MIND, BRAIN, AND EDUCATION

Mental Rotation With Tangible Three-Dimensional Objects: A New Measure Sensitive to Developmental Differences in 4- to 8-Year-Old Children

Zachary Hawes[1], Jo-Anne LeFevre[2], Chang Xu[2], and Catherine D. Bruce[3]

ABSTRACT— There is an emerging consensus that spatial thinking is fundamental to later success in math and science. The goals of this study were to design and evaluate a novel test of three-dimensional (3D) mental rotation for 4- to 8-year-old children ($N = 165$) that uses tangible 3D objects. Results revealed that the measure was both valid and reliable and indicated steady growth in 3D mental rotation between the ages of 4 and 8. Performance on the measure was highly related to success on a measure of two-dimensional (2D) mental rotation, even after controlling for executive functioning. Although children as young as 5 years old performed above chance, 3D mental rotation appears to be a difficult skill for most children under the age of 7, as indicated by frequent guessing and difficulty with mirror objects. The test is a useful new tool for studying the development of 3D mental rotation in young children.

Spatial thinking, that is, the ability to generate, retain, retrieve, and transform well-structured visual images (Lohman, 1996) has been linked to performance across a range of academic disciplines, including mathematics (Mix & Cheng, 2012), science (Wai, Lubinksi, & Benbow, 2009), geography (Orion, Ben-Chaim, & Kali, 1997), physical education (Pietsch & Jansen, 2012), and the arts (Goldsmith, Winner, Hetland, Hoyle, & Brooks, 2013). Moreover, spatial thinking can be improved through targeted training in people of all ages (Uttal et al., 2013). Although such findings present a strong case for the inclusion of spatial thinking in educational curricula (National Council of Teachers of Mathematics [NCTM], 2006; National Research Council [NRC], 2006), it continues to be a neglected area of teaching and learning, particularly within early education contexts (Clements, 2004; Clements & Sarama, 2011). The implementation of spatial thinking into early education requires a detailed understanding of (1) when specific spatial skills, such as mental rotation, first emerge, (2) how they develop over time, and (3) the types of activities that further their development. A necessary first step is to develop valid and reliable measures of spatial skills that can be used with children in the early grades. Accordingly, the purpose of this study was threefold: first, to develop a three-dimensional (3D) mental rotation measure appropriate for young children (4–8 years of age); second, to evaluate the measure in terms of age-appropriateness, test–retest reliability, and its relation with two-dimensional (2D) mental rotation and executive functioning; and third, to use the measure to gain insight into the development of 3D mental rotation skills in early childhood.

Mental rotation is a specific aspect of spatial thinking that is defined as the ability to mentally rotate 2D or 3D objects (Shepard & Metzler, 1971). Mental rotation is often measured by asking people to identify matching shapes presented in different orientations (see Figure 1). In studies with adolescents

[1]Department of Applied Psychology and Human Development, Ontario Institute for Studies in Education, University of Toronto
[2]Department of Psychology, Institute of Cognitive Science, Carleton University
[3]School of Education and Professional Learning, Trent University

Address correspondence to Zachary Hawes, Department of Applied Psychology and Human Development, University of Toronto, Toronto, Ontario, M5R 2X2 Canada; e-mail: zack.hawes@utoronto.ca

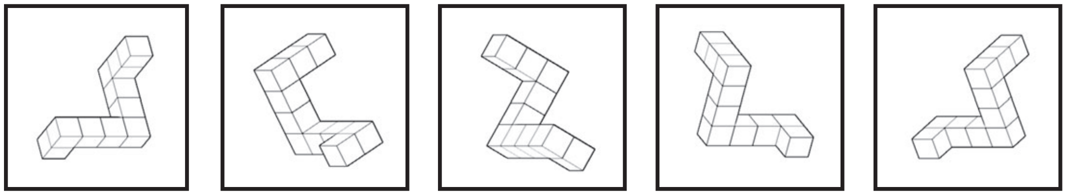

Fig. 1. Example of types of items used in the Vandenberg and Kuse (1978) Mental Rotations Test. Participants are presented with a target item (far left) and four response items of which two are identical to the target but rotated in depth. For each item, participants must select the two items believed to be identical to the target. Points are awarded only with the correct identification of both response items. Permission to use stimuli granted by Michael Peters (see Peters & Battista, 2008).

and adults, 3D mental rotation tests are widely accepted as a valid and reliable measure of spatial ability. Studies with adolescents and adults have revealed an especially close relationship between 3D mental rotation skills and math performance, with specific links to performance in geometry (Battista, 1990; Delgado & Prieto, 2004), algebra (Tolar, Lederberg, & Fletcher, 2009), word problems (Hegarty & Kozhevnikov, 1999), mental arithmetic (Kyttälä & Lehto, 2008), and advanced mathematics (e.g., function theory, mathematical logic, computational mathematics; Wei, Yuan, Chen, & Zhou, 2012). Furthermore, 3D mental rotation skills have been shown to predict performance on the Mathematics Scholastic Aptitude Test (SAT−M; Casey, Nuttall, Pezaris, & Benbow, 1995). In addition, mental rotation skills also play an important role in the learning of and achievement in science, technology, engineering, and mathematics disciplines (i.e., STEM; see Newcombe & Frick, 2010; Wai et al., 2009). Thus, for adolescents and adults, 3D mental rotation is a source of individual differences in a variety of important and complex tasks.

