Distribution Agreement

In presenting this thesis or dissertation as a partial fulfillment of the requirements for an advanced degree from Emory University, I hereby grant to Emory University and its agents the non-exclusive license to archive, make accessible, and display my thesis or dissertation in whole or in part in all forms of media, now or hereafter known, including display on the world wide web. I understand that I may select some access restrictions as part of the online submission of this thesis or dissertation. I retain all ownership rights to the copyright of the thesis or dissertation. I also retain the right to use in future works (such as articles or books) all or part of this thesis or dissertation.

Signature:

________________________________ ________________

Jillian Lauer Date

Spatial Ability in Infancy Predicts Spatial and Mathematical Competence at Preschool Age

By

Jillian E. Lauer
Master of Arts

Psychology

Stella Lourenco, Ph.D.
Advisor

Lynne Nygaard, Ph.D.
Committee Member

Kim Wallen, Ph.D.
Committee Member

Accepted:

Lisa A. Tedesco, Ph.D.
Dean of the James T. Laney School of Graduate Studies

Date

Spatial Ability in Infancy Predicts Spatial and Mathematical Competence at Preschool Age

By

Jillian E. Lauer
B.S., Tulane University, 2011

Advisor: Stella Lourenco, PhD

An abstract of
A thesis submitted to the Faculty of the
James T. Laney School of Graduate Studies of Emory University
in partial fulfillment of the requirements for the degree of
Master of Arts
in Psychology
2015

Abstract

Spatial Ability in Infancy Predicts Spatial and Mathematical Competence at Preschool Age

By Jillian E. Lauer

From using tools to reading maps and deciphering diagrams, activities that are essential to everyday functioning often require us to form, transform, and rotate mental representations of objects and spatial layouts. The ability to perform such transformations, often measured via mental rotation tasks, is a hallmark of visuospatial reasoning and has been shown to predict math achievement as early as preschool age. Research suggests that mental rotation processes emerge even earlier in development, however, with infants exhibiting considerable individual differences in performance on implicit mental rotation tasks. Nevertheless, little is known about the origins of inter-individual variation in these abilities or the cognitive processes that underlie associations among spatial and mathematical cognition. Here, we adopted a longitudinal design to investigate the stability of individual differences in mental rotation abilities between infancy and preschool age and to examine the role of early visuospatial processes in later mathematical competence. Between 6 and 13 months of age, 53 infants completed a spatial change detection task designed to assess mental rotation abilities. At 4 years of age, these children completed a battery of tasks that measured various aspects of spatial and quantitative reasoning as well as general cognitive abilities. We found that performance on the spatial change detection task in infancy significantly predicted both spatial and mathematical aptitude at 4 years of age as measured by performance on a widely used mental transformation task and a standardized math test. This predictive relation could not be attributed to general cognitive abilities, such as working memory and processing speed, or to verbal competence. Our findings demonstrate developmental continuity in visuospatial processing between infancy and preschool age and suggest that primitive spatial processes present in the first year of life serve as precursors to later spatial and mathematical reasoning.

Spatial Ability in Infancy Predicts Spatial and Mathematical Competence at Preschool Age

By

Jillian E. Lauer
B.S., Tulane University, 2011

Advisor: Stella Lourenco, PhD

A thesis submitted to the Faculty of the
James T. Laney School of Graduate Studies of Emory University
in partial fulfillment of the requirements for the degree of
Master of Arts
in Psychology
2015

Table of Contents

Title Page 1
Abstract 2
List of Tables 4
List of Figures 5
Introduction 6
Method 10
Results 15
Discussion 18
Tables 23
Figures 27
References 30
Appendix A 39
Appendix B 50

Spatial Ability in Infancy Predicts Spatial and Mathematical Competence at Preschool Age

Master's Thesis

Jillian E. Lauer

Faculty Advisory Committee:

Stella F. Lourenco, Ph.D. (Advisor)

Lynne Nygaard, Ph.D.

Kim Wallen, Ph.D.

Emory University

Abstract

From using tools to reading maps and deciphering diagrams, activities that are essential to everyday functioning often require us to form, transform, and rotate mental representations of objects and spatial layouts. The ability to perform such transformations, often measured via mental rotation tasks, is a hallmark of visuospatial reasoning and has been shown to predict math achievement as early as preschool age. Research suggests that mental rotation processes emerge even earlier in development, however, with infants exhibiting considerable individual differences in performance on implicit mental rotation tasks. Nevertheless, little is known about the origins of inter-individual variation in these abilities or the cognitive processes that underlie associations among spatial and mathematical cognition. Here, we adopted a longitudinal design to investigate the stability of individual differences in mental rotation abilities between infancy and preschool age and to examine the role of early visuospatial processes in later mathematical competence. Between 6 and 13 months of age, 53 infants completed a spatial change detection task designed to assess mental rotation abilities. At 4 years of age, these children completed a battery of tasks that measured various aspects of spatial and quantitative reasoning as well as general cognitive abilities. We found that performance on the spatial change detection task in infancy significantly predicted both spatial and mathematical aptitude at 4 years of age as measured by performance on a widely used mental transformation task and a standardized math test. This predictive relation could not be attributed to general cognitive abilities, such as working memory and processing speed, or to verbal competence. Our findings demonstrate developmental continuity in visuospatial processing between infancy and preschool age and suggest that primitive spatial processes present in the first year of life serve as precursors to later spatial and mathematical reasoning.

