students understand dynamic processes, such as transformations involving chemical molecules and geological formations (e.g., Uttal et al., 2013) and to strengthen math skills by facilitating children's use of mental visual models to represent complex math problems (Mix et al., 2016). As early as 3 years of age, researchers have found a relationship between children's spatial skills and math abilities (Verdine et al., 2014). There are also significant individual differences in spatial skills even prior to school entry (Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2017),

pointing to the importance of learning experiences in early childhood (e.g., Lombardi, Casey, Thomson, Nguyen, & Dearing, 2017). Importantly, spatial skills are malleable (Uttal et al., 2013). Further, spatial skills in elementary school longitudinally predict students' choice of STEM college majors via children's greater math skills and greater math self-concepts in the intervening years (Tian et al., 2023). Given these longitudinal relations, early intervention could improve children's spatial skills, with potential downstream impacts on math motivation and STEM success. Thus, it is important to identify specific types of spatial skills that may be particularly beneficial for young children and to develop scalable home and school interventions (e.g., books and games) to improve these skills. Therefore, this study examined the impact of a book-reading intervention with 4- to 5-year-old children to improve mental rotation skills, a spatial skill that is a strong predictor of achievement and later success in STEM careers (Uttal et al., 2013; Wai

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et al., 2009).

Development of mental rotation skills

Spatial skills encompass a suite of related but distinct abilities involved in mentally representing and manipulating visuospatial information, including shapes and locations as well as the spatial relations between and within objects (Uttal et al., 2013). Theoretically, spatial skills can be categorized according to whether they involve within-object (intrinsic) or between-object (extrinsic) relations, and whether the mental representation involves movement (dynamic) or not (static), resulting in a 2×2 framework for categorizing spatial skills (i.e., intrinsic-static, intrinsic-dynamic, extrinsic-static, or extrinsic-dynamic; Uttal et al., 2013).

Mental rotation is an intrinsic-dynamic skill involving the ability to mentally rotate an object in order to match it to a reference object, and is one of the most studied forms of spatial skills since the 1970s (Shepard & Metzler, 1971). Mental rotation abilities are closely related to many areas of mathematics including geometry (Delgado & Prieto, 2004), numerical representations (Thompson, Nuerk, Moeller, & Cohen Kadosh, 2013), and solving mental math problems (Kytälä & Lehto, 2008). Because mental rotation skills are a strong predictor of achievement and later success in careers in STEM (Uttal et al., 2013; Wai et al., 2009), recent research has focused on studying the emergence of mental rotation skill in very young children (Hespos & Rochat, 1997; Möhring & Frick, 2013). Some studies have found that infants as young as 4 months of age have some level of mental rotation skills, as shown using violation of expectation paradigms (Hespos & Rochat, 1997; Möhring & Frick, 2013). Between 2 and 3 years of age, toddlers begin to make more accurate manual pre-adjustments when attempting to fit blocks into a shape sorter (Pedrett, Kaspar, & Frick, 2020). By 3 years of age children can more consistently choose the correct shaped objects in tasks involving rotating blocks to fit into a shape sorter (Shutts, Ornklöo, Von Hofsten, Keen, & Spelke, 2009). The age at which preschoolers succeed at mental rotation tasks that are presented as static images, such as discriminating between different 2D images of rotated objects, ranges from 3 to 5 years (Frick, Ferrara, & Newcombe, 2013; Frick, Hansen, & Newcombe, 2013; Hawes, Moss, Caswell, & Poliszczuk, 2015; Krüger, Kaiser, Mahler, Bartels, & Krist, 2014; Marmor, 1975; Noda, 2010).

One challenge in studying mental rotation in early childhood is that many age-appropriate tasks aimed at measuring mental rotation can, in fact, be solved using either mental rotation or other cognitive strategies. For example, in the widely-used Children's Mental Transformation Task (CMTT; Levine, Huttenlocher, Taylor, & Langrock, 1999), children must determine what shape two pieces would make when moved together. Although children may solve this task using mental rotation, they can also solve it using other strategies such as matching perceptual features. To prevent feature-matching strategies, other tasks use mirror-image foils to control all perceptual features, such as the Picture Rotation Task (PRT; Casasola, Wei, Suh, Donskoy, & Ransom, 2020; Quaiser-Pohl, 2003). With appropriate design and instructions, children as young as 4 years of age can succeed at mental rotation tasks with mirror-image foils (Casasola et al., 2020; Frick, Hansen, & Newcombe, 2013). Whereas many studies have treated mental transformation and mental rotation tasks as interchangeable, we adopt the distinction articulated by Gunderson and Hildebrand (2021): that *mental transformation tasks* are tasks that can be solved using mental rotation but can also be solved using other strategies, and *mental rotation tasks* use mirror-image foils in order to prevent alternative strategies and require mental rotation. Here, our primary interest is in whether book-reading can improve children's mental rotation skills, and we consider mental transformation as a near-transfer task.

Against this backdrop of normative developmental changes in mental rotation skills are substantial individual differences (e.g., Frick, Hansen, & Newcombe, 2013) and clear evidence for malleability to environmental influences (Uttal et al., 2013). In early childhood, more

frequent play with blocks and construction toys has been shown to positively correlate with mental rotation abilities (Baenninger & Newcombe, 1989; Jirout & Newcombe, 2015). Similarly, children who more frequently played with puzzles at home when children were 2 to 4 years old had higher mental transformation skills (Levine, Ratliff, Huttenlocher, & Cannon, 2012). In addition to providing opportunities for children to mentally represent objects and visualize their movements, blocks and puzzles also elicit spatial language from parents (e.g., Casasola et al., 2020), which in turn is related to children's higher spatial skills (Casasola et al., 2020; Polinsky, Perez, Grehl, & McCrink, 2017; Pruden, Levine, & Huttenlocher, 2011).

In addition to individual differences, there has been a large body of research on sex and gender differences in mental rotation ability (Halpern et al., 2007; Levine et al., 1999; Linn & Petersen, 1985). A meta-analysis by Lauer, Yhang, and Lourenco (2019) reviewed 303 effect sizes of gender differences in mental rotation and found that while there was only a slight male advantage during early childhood (effect size of $g = 0.20$ at age 3 to 7 years), the gender difference grew to a moderate effect size during adolescence ($g = 0.54$ by age 13 to 17 years). Although there is no single definitive explanation for this gender difference, one theory points to gender differences in the environmental factors that promote mental rotation skills. Many activities such as blocks, construction toys, and computer games that have been shown to improve spatial skills are engaged in more often by boys than girls (Connor & Serbin, 1977; De Lisi & Wolford, 2002).

Given these sex and gender differences in engagement with spatially-stimulating toys and activities, one motivation for the present study was to determine whether an activity that is more gender-neutral (or female-typed) – book-reading – could also have positive effects on young children's mental rotation skills. Based on self-reports and observations in preschool classrooms, preschool-aged boys and girls do not differ in their interest and engagement in literacy activities (Baroody & Diamond, 2013), although parents report more frequent book-reading with their daughters than sons (e.g., Højen, Schmidt, Møller, & Flansmose, 2022). Therefore, we were interested in creating a context that would be engaging for both boys and girls and that, if effective, could lead to scalable intervention materials for practicing these critical spatial skills.