Much less is known about the relation between 3D mental rotation skills and learning outcomes and cognitive performance in young children. This limitation may reflect the dearth of appropriate measures. Although researchers have made considerable headway in measuring young children's 2D mental rotation skills (e.g., see Levine, Huttenlocher, Taylor, & Langrock, 1999) the same cannot be said of 3D mental rotation. Studies using 2D stimuli reveal that the ability to perform mental rotations and spatial transformations emerges some time around the fifth year of life (Frick, Ferrara, & Newcombe, 2013; Frick, Hansen, & Newcombe, 2013; Levine et al., 1999). Developmentally appropriate measures of 3D mental rotation skills are needed to confirm whether 3D mental rotation follows a similar developmental trajectory as that of 2D mental rotation.

Several studies suggest that 3D mental rotation tasks may be too cognitively demanding for elementary school children (Hoyek, Collet, Fargier, & Guillot, 2012; Jansen, Schmelter, Quaiser-Pohl, Neuburger, & Heil, 2013). For example, Jansen and colleagues (2013) tested children in second and fourth grade ($N = 449$) with one of three different mental rotation stimuli: 3D animal drawings, 2D letters, or 3D cube figures. The cube figures were similar to those used in mental rotation tasks designed for adults. Children tested with the 3D animal drawings or the 2D letters performed above chance and demonstrated linear response patterns as determined by angular disparity, suggesting some ability to perform mental rotation tasks. In contrast, children tested with the 3D cubes performed at chance (see also Hoyek et al., 2012). Thus, the evidence suggests that even children as old as 7 to 10 years have difficulty rotating 3D cube figures.

We identified four task features that may contribute to the difficulties young children encounter with traditional measures of 3D mental rotation. First, traditional paper-and-pencil measures require participants to mentally rotate 2D representations (i.e., black and white line drawings) of 3D figures; a task presumably high in cognitive demand due to the level of abstraction required. These traditional stimuli are difficult even for adults; figures that have fewer encoding demands are easier to mentally rotate (Alington, Leaf, & Monaghan, 1992; Hoyek et al., 2012). Second, comparing five stimuli and having to select the two figures that match the target, as is required in Vandenberg and Kuse (1978), presents an additional level of high cognitive demand. Third, time constraints may be inappropriate for young children in that children may feel that they should complete the task quickly, at the expense of a more effortful, deliberate, and thus potentially accurate solution. Fourth, children might not understand the requirement to distinguish between the target and mirror figures and instead "see" the target and mirror as equivalent. Recently, it has been suggested that prior to testing, children should be asked to distinguish pairs of stimuli as the "same" or "different" (Hoyek et al., 2012), providing an opportunity for the child to recognize the mirror image as distinct from the target.

We designed a new measure of 3D mental rotation by considering these task features and tested whether it was sensitive to the development of 3D mental rotation in early elementary school children. A central difference between our task and those used with older children and adults is the use of *tangible* 3D wooden block figures as stimuli. Our stimuli were based on the 2D line drawings of 3D cube figures by Shepard and Metzler (1971) and the multiple-choice test approach of Vandenburg and Kuse (1978; see Figure 1). Several recent findings suggest that young children might perform better on a tangible measure of 3D mental rotation relative to traditional paper-and-pencil measures. For example, one study showed that at approximately 22 months of age infants are capable of physically manipulating objects to fit into apertures, a task said to rely on mental rotation skills (Örnkloo & von Hofsten, 2007). Frick, Hansen et al. (2013) compared 4 and 5-year-olds' 2D mental rotation skills using both a tangible and paper version of the task. Children demonstrated slightly higher scores on the tangible task, although the difference between the two presentation modes was not statistically significant. These studies suggest that the poor performance of young children on mental rotation tasks may be due, in part, to characteristics of the measures used.

Given our effort to reduce the complexities of 3D mental rotation, and previous research indicating that children of approximately 5 years of age can engage in dynamic spatial thinking (Frick, Ferrara et al., 2013; Levine et al., 1999), we predicted that children would be capable of performing an appropriately designed 3D mental rotation task by 5 years of age. We also hypothesized that the skill would continue to develop from age 5 to 8. Participants were also tested on well-established measures of 2D mental rotation (i.e., a version of the Children's Mental Transformation Task; Levine et al., 1999) and executive functioning (Cameron Ponitz et al., 2008). We hypothesized that if our 3D mental rotation measure was measuring children's dynamic spatial transformation skills, we should see a high correlation and a similar developmental trajectory as performance on the 2D mental rotation measure. However, it is also possible that performance on our 3D measure depends on executive functioning, given the task requires the engagement of working memory (temporary visuospatial maintenance), inhibitory control (resisting the temptation to grab at figures; ignoring the mirror image), and flexible attention (shifting focus between multiple figures). These are the same task requirements said to underlie performance on the selected executive function task (McClelland & Cameron, 2012). Thus, we were interested in testing whether our task shared unique variance with 2D mental rotation, above and beyond variance explained by general executive functioning ability. A final objective was to examine individual differences in 3D mental rotation based on response patterns. That is, whether children could be classified according to their selection of the target, mirror, and structurally distinct figure.