Interventions to improve young children's mental rotation skills

Given the strong correlation between spatial skills such as mental rotation and math achievement, it is of interest to understand how interventions can be implemented to train these key spatial skills (Hawes, Gilligan-Lee, & Mix, 2022; Uttal et al., 2013). In addition, randomized intervention studies provide direct tests of the malleability of mental rotation skills, avoiding the potential confounds of correlational studies. In a meta-analysis, Uttal et al. (2013) found that spatial skills training, among participants age 7 years to adults, was effective in increasing both accuracy and response time on mental rotation tasks. Consistent with this, a more recent meta-analysis with participants from age 3 years to adults also found medium effect size of spatial training on spatial skills (Hawes et al., 2022). However, despite overall positive effects of mental rotation training in these meta-analyses, it is not clear whether these positive effects extend to preschoolers because the large majority of studies have focused on older children.

Although there are interventions that involve spatial training for preschool age children to improve their math and executive functioning (Schmitt, Korucu, Napoli, Bryant, & Purpura, 2018), mental transformation (Xu & LeFevre, 2016), and visuo-spatial ability (Cornu, Schiltz, Pazouki, & Martin, 2019), only a few studies to date have specifically studied the effects of mental rotation training on children younger than 6 years of age. One such study by Frick, Ferrara, and Newcombe (2013) tested a mental rotation training with preschool children, randomly assigning them to manual rotation, observation-based learning, or no training conditions. Afterward, all children played a computer game assessing their ability to match shapes with

holes, revealing that while 3.5- to 4.5-year-olds performed at chance, 4.5- to 5.5-year-olds showed improved accuracy after both manual and observational training (versus no training), with no significant difference between the two methods. A more recent mental rotation training study with 3- to 5-year-olds had a much higher dosage of training (Fernández-Méndez, Contreras, & Elosúa, 2018), with multiple trials which increased in difficulty over the course of three days. In the training, children needed to select which of two images (a correct answer and a mirror-reversed image) could be rotated or translated to fit into a target shape. After choosing, children were allowed to manually rotate the shapes to check their answer. The study found significant improvement in mental rotation abilities for 4- to 5-year-olds, but not for 3-year-olds, compared to a control group. These studies suggest that children ages 3 to 5 years can benefit from mental rotation training, with greater effects among older children in this range.

Another training study focused on the effects of gesture and visualization on mental rotation among 4- to 6-year-old children (Wakefield et al., 2019). They found that both boys and girls improved more from gesturing the rotation of an image (without seeing the outcome) than from using a similar hand movement to rotate the image on a touch screen (while seeing the outcome). Further, boys, but not girls, improved just as much from imagining the outcome of the rotation (without seeing it) as from gesturing. Unlike most other training studies that have allowed children to see dynamic rotations and the outcomes of the rotations, these results suggest that static images along with gestures may be as effective (or even more effective) than dynamic images in improving mental rotation skills.

It is worth noting that, although not focused on mental rotation, several other studies involving spatial training with children younger than 6 years provide support for the malleability of children's spatial skills at this age (e.g., Bower et al., 2020; Cornu et al., 2019; Hawes et al., 2022; Hawes, Moss, Caswell, Naqvi, & MacKinnon, 2017; Schmitt et al., 2018; Xu & LeFevre, 2016). For example, in a spatial training study by Bower et al. (2020), 3-year-olds were asked to build various objects to match a target image using concrete materials (2D cutout shapes). They found that children in all training conditions increased their 2D spatial assembly skills from pretest to posttest compared to the "business-as-usual" control group, although this did not transfer to 3D spatial assembly skills or math achievement. In a subsequent study, they extended these results to show that both concrete and digital trainings were effective in promoting 3-year-olds' 2D spatial assembly skills (Bower et al., 2025). Although these studies did not directly focus on mental rotation training, they show that children as young as 3 years of age can benefit from spatial training.

Intervention studies have also established that spatial training can lead to transfer to untrained spatial and mathematical skills, although these results have largely been obtained in children over 6 years of age. For example, in a study of 8-year-olds, training spatial scaling led to near-transfer to mental rotation, an untrained spatial skill (Gilligan, Thomas, & Farran, 2020). A meta-analysis of 29 training studies involving participants ages 3 to 20 years found that the effect of spatial training on transfer to mathematics skills was significantly positive, with an overall effect size of $g = 0.28$ (Hawes et al., 2022). Further, the duration of training ranged from 5 min to 44 h, and remarkably, training duration did not impact the size of the transfer effect. Theoretically, even a short duration of spatial training may impact math performance by shifting the types of strategies children use during math problem-solving. Indeed, a 4-min spatial training with 2nd- and 3rd-graders led to changes in arithmetic strategies and improvements in arithmetic performance (Zhang & Gunderson, 2025).

Particularly relevant to our study of preschoolers, Hawes et al. (2022) found that the effect of spatial training on mathematics was larger for older than younger students, suggesting that transfer effects may be difficult to obtain in preschool-aged children. Nevertheless, some recent research suggests that spatial training can lead to near- and far-transfer even among preschoolers. In a recent study with 3-year-olds,

2D spatial assembly training with gestural feedback led to improvements in 3D spatial assembly, an example of near transfer within the spatial domain (Bower et al., 2025). Further, across two studies, 3-year-olds from low-socioeconomic status backgrounds improved in math problem-solving after 2D spatial assembly training with concrete modeling feedback, an example of far transfer to the math domain (Bower et al., 2020; Bower et al., 2025).

In sum, there is limited research on mental rotation training with preschoolers and a lack of consensus about what age mental rotation training is useful and effective. Whereas there is some evidence that mental rotation training can be useful for 4- to 5-year-olds (Fernández-Méndez et al., 2018), other researchers have argued that mental rotation interventions are not helpful for children younger than 5 years of age (Frick, Ferrara, & Newcombe, 2013). Further, although spatial skills training can lead to near-transfer to other spatial skills and far transfer to mathematics skills in older children (e.g., Gilligan et al., 2020; Hawes et al., 2022), little research has investigated transfer effects in preschoolers. More research is needed to determine at what age mental rotation training is effective and what methods to use to improve early mental rotation abilities.

Challenges to spatial activities and benefits of book-reading as an intervention platform

Although studies have shown repeatedly that spatial skills are malleable and spatial activities are associated with improvements in children's spatial skills, increasing the quantity of spatial activities at home such as play with blocks, puzzles, and video games has some practical challenges. First, these types of spatial activities are expensive, and families of low socioeconomic status (SES) may not be able to afford them. Consistent with this, Levine, Vasilyeva, Lourenco, Newcombe, and Huttenlocher (2005) found that children from higher SES groups performed better than lower SES groups on spatial transformation tasks and argued that lack of funds to buy spatial activities may be the cause, although this was not explicitly tested (Levine et al., 2005). Second, gender biases in parents' beliefs about their children's toy preferences could discourage parents from buying spatial activities for their daughters and encourage buying them for their sons. This could be why girls have been found to play with spatial toys less than boys and could be a contributing factor to the gender gap in spatial skills (Jirout & Newcombe, 2015). Third, the presence of spatial activities at home does not guarantee that there will be high-quality parent-child interactions with these activities. Indeed, a month-long parent-led intervention, in which researchers mailed four different spatial toys to parents and asked them to play with their preschooler for at least one hour per week, had no impact on children's mental rotation skills compared to an active control group (Tian et al., 2025). High-quality parent-child interactions require parents to have the time and motivation to engage in spatial activities with their child and may require parents to know of the importance of spatial language and gesture (Borriello & Liben, 2018; Polinsky et al., 2017).

Considering these drawbacks of spatial activities such as blocks, puzzles, and video games, an alternative learning activity that mitigates these drawbacks is book-reading. Books can be inexpensive or free at schools and libraries and are appealing to both girls and boys (Baroody & Diamond, 2013). Book-reading has been successfully used in previous research as a tool to promote high-quality parent-child (Gibson, Gunderson, & Levine, 2020; Mol, Bus, De Jong, & Smeets, 2008; Purpura et al., 2021; Szechter & Liben, 2004) and teacher-child interactions (van den Heuvel-Panhuizen, Elia, & Robitzsch, 2016) in many different subjects. Books may also be especially helpful in addressing the gender gap as girls might be more likely to learn from books than boys. Supporting this, in a 3-month intervention study from the Netherlands in which teachers read books that incorporated math learning, girls in the intervention group (versus a business-as-usual control) significantly increased their number, measurement, and geometry scores while boys

did not, and the effect size for girls was three times higher than boys (van den Heuvel-Panhuizen et al., 2016).

While there is much research on the benefits of book-reading for children's math (Carrazza & Levine, 2025; Gibson et al., 2020; Purpura et al., 2021; Purpura, Napoli, Wehrspann, & Gold, 2017; Szechter & Liben, 2004; van den Heuvel-Panhuizen et al., 2016) and literacy skills (Huebner & Meltzoff, 2005; Lever & Sénéchal, 2011; Mol et al., 2008), there is limited research on the benefits of book-reading for children's spatial skills. One study by Szechter and Liben (2004) investigated whether the quantity and quality of parent spatial talk and behaviors during book-reading significantly related to children's performance on spatial-graphic measures, which involve representations such as drawings or maps. Experimenters observed parents reading the book *Zoom* to their preschool children; in this book, each page is a more distant zoomed out vantage point of a picture. Parents who spoke and gestured more about spatial relations and concepts while reading *Zoom* had children who scored higher on spatial-graphic assessments. Although this study found a correlation between parent behaviors during spatial book-reading and children's spatial skills, it does not prove a causal relationship. The current study aimed to investigate the causal effect of spatial book-reading – which encourages spatial talk and gesture – on children's mental rotation skills.

It is worth noting that most prior research on the benefits of book-reading involves narrative storybooks, whereas in our study, the book-reading context involved nonnarrative picture books. The books were designed with a series of sequential questions to solve, similar to an activity book. We reasoned that including a narrative could distract children and reduce their focus on mental rotation practice, in line with research showing that children's learning benefits from minimizing distractions (Eng, Godwin, & Fisher, 2020; Tare, Chiong, Ganea, & DeLoache, 2010). Indeed, several studies demonstrating positive effects of book-reading on math concepts among preschoolers have used nonnarrative (Gibson et al., 2020) or minimally-narrative books (Griffin et al., 2024).

The current study

The current study aimed to determine whether a book-reading intervention can be used to improve mental rotation skills among 4- and 5-year-old children. Although the ultimate goal of this line of research is to determine whether book-reading can be an effective intervention for mental rotation skills when implemented by parents and teachers, this initial study tested the effectiveness of the books when read by an experimenter. This ensured more consistency in the book-reading experience between children and fewer distractions compared to parents reading to their children at home. Using a book format is also significant because, other than the first two practice questions in each book, children could not see the outcome of the rotation. Nearly all prior studies have used either physical intervention materials (e.g., blocks, puzzles) or animated images on a screen in which children could see the outcome of the rotation by physically manipulating the materials or observing them on a screen. However, at least one prior study supports the concept that seeing the outcome of the rotation is not necessary for children to improve their mental rotation skills (Wakefield et al., 2019).

The current study used a pretest-intervention-posttest design to assess the impact of our intervention books on children's mental rotation skills. Children were randomly assigned to the intervention or an active control group to address potential practice effects. We included several control measures – child age, verbal IQ, and pretest scores on each outcome measure – to strengthen the internal validity of our results. We conducted this study with 4- and 5-year-olds because of the significant

individual differences in spatial skills prior to school entry (Verdine et al., 2017). By intervening early, the gains that children make in their mental rotation skills could lead to greater success in STEM fields in the future.

The study's design and analysis plan were preregistered on Open Science Framework (OSF; <https://osf.io/7eg53>). We preregistered two primary hypotheses. First, we hypothesized that an experimental group that read books that incorporate mental rotation practice would result in higher mental rotation scores at posttest compared to a control group who read books that did not practice mental rotation skills. Second, we hypothesized that the experimental group would have higher scores on a mental transformation task – a near transfer task – compared to a control group at posttest. Although our book design was more similar to mental rotation tasks, we expected improvements in mental rotation skills to also be helpful on mental transformation tasks.

We also explored whether improving mental rotation skills led to far transfer to math skills or spatial vocabulary skills. Further exploratory analyses investigated whether there was a greater effect of book reading for children who scored lower in mental rotation skills at pretest. Finally, although we did not expect gender differences at this age based on prior research (e.g., Lauer et al., 2019), we investigated whether there were any gender differences in any of the measures at pretest or posttest.

Methods

Participants

Our planned sample size was 80 4- to 5-year-old children, after exclusions. This sample size was determined from a power analysis to obtain a medium sized effect of $f = 0.317$, with power = .80 at the standard .05 alpha level, consistent with the meta-analytic effect size of spatial training on spatial skills found by Hawes et al. (2022). We used G*Power to conduct a power analysis. However, the need to exclude one participant was discovered after data collection was complete and it was not feasible to restart data collection. Therefore, our analytic sample was 79 participants, which deviates slightly from the preregistered 80 participants.

Children were recruited from Catholic and private schools in an eastern U.S. city. Of the analytic sample, 54% were White, 3% were Black, 6% were Hispanic, 5% were Asian, 8% were Multiracial, and 24% chose not to report their race. Among families who reported language(s) spoken at home, for 92% of children, English was their primary language ($n_{\text{lang}} = 65$). The average highest level of parent education was 16.51 years ($SD = 2.02$, $n_{\text{edu}} = 65$) which is the equivalent to more than a Bachelor's degree, and the average household income was \$85,530 ($SD = \$27,830$, $n_{\text{income}} = 61$). Our sample included 40 girls and 39 boys. Descriptive statistics of these demographic variables broken down by condition can be found in Table 1.

An additional seven participants who consented and assented to the study were excluded based on our preregistered exclusion criteria: they did not complete at least 50% of the PRT and CMTT items at pretest ($n = 1$), did not complete at least four of the six reading days ($n = 4$), scored 3 standard deviations below the national norm in their verbal IQ score (Kaufman Brief Intelligence Test [KBIT-2]) ($n = 1$) as this might have been an indication of a developmental disability or poor English language proficiency, or the posttest was not completed by 18 days after pretest ($n = 1$).

We had planned to exclude children if the experimenter read a book from a different condition to the child (a type of experimenter error), or if they did not complete at least 50% of the PRT and CMTT items at

Table 1
Descriptive Statistics of Variables.

Variables	Mental Rotation Condition		Control Condition	
	n	M (SD)	n	M (SD)
Age (years)	40	5.14 (0.56)	39	5.12 (0.46)
Gender				
Girls	21		19	
Boys	19		20	
Parent Education (years)	34	16.65 (2.07)	31	16.35 (1.99)
Income (thousands)	32	91.80 (22.14)	29	78.62 (31.98)
Pretest Measures				
Mental Rotation	40	.59 (.24)	39	.58 (.23)
Mental Transformation	40	.42 (.18)	39	.40 (.19)
Spatial Vocabulary	40	.79 (.14)	39	.74 (.17)
Number Sense (W)	40	446.95 (15.97)	39	440.74 (17.34)
KBIT (SS)	39	104.00 (12.63)	39	103.26 (13.71)
Reading Measures				
Enjoyment (Day 1)	40	5.47 (1.03)	39	5.74 (0.41)
Enjoyment (Day 6)	33	5.42 (0.89)	36	5.74 (0.54)
Posttest Measures				
Mental Rotation	40	.75 (.21)	39	.58 (.27)
Mental Transformation	40	.49 (.21)	39	.48 (.23)
Spatial Vocabulary	40	.81 (.14)	39	.83 (.16)
Number Sense (W)	40	448.18 (13.18)	39	442.79 (17.08)

Note. KBIT (SS) = Kaufman Brief Intelligence Test Standard Score.

posttest, but did not need to do so. Following our preregistered task-wise exclusion criteria, we excluded one participant's KBIT-2 verbal IQ score because the ceiling criteria were not met due to experimenter error. We had also planned the following task-wise exclusion criteria, but no task-level data were excluded for these reasons: data from the Woodcock-Johnson IV Tests of Early Cognitive and Academic Development (ECAD) Number Sense subtest would be excluded if basal and ceiling were not met (a type of experimenter error), and pretest and posttest data on other measures would be excluded if the participant completed less than 50% of the assessment.