METHOD

Participants

One hundred and sixty-five children (94 boys) between the ages of 4 and 8 years ($M = 6.0$ years, $SD = 0.9$, range = 4.3 to 8.1 years) were recruited from four urban schools located in low-socioeconomic (SES) neighborhoods in two Canadian cities. Two additional children were recruited but their data were excluded because they failed to follow instructions. Children represented diverse ethnicities. The University of Toronto, Trent University, and the ethics committees of the appropriate school boards approved the study. Participating children's parent(s) provided written consent. One hundred twelve of the participants also completed an assessment of executive functioning. Data for five of these children were discarded because of extremely low performance (3 standard deviations below the mean). Not all children completed the executive functioning measure or were retested due to time constraints and/or scheduling conflicts with the participating schools. To examine test–retest reliability, 111 children took part in a second assessment of 3D and 2D mental rotations for 4 months (±2 weeks) after the first assessment was administered.

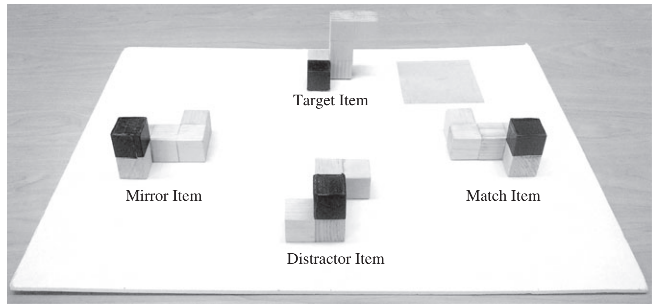

Fig. 2. Example of an item from the 3D mental rotation block task.

Materials

3D Mental Rotation Test

The 3D Mental Rotation Block Task (3D-MR) consisted of 16 test items (see Figure 2), each item comprising four block figures. Each block figure was constructed of five or six square inch wooden blocks glued together and included a single blue block in an attempt to reduce encoding and executive function demands by providing children with a "mental anchor" to aid performance (Alington et al., 1992). In each set, the target figure was glued to the back of a 38 × 50.5 cm piece of white foam board. The other three figures included an identical replica of the target figure, a mirror image of the target, and a structurally distinct figure. Items varied on angle of rotation (ranging from 45° to 225°), type of rotation (around the vertical axis, horizontal axis, and both vertical and horizontal axis), and positioning (upright versus supine/prone).

2D Mental Rotation Test

The 2D Mental Rotation Test Task (2D-MR) consisted of 16 mental rotation items from Levine and colleagues' (1999)

Children's Mental Transformation Task (CMTT: Form D; note that only items requiring mental rotation were included). Children were presented with a printed bisected shape (e.g., two triangles) where the pieces were set apart and rotated 60° from one another on the same plane (direct rotation items) or rotated 60° from one another on the diagonal plane (diagonal rotation items). Below this, children were presented with four shapes and asked to indicate which figure the bisected pieces could make if put together (e.g., a diamond results when the two triangles are rotated and translated). Half the items required children to perform a direct rotation and the other half required children to rotate items along a diagonal plane. This test was selected as a general measure of children's dynamic spatial transformation skills as it has been widely used with our target age group (see Harris, Newcombe, & Hirsh-Pasek, 2013; Levine et al., 1999).

Executive Function Test

The executive functioning task was our own adapted version of the Head-Toes-Knees-Shoulders task (Cameron Ponitz et al., 2008). The task requires children to engage in flexible attention, working memory, and inhibitory control (McClelland & Cameron, 2012), three factors shown to underlie executive functioning (Miyake et al., 2000). In this task, children listen to an instruction to touch a body part (e.g., "Touch your toes") and then must touch the opposite body part (e.g., head). Previous reports indicate the measure is valid and reliable with children aged 4–7 (see Cameron Ponitz et al., 2008).

Procedure

All testing was carried out in a quiet room provided by the schools. In a 10–12-min session, children were administered the 2D-MR and executive function tasks (in that order). Two to three days later they did the 3D-MR task in a 10-min session.

For the 2D-MR task, children were asked to point to the picture that could be made by putting the bisected pieces together. The test consisted of 16 items (no practice), with children receiving a score of 1 for each correct selection. For the executive functioning task, children were asked to stand approximately 5 feet in front of the experimenter. First, the experimenter asked children to touch their head, toes, knees, and shoulders (two times each). This procedure allowed the experimenter to establish habitual responses and to confirm that children could identify the four body parts. For the next 10 trials, children were required to touch their head when told to touch their toes and vice versa. For the final 10 trials, children had to remember to touch the opposite body part for their head and toes, and to touch their shoulders when told to touch their knees and vice versa. Thus, the first 10 trials required opposing responses to two body parts (two-rule condition), whereas the second 10 trials required opposing responses to four body parts (four-rule condition). Children were awarded two points for correctly touching the opposite body part, 1 point for correcting a movement initiated in the wrong direction, and 0 points for touching the wrong body part. Children received a total score out of 40.

For the 3D-MR task, participants sat to the left of the experimenter. To familiarize participants with the task, children were asked to identify whether two figures were the "same" or "different." Children were presented with a matching pair, a pair differing in structure (one block located in a different position), and a mirrored pair. All children were shown how the mirror pair differed. Next, children were told that they would be playing a "matching game" and were to play the role of "shape detectives." An assistant to the experimenter set up items ahead of time and passed items to the experimenter when ready. A booklet described how to set up each item (similar to the image presented in Figure 2). Items were positioned equidistant, 22 cm, from the target item. For each item, the child was handed a 29.5 × 45 cm folder and asked to shield his/her view. For the practice item only, the experimenter removed the "shield" from view and instructed, "One of these shapes [pointing to each shape from left to right] is the perfect match for this one at the back [pointing to the target item located at the back of the board]. Only one of these shapes can be made to look and go the same way as this one [again pointing to the target]. When you think you know the perfect match please point to it." For the following 16 test items, participants were simply reminded to "point to the perfect match" before the shield was removed. After the child pointed to their choice, the experimenter asked him/her to pick up the shape and make it "look and go the same way" as the target shape (see Figure 3). The child was asked to complete this comparison portion of the task on the 8 × 8 cm square of green paper to the right of the target item. For all unsuccessful matches, children were offered the opportunity to try another option. Thus, children received feedback about the correctness of their responses. With the exception of the sample item, no instruction or praise was offered and feedback was limited to informing children (if need be) of incorrect matches during the comparison phase. Unlike other mental rotation tasks there was no time restriction. Scoring was based on the initial item selected. Children were awarded 1 point for each correct selection.

RESULTS

Performance on the 3D- and 2D-MR tasks was significantly correlated with age (see Figure 4 and Table 1). Participants were divided into six age groups based on 6-month intervals except at both extremes of the age distribution where 1-year groups (i.e., 4- to 5-year-olds and 7- to 8-year-olds) allowed for approximately equal number of participants per group. For each age group, performance was compared to chance,

Fig. 3. Testing procedures for the 3D mental rotation block task. To begin, each test item was shielded form view. Prior to revealing the figures, participants were reminded to look carefully at the three options below the target and point to the item that matched the target. Once the shield was removed and an item was selected, participants were asked to place the item to the right of the target and demonstrate how it could be made to match the target. This same procedure was repeated for all 16 items.

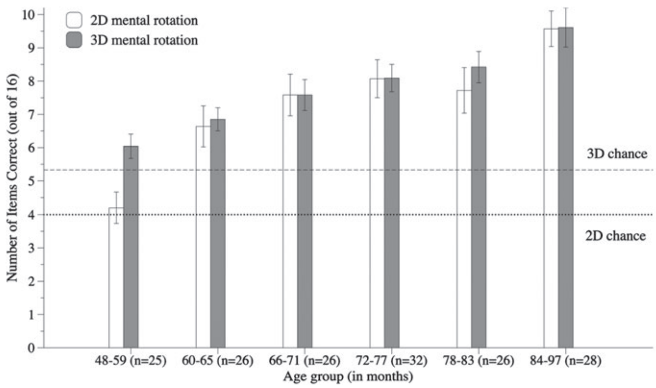

Fig. 4. Mean number of items correct as related to age. Error bars represent standard error of the mean for each group. Segmented lines indicate chance level performance. All age groups performed significantly above chance, except for the youngest age group.

defined as 5.33 (i.e., 16 items divided by 3 answer choices) on the 3D-MR measure and 4 (i.e., 16 items divided by 4 answer choices) on the 2D-MR measure. Children in the 4- to 5-year-old group did not perform above chance on the 2D-MR task, $t(24) = 0.43, p = .67, d = .09$. On the 3D-MR task, 4- to-5-year-olds performed slightly better, although not significantly different from chance, $t(24) = 1.93$, $p = .07$, $d = .39$. The 3D-MR task may be a bit easier than the 2D-MR task because there are fewer answer alternatives. Children in the other age groups performed significantly better than chance on both tasks, ps < .05.

As shown in Table 1, 2D and 3D mental rotations were correlated with age and executive functioning but not with gender. A partial correlation was calculated to determine whether the relation between 2D and 3D mental rotations remained significant after controlling for age and executive functioning. The partial correlation between 2D and 3D mental rotations was significant, $r(100) = .32$, $p < .001$, whereas the partial correlation between 3D mental rotation and executive functions was not significant when 2D mental rotation and age were controlled, $r(100) = .19, p > .05$. Thus, the two mental rotation tests are correlated above and beyond their shared relations with age and executive functioning.