Procedure

This study used a between-subjects design with a training group where children were read books by an experimenter that practice mental rotation skills (Mental Rotation Book Condition) and an active control group where children are read books by an experimenter that did not contain mental rotation practice (Control Book Condition). We used blocked randomization, such that children within a classroom were randomly assigned to each condition. The study used a pretest-training-posttest design. Both conditions received the same measures at pretest and posttest. Pretest and posttest included the following tasks in this order: a mental rotation task (PRT Version A or B – counterbalanced so that children who completed version A at pretest completed version B at posttest and vice versa), spatial vocabulary, a mental transformation task (CMTT), and a math achievement assessment (ECAD Number Sense). Children also completed a verbal IQ test (KBIT-2) at pretest only.

There were eight sessions total over approximately 1.5 weeks. At session one, an experimenter administered the pretest measures. During sessions two to seven, an experimenter read to the children, one book per session. Following our preregistered criteria, children were required to complete at least four book-reading sessions to be retained in the sample; all included participants completed five or six book-reading sessions. During session eight, an experimenter administered the posttest measures. The pretest and posttest sessions were allowed to occur on the same day as a book-reading session; children completed no more than one book-reading session per day. Posttest was administered 4–15 days after the pretest ($Mdn = 9$ days). In each condition, two parallel versions of the book were provided (matched within the Mental Rotation Book condition for number of examples of rotation and angles of rotation; matched across all conditions for word count and number of pages). The child was allowed to pick one of the books from their

Pretest and Posttest Measures

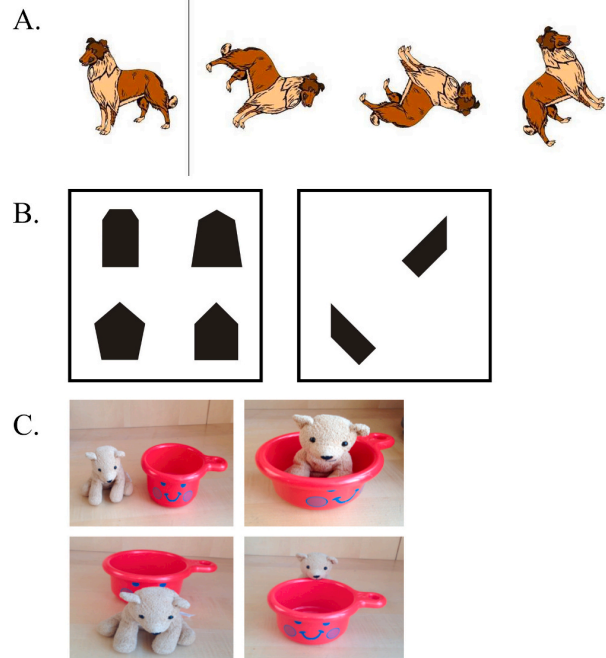


Fig. 1. Pretest and Posttest Measures Note: (A) Picture Rotation Task, (B) Childrens Mental Transformation Task (CMTT), (C) Spatial Vocabulary. Reprinted with permission from Casasola et al. (2020).

condition to read during each book-reading session.¹

Pretest and posttest materials

The Picture Rotation Task (PRT)

The PRT (see Fig. 1A), originally created by Quaizer-Pohl (2003) and adapted by Casasola et al. (2020), assesses children's mental rotation skills. The adapted task has two versions (A and B) with three practice items and 12 test items in each version. The two versions have the same practice items but different test items. Children completed either version A or B at pretest, and the alternative version at posttest. For each question, children were shown three images rotated either 45°, 90°, 130°, or 180° degrees clockwise or counterclockwise next to an upright target image. Children were asked to choose which of the three rotated images would be facing in the same direction as the target image if it were right side up. Children must mentally rotate the images in order to select the correct answer. All images were of animals or people. This assessment was scored by calculating the total percent accuracy. Cronbach's alpha for pretest PRT was .70 for version A and .76 for version B. Cronbach's alpha for posttest PRT was .84 for version A and .80 for version B.

¹ Additionally, we included an optional parent questionnaire to explore the spatial and verbal home learning environment. The questionnaire included questions about the frequency of spatial and literacy home learning activities, recognition of children's book titles and spatial games, beliefs about their child's abilities, interest, and importance of their abilities, beliefs about their own abilities, and their theories of intelligence. However, only 24 parents completed the questionnaire, and it was not part of our preregistered hypotheses or analysis plan. Due to lack of statistical power caused by the low response rate, we did not analyze the questionnaire data for the purposes of this paper.

Children's Mental Transformation Task (CMTT)

The CMTT (see Fig. 1b) was developed by Levine et al. (1999). For this task children were shown a target image with two halves of a picture and four different completed pictures below them. Children were asked to point to one of the four pictures that the two half pieces would make if they were put together. There were 24 items total: six involving rotation and translation, six involving rotation only, six involving translation only, and six involving direct movement. The same version of the task was used for pretest and posttest. This assessment was scored by calculating the total percent accuracy. Cronbach's alpha for the CMTT was .75 at pretest and .82 at posttest.

Spatial vocabulary

Children's receptive vocabulary for spatial terms was measured using an abbreviated version of a spatial vocabulary assessment developed by Casasola et al. (2020) (see Fig. 1C). For this study, we selected only the nine items that related to spatial relations and configurations and omitted the items identifying shapes. For this task children were shown nine images of a bear in different configurations relative to a red cup (e.g., "point to the picture where the bear is in the cup."). The spatial terms tested were "in", "under", "behind", "below", "far away", "to the left of", "in the middle", "to the right", and "upside down". The same version of the task was used for pretest and posttest. This assessment was scored by calculating the total percent accuracy. Cronbach's alpha for spatial vocabulary was low for pretest at .36 and posttest at .42.

Math achievement

The Woodcock-Johnson IV Tests of Early Cognitive and Academic Development (ECAD) Number Sense subtest (ECAD; Schrank et al., 2015) assessed children's math skills, such as number recognition, counting, and estimating quantities. Questions included items that were similar to questions like "Count these items out loud" and "What number comes between four and six?". This assessment was scored using *W* scores (a Rasch-based metric; Wendling et al., 2015). The Number Sense subtest is normed for children ages 2 to 7 years, with a published median test reliability of .79 (LaForte et al., 2015).