We used *k*-means cluster analysis based on the percentage choice of each of the three possible options in the 3D-MR task: target, mirror item, or foil. Three groups were identified (see Table 2): successful rotators, who chose the correct match on the majority of trials; children who were "mirror-confused" and could not reliably discriminate between the correct figure and its mirror image; and finally, children who guessed and thus were equally likely to choose all three alternates. As shown in Figure 5, age and group membership were related, $\chi^2(10, N = 163) = 28.55$, $p = .001$. As age increased, children became less likely to guess and more likely to choose the target. Not until the age of 7 did many children consistently select the target item on a majority of trials.

Table 1
Correlations Among Age, Gender, and Cognitive Measures

Measures	*1*	*2*	*3*	*4*
1. Age (months)				
2. Gender	.09			
3. Executive functioning	.37**	.06		
4. 2D mental rotation	.43**	−.06	.36**	
5. 3D mental rotation	.44**	−.03	.38**	.50**

(*p < .05. **p < .01)

Table 2
Mean Percentage of Responses on the 3D-MR Task by Each of Three Groups Identified in the Cluster Analysis

	Response Groups		
Item type	*Guessers* ($n = 50$)	*Mirror-confused* ($n = 64$)	*Successful rotators* ($n = 49$)
Target	35	43	68
Mirror	34	45	25
Distractor	31	12	6

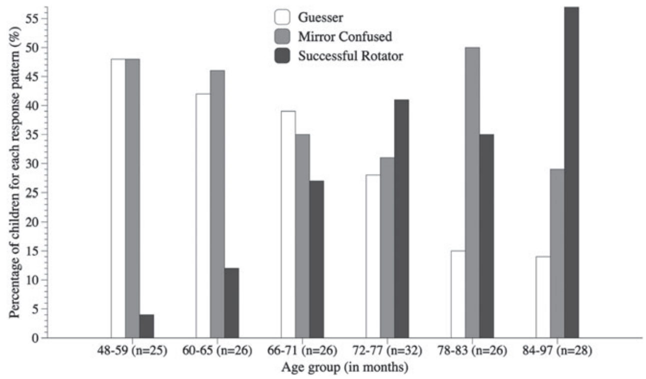

Fig. 5. Percentage of children showing each response pattern (based on cluster analysis) by age.

To explore the relation between 3D group membership and 2D mental rotation performance, children's 3D mental rotation performance was analyzed according to 3D group membership (guesser, mirror-confused, successful rotator) using an ANOVA. The main effect of 3D group membership on 2D mental rotation performance was significant, $F(2, 157) = 14.01$, $MSE = 9.73$, $\eta_p^2 = .15$, $p < .001$. Post hoc tests were conducted using Tukey's honestly significant difference test (HSD = 1.45). Children classified as "successful rotators" performed significantly better on the 2D-MR task ($M = 9.2$) than children who were "mirror-confused" ($M = 7.2$, $p = .003$). Children in the "mirror-confused" group marginally outperformed "guessers" ($M = 5.8$, $p = .076$). Thus, successful 3D mental rotation performance was strongly related to success on 2D mental rotation.

Finally, the 2D and 3D mental rotation tests were analyzed in terms of their psychometric properties. The correlation between performance at Time 1 and Time 2 was significant for 2D-MR task, $r(116) = .66$, $p < .001$, and for 3D-MR task, $r(111) = .70$, $p < .001$, demonstrating acceptable test–retest reliability. Internal reliability of the 2D-MR task was acceptable (split-half, $r = .69$, based on the odd/even items model; Cronbach's $\alpha = .70$). The internal reliability of the 3D measure was calculated based on a partial credit model (see Harris et al., 2013). Children were assigned a score of 0 for choosing the distractor, a 1 for choosing the mirror object, and a 2 for choosing the target object. The internal reliability was moderate when all participants were included, Cronbach's $\alpha = .55$, presumably because many children were guessing. However, when only the oldest age group of children was included (7- and 8-year-olds, $n = 28$), the internal reliability of the 3D measure was acceptable, Cronbach's $\alpha = .71$. Thus, the measure was moderately reliable for children in the age range where the majority of children were successful on the task.

DISCUSSION

The goal of this study was to develop a measure of 3D mental rotation that is sensitive to developmental differences in performance in children younger than 8 years of age. Considerable efforts were taken to reduce the cognitive demands typical of 3D mental rotation measures used with adolescents and adults. Results revealed that our test was indeed sensitive to developmental differences, had acceptable test–retest reliability, and was highly correlated with a frequently used measure of 2D mental rotation (Levine et al., 1999), even after controlling for executive functioning.

Results revealed considerable development in 3D mental rotation throughout the early elementary school grades (Pre-K to 2nd Grade). With the exception of the youngest age group, 4- to 5-year-olds, children performed significantly above chance on both measures of mental rotation. This finding corroborates previous research that suggests the emergence of 2D mental rotation takes place during the fifth year of life (Frick, Hansen et al., 2013). To our knowledge, this is the first study to show that 3D mental rotation also begins to emerge during this same period of development.

To better understand the developmental course of 3D mental rotation, cluster analyses were carried out to examine individual differences in response patterns. Three response patterns emerged. Children were classified as (1) guessers, (2) mirror-confused, such that they had difficulty distinguishing objects and their mirrors, and (3) successful rotators. The number of successful rotators increased significantly with age. For example, only 4% of the 4- to 5-year olds were classified as successful rotators as compared to 57% of the 7- to 8-year olds. Although rotation performance increased gradually for 5- to 7-year-olds, only 29% of children were classified as successful in this age range. Thus, above-chance performance of the group of children observed across this age range reflects the success of a minority of "precocious" children (see Harris et al., 2013). Given evidence that spatial abilities are unique predictors of achievement in science and mathematics, explaining more variance than mathematics or verbal skills alone (Verdine et al., 2014; Wai et al., 2009), it is important to identify and study potential factors, such as the influence of early experiences, that contribute to the development of strong spatial skills. As Wai et al. (2009) explain, some individuals are high in spatial abilities but not exceptional in math or verbal abilities: These individuals may constitute an "untapped pool of talent" for STEM disciplines and increased efforts are needed to identify and provide educational opportunities to serve these spatially talented students. Our measure provides a potential means for identifying spatially talented young children.

In this study, we did not find evidence of gender differences in performance on either the 2D-or 3D-MR tasks. In studies with older children and adults, robust gender differences are found on measures of mental rotation (Linn & Petersen, 1985;

Voyer, Voyer, & Bryden, 1995) whereas the findings are mixed for younger children. Levine and colleagues (1999) did find gender differences on the full version of the 2D CMTT for children as young as 4½ years of age, whereas Harris et al. (2013) did not find a gender difference for 4- to 7-year-olds on this task. One possibility for why we—and others—have not found a gender effect in mental rotation performance in young children may have to do with population characteristics. Levine, Vasilyeva, Lourenco, Newcombe, and Huttenlocher (2005) conducted a longitudinal study to examine whether the male spatial advantage varied across children from different SES groups. Children's mental rotation and map skills were assessed in the fall and spring of second and third grades. Although boys from middle- and high-SES backgrounds outperformed girls, there was no gender difference in the performance of low-SES children. Thus, the absence of gender differences in our study may have been influenced by our sample of children from low-SES backgrounds. In summary, our findings, along with other failures to demonstrate gender differences in children younger than 10 years of age (see Neuburger, Jansen, Heil, & Quaiser-Pohl, 2011, for a discussion on why gender differences might not exist prior to ten years of age), indicate that more research is needed to investigate social, biological, and educational factors that may influence the development of mental rotation performance.

Although mental rotation is often assumed to be an innate cognitive ability (Johnson & Bouchard, 2005), recent research suggests it improves with practice (Uttal et al., 2013). In a large meta-analysis evaluating the effects of spatial training, it was found that even the control groups demonstrated larger than expected gains (e.g., often exceeding 0.4 standard deviations) on spatial measures as a result of test–retest effects (see Uttal et al., 2013; Uttal, Miller, & Newcombe, 2013). Moreover, simply exposing young children to spatial tests produces improvements in their spatial skills. For example, Levine and colleagues (1999) found that 5-year-olds performed significantly better on the second half of two different versions of tests assessing children's mental rotation and translation skills. In our own work with early years teachers and students, young children learn mental rotation as a result of carefully designed activities and lessons targeting the cognitive skill (Hawes, Moss, Chang, & Naqvi, 2013). Hence, although this study demonstrated that the majority of children under 7 years old struggled with 3D mental rotation, this finding does not imply that younger children are incapable of the cognitive activity. Future research is needed to further examine the malleability of mental rotation, especially in the early years, and determine effects of training and instruction on performance.

The individual response patterns revealed in this study offer potentially important information for designing appropriate educational interventions aimed at improving young children's spatial thinking. For example, the finding that the children progressed from "guessers" to "mirror-confused" to "successful mental rotators" suggests a natural instructional sequence to follow when teaching or training mental rotation in young children. Furthermore, given that the major source of difficulty in the task was in distinguishing an object from its mirror, instruction aimed at facilitating understanding of mirror images might prove especially beneficial in improving children's mental rotation competencies.

The sources of shared variance in children's performance on both the 2D and 3D measures of mental rotation also deserve further investigation. In contrast to the 3D-MR task, the 2D-MR task did not require participants to distinguish between objects and their mirrors. Thus, both measures appear to capture a general dynamic spatial transformation ability that goes beyond distinguishing objects and their mirrors. A potentially fruitful area of research concerns whether training with the 3D stimuli transfers to performance on the 2D task and vice versa. More specifically, does training that facilitates an understanding of mirror objects transfer to improved learning on spatial measures that do not require this skill, such as the measure of 2D mental rotation reported here? More research is needed to better understand both the specific and more general mechanisms that underlie mental rotation, especially in young children.