Verbal IQ

As a control, we assessed verbal IQ at pretest only using the Kaufman Brief Intelligence Test Verbal Knowledge and Riddles subtests (KBIT-2; Kaufman & Kaufman, 2004). The Verbal Knowledge subtest assessed receptive vocabulary. Children were shown six images and asked to point to the picture that matched a given word, for example, "Point to dog." The Riddles subtest involved expressive vocabulary, for example, "What is pointy and is used to eat food?" This assessment was scored by converting raw score and child age into a standard score. Both the Verbal Knowledge and Riddles subtests are normed for ages 4 to 90 years. Published internal-consistency reliabilities for the Verbal Knowledge subtest for 4-year-olds and 5-year-olds are .87 and .85 respectively. Internal-consistency reliabilities for the Riddles subtest for 4-year-olds and 5-year-olds are .72 and .77 respectively (Kaufman & Kaufman, 2004).

Book enjoyment

After each reading session the experimenter asked the child questions about how much they enjoyed reading the books on a 6-point Likert scale from 1 = *really did not like them*, to 6 = *really liked them*. The experimenter then asked if the book today made them feel happy or sad on a 6-point Likert scale from 1 = *really sad*, to 6 = *really happy*. Lastly children were asked how much fun reading the book was: 1 = *not that fun*, 2 = *a little fun*, or 3 = *really fun*. To create an overall score, we multiplied the final item by two so that it was on a similar scale to the other items, then averaged the three items. Although they were not a

primary dependent variable, we included these questions to check whether children's enjoyment differed between the control and experimental conditions or from the first reading day to the last reading day.

Intervention books

The research team designed two versions of both the mental rotation books and the control books, one with human characters and one with animal characters. All books contained four different question types for a total of 14 problems. The first two problems in each book were practice problems where children could see the outcome of their answer choice. All four books were matched for word count and page count. Experimenters who read the books were trained to always give children feedback on questions they got wrong and to work with the child until they answered the question correctly in order to move to the next page. The books were designed to encourage the child and the adult reader to interact through prompts without excessive distractions on each page.

Mental rotation books

The mental rotation intervention books consisted of four question formats that all practiced mental rotation (see Fig. 2 for example pages). There were two versions of the book, one with animals and one with people. The question formats and angles of rotation were matched between both books. The questions were all loosely influenced by existing mental rotation tasks. The two practice questions were inspired by the format of the Ghost Puzzle Task (Frick, Hansen, & Newcombe, 2013). For each practice problem, children were shown two rotated images and asked which one would match the target image if it were right side up (Fig. 2A).

The two practice problems explained the incorrect and correct answer and showed the outcome of the rotation. The next three pages followed the same format as the practice problems but did not show the outcome of the rotation (Fig. 2B). The next two questions were loosely inspired by the PRT (Quaiser-Pohl, 2003) (Fig. 2C). For the next five questions children had to choose which direction the animal or person would be walking towards if they were turned over (Fig. 2D). Finally, on the last two questions, children needed to choose which image would also be marching in the direction of the parade if they were right side up (Fig. 2E). If children answered a question incorrectly, experimenters were trained to prompt the child by saying "That's not quite right, try and turn it in your mind", followed by a grasping and turning gesture.

Control books

The control books were designed to closely match the mental rotation books in terms of page count, word count, style, and types of images, while replacing all mental rotation practice with other questions (see Fig. 3 for example pages). There were two versions of the book, one with animals and one with people. The first two practice questions involved a matching game where children needed to identify which item on the page matched the target image (Fig. 3A). The two practice problems explained the incorrect and correct answers and showed the correct answer. The next three questions followed the same format as the practice problems but did not explain the correct answer (Fig. 3B). The next two questions had the same layout as the PRT (Quaiser-Pohl, 2003), but there was no rotation involved and it was simply a matching task (Fig. 3C). On the next five questions, children had to choose which direction the animal or person was walking towards (Fig. 3D). Finally, on the last two questions, children needed to choose which image matches the animals or people in the parade (Fig. 3E). If children answered a question incorrectly, experimenters were trained to use pointing gestures and verbally prompt the child by repeating the question and then drawing attention to relevant clues on the page (e.g., "look at the bows, are these bows the same?").

Mental Rotation Book Example Pages

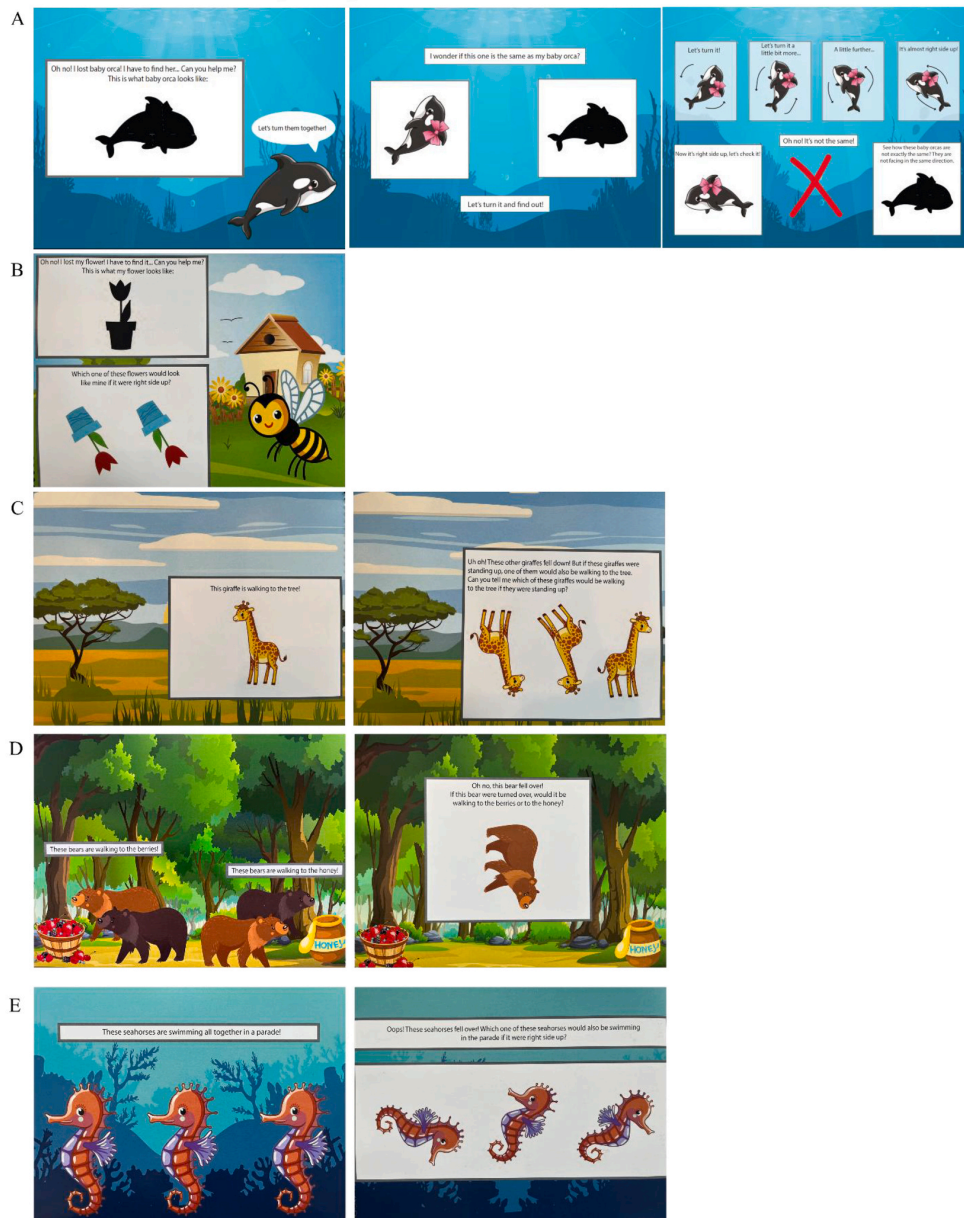


Fig. 2. Mental Rotation Book Example Pages Note: (A) An example of a practice question, on which children were shown the outcome of rotation, (B) the first question type where children needed to choose which rotated image matches the target image on the top if they were right side up, (C) the second question type where children needed to choose which rotated image on the right would be walking in the same direction as the target image on the left if they were standing up, (D) the third question type where children needed to choose which direction the rotated image on the right would be going if it were turned over, (E) the fourth question type where children needed to choose which rotated image on the right would be going in the same direction as the images on the left if they were right side up.

Results

Data and analysis scripts are publicly available on OSF (<https://osf.io/6z5rx>).

Preliminary analyses

The means and standard deviations for all measures can be found in Table 1, and the correlations between variables can be found in Table 2.

Preregistered analyses

To test Hypothesis 1, we conducted an analysis of covariance (ANCOVA) with mean accuracy on PRT at posttest as the dependent variable. We included condition as a between-subjects factor, and included age, verbal IQ, and mean accuracy on PRT at pretest as covariates. Consistent with our first hypothesis, condition was a significant predictor of posttest PRT mean accuracy, $F(1, 73) = 13.89, p < .001, \eta_p^2 = 0.16, 95\% \text{ CI } [0.04, 0.31]$ such that children in the Mental Rotation Book condition outperformed those in the Control Book condition in

Control Book Page Example Pages

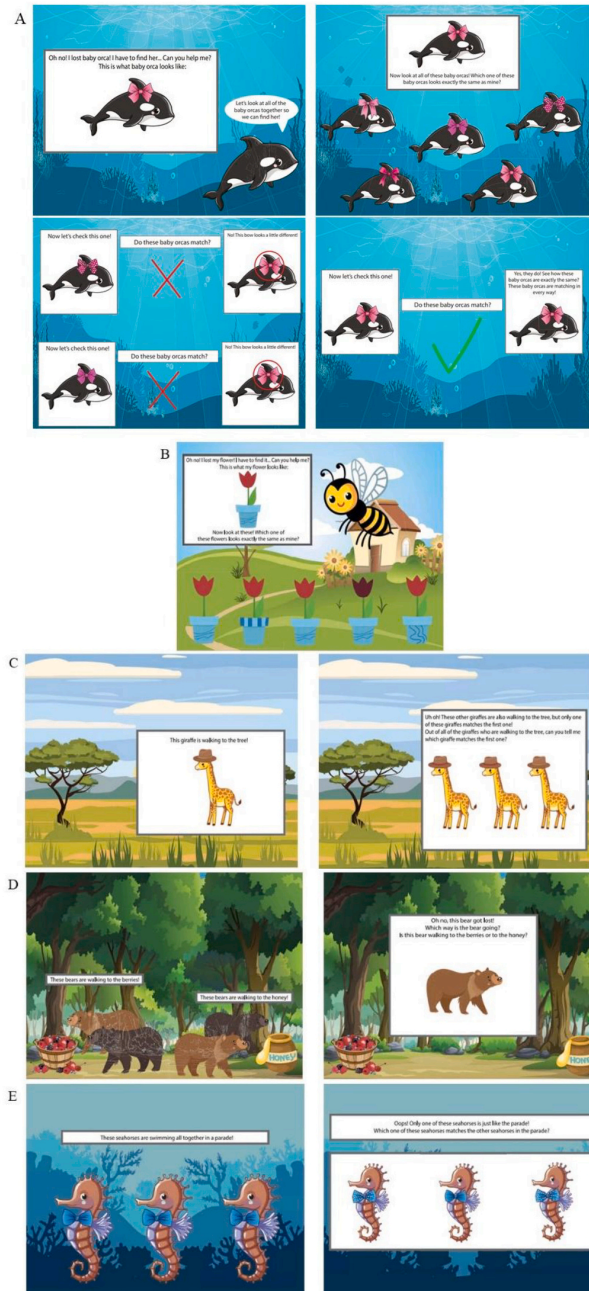


Fig. 3. Control Book Page Example Pages Notes. (A) An example practice question where children were shown the correct answer to a matching question, (B) the first question type where children needed to choose which image matches the target image on the top, (C) the second question type where children needed to choose which image on the right matches the target image on the left, (D) the third question type where children needed to choose which direction the image on the right was going, (E) the fourth question type where children needed to choose which image on the right matched the images on the left.

PRT accuracy at posttest. Further, children in the Mental Rotation Book condition significantly improved their PRT mean accuracy from pretest ($M = .59$, $SD = .24$) to posttest ($M = .75$, $SD = .21$), $t(39) = 4.64$, $p < .001$; $d = 0.73$, 95% CI [0.43, 1.16], whereas those in the control group did not, $t(38) = 0.07$, $p = .945$; $d = 0.01$, 95% CI [-0.32, 0.33] (see Fig. 4).

Inconsistent with our second hypothesis, condition was not a significant predictor of posttest mental transformation accuracy, $F(1, 73) = 0.27$, $p = .606$, $\eta_p^2 = 0.01$, 95% CI [0.00, 0.07], controlling for age, pretest mental transformation accuracy, and verbal IQ. Children in the Mental Rotation Book condition and the control group condition both significantly improved from pretest (Mental Rotation Book Condition: $M = .42$, $SD = .18$; Control Condition: $M = .40$, $SD = 0.19$) to posttest (Mental Rotation Book Condition: $M = .49$, $SD = .21$; Control Condition: $M = .48$, $SD = .23$); Mental Rotation Book Condition: $t(39) = 2.66$, $p = .011$; $d = 0.42$, 95% CI [0.08, 0.82]; Control Condition: $t(38) = 3.67$, $p < .001$; $d = 0.59$, 95% CI [0.32, 0.89] (see Fig. 5).

Preregistered exploratory analyses

Our preregistered exploratory analyses first examined whether mental rotation training transferred to math skills. Specifically, we conducted an ANCOVA with ECAD-Number Sense W score at posttest as the dependent variable. We included condition as a between-subjects factor, and age, verbal IQ, and ECAD-Number Sense W score at pretest as covariates. We found that condition was not a significant predictor of posttest math achievement, $F(1, 73) = 0.21$, $p = .648$, $\eta_p^2 = 0.00$, 95% CI [0.00, 0.07] in this model. We also found that math achievement did not significantly improve in either condition from pretest to posttest ($ps > .05$).

Our second preregistered exploratory analyses considered whether there was a greater effect of mental rotation book reading for children who scored lower in mental rotation skill at pretest. We conducted an ANCOVA with mean accuracy on PRT at posttest as the dependent variable, with predictors of condition and a condition $\times$ pretest PRT interaction. We also included age, verbal IQ, and mean accuracy on PRT at pretest as covariates. We found the interaction of condition $\times$ pretest PRT accuracy was not a significant predictor of posttest PRT accuracy, $F(1, 72) = 2.89$, $p = .093$, $\eta_p^2 = 0.04$, 95% CI [0.00, 0.15].

Additional exploratory analyses

Given the unexpected null effect of condition on mental transformation performance, we explored whether training condition impacted those mental transformation items that involved rotation (12 of the 24 items). In an ANCOVA, condition was not a significant predictor of accuracy on this subset of items, $F(1, 73) = 0.53$, $p = .467$, $\eta_p^2 = 0.01$, 95% CI [0.00, 0.09], controlling for pretest performance on the same items, age, and verbal IQ. Unexpectedly, performance on this subset of mental transformation items significantly improved from pretest to posttest in the Control Book condition, $t(38) = 2.54$, $p = .015$, $d = 0.41$, 95% CI [0.14, 0.69], but not in the Mental Rotation Book condition, $t(39) = 1.33$, $p = .190$, $d = 0.21$, 95% CI [-0.10, 0.59].