We hypothesized that the inclusion of a single blue cube would aid mental rotation performance by providing participants with a "mental anchor." However, it is possible that the colored cube may have negatively influenced strategy choice. For example, research indicates that successful mental rotation performance is achieved through a "holistic" approach, whereby participants report visualizing the rotations of whole objects. A less effective "analytical" or "piecemeal" approach involves analyzing and rotating specific parts of the figure (e.g., see Khooshabeh, Hegarty, & Shipley, 2013). It is possible that the blue cube influenced participants to adopt an "analytical" or "piecemeal" approach. Another variable that must be considered when interpreting our findings deals with the role that feedback played in task performance. By having participants physically check the accuracy of their selected responses, we forfeit control over this variable and do not know what effect feedback had on performance. In future studies, we intend to experimentally manipulate both the presence of the blue cube and the availability of feedback to determine their influence on performance.

Given the close relationship between spatial thinking and performance in math and science, coupled with new evidence that spatial thinking is malleable (Uttal et al., 2013), there is an increasing need for interventions aimed at supporting and enriching these important skills (NCTM, 2006; NRC, 2006; Newcombe, 2010). Early education and training of spatial skills is especially desirable, as early interventions have the largest and longest lasting effects (Heckman, 2006). Addressing the current neglect of spatial thinking in early years classrooms will take effort, time, and resources, but the payoff might be increased student interest and success in STEM disciplines. This study offers a new means of measuring young children's spatial thinking and has the potential to inform the success of educational interventions.

Acknowledgments—We offer special thanks to Sarah Bennett, Mischa Berlin, Diana Chang, Tara Flynn, and Sarah Naqvi for their help in data collection. We are also extremely grateful to the schools and students who participated. This research was supported in part by grants awarded to Cathy Bruce from the Ontario Ministry of Education and the Social Sciences and Humanities Research Council of Canada.

REFERENCES

Alington, D. E., Leaf, R. C., & Monaghan, J. R. (1992). Effects of stimulus color, pattern, and practice on sex differences in mental rotations task performance. *Journal of Psychology*, *126*, 539–553.

Battista, M. (1990). Spatial visualization and gender differences in high school geometry. *Journal for Research in Mathematics Education*, *21*(1), 47–60.

Cameron Ponitz, C., McClelland, M. M., Jewkes, A. M., Connor, C. M., Farris, C. L., & Morrison, F. J. (2008). Touch your toes! Developing a direct measure of behavioral regulation in early childhood. *Early Childhood Research Quarterly*, *23*, 141–158.

Casey, B., Nuttall, R. L., Pezaris, E., & Benbow, C. P. (1995). The influence of spatial ability on gender differences in mathematics college entrance test scores across diverse samples. *Developmental Psychology*, *31*, 697–705.

Clements, D. H. (2004). Geometric and spatial thinking in early childhood education. In D. Clements, J. Sarama, & M. A. DiBaise (Eds.), *Engaging young children in mathematics: Results of the conference on standards for pre-school and kindergarten mathematics education* (pp. 83–90). Mahwah, NJ: Lawrence Erlbaum.

Clements, D. H., & Sarama, J. (2011). Early childhood teacher education: The case of geometry. *Journal of Mathematics Teacher Education*, *14*, 133–148.

Delgado, A. R., & Prieto, G. (2004). Cognitive mediators and sex-related differences in mathematics. *Intelligence*, *32*(1), 25–32.

Frick, A., Ferrara, K., & Newcombe, N. S. (2013). Using a touch screen paradigm to assess the development of mental rotation between 3½ and 5½ years of age. *Cognitive Processing*, *14*(2), 117–127. doi:10.1007/s10339-012-0534-0

Frick, A., Hansen, M. A., & Newcombe, N. S. (2013). Development of mental rotation in 3- to 5-year-old children. *Cognitive Development*, *28*, 386–399. doi:10.1016/j.cogdev.2013.06.002.

Goldsmith, L. T., Winner, E., Hetland, L., Hoyle, C., & Brooks, C. (2013). *Relationship between visual arts learning and understanding geometry*. Paper presented at the Biennial Meeting of the Society for Research in Child Development, Seattle, WA.

Harris, J., Newcombe, N. S., & Hirsh-Pasek, K. (2013). A new twist on studying the development of dynamic spatial transformations: Mental paper folding in young children. *Mind, Brain, and Education*, *7*(1), 49–55.

Hawes, Z., Moss, J., Chang, D., & Naqvi, S. (2013). Math for young children: A professional development model that bridges cognitive science and mathematics education. In M. Martinez & A. Castro Superfine (Eds.), *Proceedings of the 35th Annual Meeting of the North American Chapter of the International Group for the Psychology of Mathematics Education*. Chicago, IL: University of Illinois at Chicago.

Heckman, J. J. (2006). Skill formation and the economics of investing in disadvantaged children. *Science*, *312*(5782), 1900–1902.