We next examined whether mental rotation training transferred to spatial vocabulary skill. Specifically, we conducted an ANCOVA with spatial vocabulary accuracy at posttest as the dependent variable. We included condition as a between-subjects factor, and age, verbal IQ, and spatial vocabulary accuracy at pretest as covariates. We found that condition was not a significant predictor of posttest spatial vocabulary, $F(1, 73) = 1.00$, $p = .320$, $\eta_p^2 = 0.01$, 95% CI [0.00, 0.10]. Unexpectedly, spatial vocabulary significantly improved from pretest to posttest in the Control Book condition, $t(38) = 3.41$, $p = .002$, $d = 0.55$, 95% CI [0.27, 0.87], but not in the Mental Rotation Book condition, $t(39) = 0.75$, $p = .457$, $d = 0.12$, 95% CI [-0.20, 0.43].

We also examined children's ratings of their enjoyment of the books after each reading session. We found that there was no significant

Table 2
Correlations Between Study Variables.

Variable	1	2	3	4	5	6	7	8	9	10
1. Gender (girl = 0, boy = 1)	1									
2. Age (pretest)	-.09	1								
3. Mental Rotation (Pre)	.06	.24*	1							
4. Mental Rotation (Post)	.04	.27*	.61***	1						
5. Mental Transformation (Pre)	.19	.24*	.35**	.30**	1					
6. Mental Transformation (Post)	.08	.24*	.26*	.21	.74***	1				
7. Spatial Vocabulary (Pre)	.05	.20	.37***	.34**	.29**	.25*	1			
8. Spatial Vocabulary (Post)	-.03	.08	.23*	.23*	.23*	.39***	.32**	1		
9. Number Sense <i>W</i> Score (Pre)	-.09	.41***	.45***	.56***	.53***	.44***	.50***	.48***	1	
10. Number Sense <i>W</i> Score (Post)	-.08	.36**	.36**	.53***	.51***	.42***	.41***	.40***	.85***	1
11. KBIT SS	-.06	-.12	.33**	.36***	.32*	.18	.26*	.41***	.57***	.49***

* $p < .05$. ** $p < .01$. *** $p < .001$.

Note. KBIT SS = Kaufman Brief Intelligence Test Standard Score.

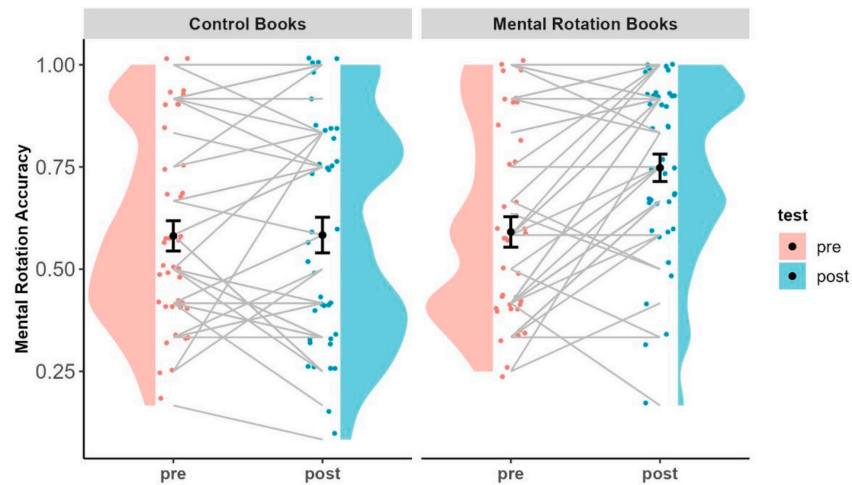


Fig. 4. Mental Rotation Accuracy by Condition and Test Note. Black points and error bars represent group means $\pm$ 1 standard error.

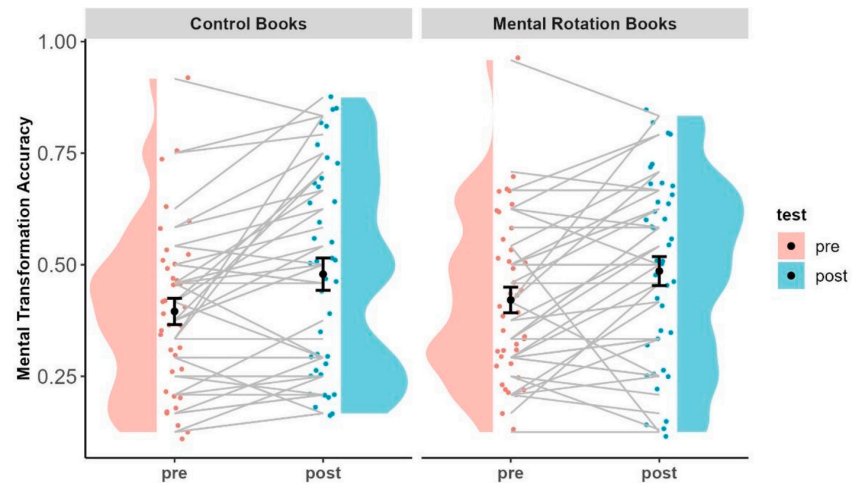


Fig. 5. Mental Transformation Accuracy by Condition and Test Note. Black points and error bars represent group means $\pm$ 1 standard error.

change in enjoyment of the books from the first reading day ($M = 5.47$, $SD = 1.03$) to the sixth reading day ($M = 5.42$, $SD = 0.89$) in the Mental Rotation Book condition, $t(32) = 0.96$, $p = .346$; $d = 0.17$, 95% CI $[-0.20, 0.52]$. There was also no significant change in enjoyment of the books from the first reading day ($M = 5.74$, $SD = 0.41$) to the sixth

reading day ($M = 5.74$, $SD = 0.54$) in the Control Book condition, $t(35) = -0.31$, $p = .755$; $d = 0.05$, 95% CI $[-0.27, 0.45]$. We also found no significant difference between the two conditions in enjoyment on the first day of book reading, $t(51.39) = 1.50$, $p = .140$, $d = 0.34$, 95% CI $[-0.08, 0.66]$ or the sixth day, $t(51.88) = 1.76$, $p = .084$, $d = 0.43$, 95%

CI [-0.04, 0.88].

Lastly, we examined whether there were any gender differences for any of the measures used or if there were any significant interaction between gender and condition within any of the ANCOVAs. Consistent with other studies finding no gender differences in math and spatial skills at this age (Lauer et al., 2019), we found no gender differences for any measure (Benjamini-Hochberg corrected $p > 0.05$) and no significant interactions between gender and condition in any ANCOVA.

Discussion

Here, we explored whether children younger than 6 years of age can improve their mental rotation skills through use of a static 2D book, a novel training method. Consistent with our first hypothesis, 4- and 5-year-old children improved their mental rotation skills from a two-week book reading intervention. This finding is significant as books are a more inclusive and accessible way to practice mental rotation compared to other more expensive and less compact activities such as blocks and puzzles. Books also have the potential to be more easily scalable for large school classrooms and can be low-cost or free through public libraries. Using books may also create more equitable learning experiences at home as parents are more likely to use more spatial language and be more engaged when playing with blocks and puzzles with their sons compared to their daughters (Levine et al., 2012).

However, inconsistent with our second hypothesis, practicing mental rotation did not transfer to improvements on a mental transformation task – a lack of near transfer within the spatial domain. Even when examining only items that involved rotation, training condition was not a significant predictor of posttest mental transformation accuracy. The lack of transfer of mental rotation training to mental transformation skills may be due to the dosage of the intervention, and a longer intervention could show transfer to mental transformation later. The lack of transfer to items involving rotation on the CMTT was a particularly surprising finding. A potential reason for the positive effects on children's mental rotation task performance, measured by the PRT, but not mental transformation, measured by the CMTT, stems from the alignment of the book intervention with each outcome measure. Specifically, the book pages practiced mental rotation in the context of discriminating mirror-image foils, using pictures of animals, people, and everyday items, consistent with the PRT. Two types of book pages (Fig. 2C and E) were directly inspired by the PRT (Fig. 1A). In contrast, the CMTT involved abstract shapes and a different question format (i.e., combining parts of shapes into a whole). This pattern of results suggests that children's improvement in mental rotation may have been relatively narrow and specific to the types of problems practiced. Future research could investigate whether training that includes a wider variety of mental rotation and transformation items leads to greater transfer. It is also worth noting that both groups improved from pretest to posttest on the CMTT, and it is possible that these large practice effects masked any potential training effects. Future research could address this by including the CMTT at posttest only.

We also found no transfer of improvement of mental rotation training to math achievement or spatial vocabulary. Regarding the lack of transfer to math achievement, it is possible that a higher dosage of intervention would be needed (Hawes et al., 2017; Schmitt et al., 2018). It is also possible that there may be a delayed improvement in math achievement. Another possibility is that, particularly for young children, such far transfer is unlikely without direct support for children to connect spatial thinking to mathematics. In a recent review, Fyfe and Borriello (2025) synthesized work training preschoolers on three cognitive skills (spatial skills, working memory, and patterning) and concluded that there is a consistent lack of far transfer to mathematics at this age. Instead, they suggest that training that directly integrates spatial thinking with mathematics may be more efficient and effective at improving math skills at this age.

In addition, the lack of transfer to spatial vocabulary gains could be

due to the very low reliability of the spatial vocabulary assessment (Cronbach's $\alpha = .36$ at pretest and $.42$ at posttest), which indicates low coherence among items and may reflect measurement issues. As a result, the assessment may not have captured gains in spatial vocabulary learned from the intervention. There could have also been a lack of transfer because the spatial terms learned in the book reading intervention (e.g., "turn" or "rotate") were not represented in the spatial vocabulary terms tested in the spatial vocabulary assessment (e.g., "in between" or "to the right"). Future research could use spatial vocabulary assessments that are well-validated and more closely aligned with the spatial concepts in the intervention.

Additional limitations to this study were that the sample was relatively high in socioeconomic status; the participants that we recruited were mostly very high income and mostly had parents with at least a Bachelor's degree. We also only tested this intervention in a very controlled setting, where children worked one-on-one with an experimenter. It is unknown whether this book-reading intervention would be similarly effective among children from lower-SES backgrounds or when administered in larger groups at school or at home.

Despite these limitations, the significant impact of the intervention on mental rotation skills shows that book reading has the potential to be an effective alternative to currently-available spatial activities. In particular, books may be attractive to both girls and boys because books are more gender-neutral than other spatial activities, like blocks, and may also more readily facilitate higher-quality parent-child interactions than these activities. Our study is important because it showed that children's mental rotation skills can improve by practicing in a book-reading context; if scaled up successfully, these books have the potential to reduce the gender gap in mental rotation ability that develops later during childhood (Lauer et al., 2019). Strengthening mental rotation skills is crucial, given their pivotal role as a predictor of future success in STEM fields and the potential for early interventions to have cascading effects on math proficiency and student motivation as children progress in their education.

This study can form the foundation for a number of potential follow-up studies. One direction for future research could be to tease apart which aspects of the book-reading intervention were necessary components for learning. A potentially critical component in our intervention was that researchers used a rotation gesture as part of their feedback when children did not initially answer correctly. Prior research has found that, when children are instructed to produce rotation gestures, it leads to improved mental rotation performance (Goldin-Meadow et al., 2012; Wakefield et al., 2019). Although we did not instruct children to produce these gestures, to the extent that the experimenters' gestures inspired children to copy the gestures, this may have been a key ingredient in the intervention's success. Further, it is possible that explicitly encouraging children to gesture could lead to even larger improvements than the ones found here.

Another important follow-up question is whether this book-reading intervention would be similarly effective when parents are reading to their child at home instead of an experimenter. In doing so, it would be important to investigate whether parents engage with the books in a similar way as the experimenters did, including whether they naturally produce rotation gestures or would do so with brief instruction (e.g., by examining videotaped recording of parent book-reading sessions), and whether variability in parents' behaviors and the dosage of book-reading impact the effectiveness of the books.

Further, researchers could ask whether these books are similarly effective in larger-group settings in a classroom as they are when reading one-on-one with an experimenter. To test this, preschool and kindergarten teachers could read the intervention books to their classes every day for two weeks to determine if children showed similar mental rotation gains after being read to in class by their teacher. It would also be beneficial to test whether older children who are able to read would also benefit from reading these books independently. This could open up opportunities for children to teach themselves mental rotation and other

STEM-related skills independently using books rather than being read to by a parent or teacher.

One key consideration is whether our design choice to use nonnarrative picturebooks, rather than incorporating mental rotation practice into a narrative, had the intended effect of improving learning by reducing distractions. One recent study found that children learned more from a narrative counting book with rich visuals than from a sparse, nonnarrative picturebook (Carrazza & Levine, 2025); thus, it is possible that embedding mental rotation practice into a goal-based narrative would lead to even larger gains. Going forward, it is important to understand how narrative and nonnarrative mental rotation books impact children's mental rotation skills and whether parents, teachers, and children would engage more frequently or more deeply with the books if a narrative were incorporated.

Finally, an important follow-up question is whether these intervention books are similarly beneficial, or more beneficial, when compared to currently-available dynamic spatial toys (e.g., blocks and puzzles) that incorporate mental rotation practice. Researchers could examine this by first determining which types of spatial activities (books or dynamic toys) elicit more spatial language and gestures (e.g., turning and rotation gestures) from both adults and children. Researchers could then investigate whether the static book-reading group or the dynamic block play group had greater spatial gains, and whether either group showed transfer to math achievement.

Overall, our study shows that book-reading is a worthwhile avenue to explore to improve young children's spatial skills. Books are more accessible than many other toys through libraries and schools. Using books at home to improve young children's spatial skills could foster more spatial learning at home and set children up for success before the start of formal schooling. Books also help to give parents the tools and guidance to create a richer home learning environment for their children. The words in the books can include spatial language and questions that promote dialogic reading techniques in the text of the book. Promoting activities, like book-reading, that parents can do with their children increases the possible dosage and benefits of that activity. The low cost of books and ease of distribution could make books a highly scalable intervention tools, with the potential to help children develop stronger mental rotation skills as an important foundation for future STEM achievement.

Ethics and integrity statement

The study was pre-registered (<https://osf.io/7eg53>). Data and analysis scripts are publicly available on OSF (<https://osf.io/6z5rx>). Study procedures and materials were approved under Temple University Institutional Review Board (IRB) protocol 24531, "Home Environment in Academic Skills and Motivation". The authors declare no conflicts of interest.

CRedit authorship contribution statement

Nadia S. Tavassolie: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lexi Sylverne:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Emily D'Antonio:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Nora S. Newcombe:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Marsha Weinraub:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Elizabeth A. Gunderson:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Data availability

The study was pre-registered (<https://osf.io/7eg53>). Data and analysis scripts are publicly available on OSF (<https://osf.io/6z5rx>).

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