Hegarty, M., & Kozhevnikov, M. (1999). Types of visual-spatial representations and mathematical problem solving. *Journal of Educational Psychology*, *91*, 684–689.

Hoyek, N., Collet, C., Fargier, P., & Guillot, A. (2012). The use of the Vandenberg and Kuse mental rotation test in children. *Journal of Individual Differences*, *33*(1), 62–67.

Jansen, P., Schmelter, A., Quaiser-Pohl, C., Neuburger, S., & Heil, M. (2013). Mental rotation performance in primary school age children: Are there gender differences in chronometric tests? *Cognitive Development*, *28*, 51–62.

Johnson, W., & Bouchard, Jr., T. J. (2005). The structure of human intelligence: It is verbal, perceptual, and image rotation (VPR), not fluid and crystallized. *Intelligence*, *33*, 393–416.

Khooshabeh, P., Hegarty, M., & Shipley, T. F. (2013). Individual differences in mental rotation: Piecemeal versus holistic processing. *Experimental Psychology*, *60*(3), 164–171.

Kyttälä, M., & Lehto, J. (2008). Some factors underlying mathematical performance: The role of visuospatial working memory and non-verbal intelligence. *European Journal of Psychology of Education*, *22*(1), 77–94.

Levine, S. C., Huttenlocher, J., Taylor, A., & Langrock, A. (1999). Early sex differences in spatial skills. *Developmental Psychology*, *35*, 940–949.

Levine, S. C., Vasilyeva, M., Lourenco, S. F., Newcombe, N. S., & Huttenlocher, J. (2005). Socioeconomic status modifies the sex difference in spatial skill. *Psychological Science*, *16*, 841–845.

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development*, *56*, 1479–1498.

Lohman, D. F. (1996). Spatial ability and G. In I. Dennis & P. Tapsfield (Eds.), *Human abilities: Their nature and assessment* (pp. 97–116). Hillsdale, NJ: Lawrence Erlbaum.

McClelland, M. M., & Cameron, C. E. (2012). Self-regulation in early childhood: Improving conceptual clarity and developing ecologically valid measures. *Child Development Perspectives*, *6*, 136–142.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wagner, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology*, *41*, 49–100.

Mix, K. S., & Cheng, Y. L. (2012). The relation between space and math: Developmental and educational implications. *Advances in child development and behavior*, *42*, 197–243.

National Council of Teachers of Mathematics (NCTM). (2006). *Curriculum focal points for prekindergarten through Grade 8 mathematics*. Reston, VA: Author.

National Research Council (NRC). (2006). *Learning to think spatially: GIS as a support system in the K-12 curriculum*. Washington, DC: National Academies Press.

Neuburger, S., Jansen, P., Heil, M., & Quaiser-Pohl, C. (2011). Gender differences in pre-adolescents' mental rotation performance: Do they depend on grade and stimulus type? *Personality and Individual Differences*, *50*, 1238–1242.

Newcombe, N. S. (2010). Picture this: Increasing math and science learning by improving spatial thinking. *American Educator*, *34*, 29–35.

Newcombe, N. S., & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain, and Education*, *4*(3), 102–111.

Orion, N., Ben-Chaim, D., & Kali, Y. (1997). Relationship between earth-science education and spatial visualization. *Journal of Geoscience Education*, *45*, 129–132.

Örnkloo, H., & von Hofsten, C. (2007). Fitting objects into holes: On the development of spatial cognition skills. *Developmental Psychology*, *43*, 404–416.

Peters, M., & Battista, C. (2008). Applications of mental rotation figures of the Shepard and Metzler type and description of a Mental Rotation Stimulus Library. *Brain and Cognition*, *66*, 260–264.

Pietsch, S., & Jansen, P. (2012). Different mental rotation performance in students of music, sport, and education. *Learning and Individual Differences*, *22*(1), 159–163.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, *171*, 701–703.

Tolar, T. D., Lederberg, A. R., & Fletcher, J. M. (2009). A structural model of algebra achievement: computational fluency and spatial visualisation as mediators of the effect of working memory on algebra achievement. *Educational Psychology*, *29*, 239–266.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, *139*, 352–402.

Uttal, D. H., Miller, D. I., & Newcombe, N. S. (2013). Exploring and enhancing spatial thinking links to achievement in science, technology, engineering, and mathematics. *Current Directions in Psychological Science*, *22*, 367–373.

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotation, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills*, *47*, 599–604.

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., Newcombe, N. S., Filipowicz, A. T., & Chang, A. (2014). Deconstructing building blocks: Preschoolers' spatial assembly performance relates to early mathematical skills. *Child Development*, *85*, 1062–1076. doi:10.1111/cdev.12165

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin*, *117*, 250–270.

Wai, J., Lubinksi, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, *101*, 817–835.

Wei, W., Yuan, H., Chen, C., & Zhou, X. (2012). Cognitive correlates of performance in advanced mathematics. *British Journal of Educational Psychology*, *82*(1), 157–181.