Keywords: spatial cognition, development, individual differences

List of Tables

Table 1. Tasks analyzed at preschool age 23

Table 2. Zero-order correlations between infant spatial preference scores and preschool task performance 24

Table 3. Partial correlations between infant spatial preference scores and preschool task performance when controlling for general cognitive abilities 25

Table 4. Rank correlations (Spearman's ρ) between infant spatial preference scores and preschool task performance 26

List of Figures

Figure 1. Spatial change detection paradigm used to assess mental rotation in infancy..27

Figure 2. Item from the Children's Mental Transformation Task administered at 4 years of age 28

Figure 3. Scatterplots showing that infants' spatial preference scores predicted preschool performance on a mental transformation task and a standardized measure of mathematical aptitude..29

Spatial Ability in Infancy Predicts Spatial and Mathematical Competence at Preschool Age

Spatial abilities are an integral component of human intelligence (Carroll, 1993), not only allowing us to solve complex spatial problems in domains such as geography, physics, and architecture (Golledge, 2002; Hegarty & Waller, 2005; Kozhevnikov, Motes, & Hegarty, 2007), but also supporting problem solving in domains that are not overtly spatial, such as deductive reasoning (De Soto, London, & Handel, 1965) and symbolic arithmetic (Cheng & Mix, 2014). Moreover, there is ample evidence that spatial thinking facilitates scientific insight. From Copernicus' heliocentric model of the solar system to Watson and Crick's (1953) discovery of the double-helical structure of DNA, visuospatial reasoning has given rise to countless scientific breakthroughs throughout history (Committee on Support for Thinking Spatially, 2006), and Einstein, Tesla, Faraday, and Watt were among the many eminent scientists who claimed that spatial thinking figured prominently in their own discoveries (Lohman, 1996). Empirical research has similarly suggested that spatial thinking cultivates scientific innovation. For instance, longitudinal studies have shown that spatial abilities in childhood predict later success in science, technology, engineering, and mathematics (STEM) disciplines (Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009), and greater spatial aptitude in adolescence is associated with later creativity in STEM fields, predicting the number of patents and publications produced in adulthood (Kell, Lubinski, Benbow, & Steiger, 2013).

How do spatial skills facilitate STEM success? There is considerable evidence that one type of visuospatial reasoning, known as mental transformation, is particularly critical to educational achievement in STEM fields (Committee on Support for Thinking Spatially, 2006; Newcombe & Frick, 2010). Mental transformation abilities are commonly assessed via mental rotation tasks, which require individuals to visualize, transform, and rotate mental images of objects (e.g., Shepard & Metzler, 1971), and performance on such tasks is associated with success across STEM domains, from anatomy and chemistry to engineering and physics (Ganley, Vasilyeva, & Dulaney, 2014; Guillot et al., 2007; Stieff, 2007). Recent research suggests that mental transformation abilities are particularly important for math achievement early in development, with individual differences in these skills predicting performance on standardized math tests in elementary school (Gunderson, Ramirez, Beilock, & Levine, 2012) and high school (Casey, Nuttall, Pezaris, & Benbow, 1995). Importantly, recent research also suggests that mental transformation abilities are malleable. Performance on mental transformation tasks improves with training in adulthood (Terlecki, Little, & Newcombe, 2008), and this training shows cross-dimensional transfer, improving math performance in elementary-school-aged children (Cheng & Mix, 2014). These studies suggest that mental transformation processes have a critical role in mathematical reasoning and that individual differences in our ability to engage in mental transformation have meaningful implications for educational attainment early in life. Nevertheless, we know little about the ontogenetic origins of these visuospatial processes or the developmental trajectory of individual differences in mental transformation skills.

Although few studies have examined mental transformation abilities in very young children, findings suggest that human infants may possess a rudimentary understanding of spatial transformations. Rochat and Hespos (1996) reported that by 4 months of age, infants are sensitive to the shape and rotational movement of abstract objects (see also Hespos & Rochat, 1997). Later research suggested that infants can detect mirror reversals in the shape of a rotating figure (e.g., Frick & Möhring, 2013; Möhring & Frick, 2013; Schwarzer, Freitag, Buckel, & Lofruthe, 2013), and similar mirror discriminations are a key component of mental rotation tasks administered to adults (e.g., Shepard & Metzler, 1971). Moreover, infants show considerable individual variability as well as sex differences in performance on implicit mental rotation measures (Moore & Johnson, 2008; 2011; Quinn & Liben, 2008; 2014), which mirror the sex differences in mental rotation that are reported in adulthood (Voyer, Voyer, & Bryden, 1995). Taken together, these findings suggest that primitive visuospatial processes present in infancy may serve as a precursor to later mental transformation ability.

Despite evidence of rudimentary mental transformation processes in infancy, research on older children has presented paradoxical findings (Frick, Möhring, & Newcombe, 2014). Children are often unable to perform above chance levels on explicit mental transformation tasks before preschool age (Frick, Hansen, & Newcombe, 2013; Frick, Ferrara, & Newcombe, 2013; Kosslyn, Margolis, Barrett, Goldknopf, & Daly, 1990), calling into question whether implicit visuospatial measures administered in infancy assess the same cognitive constructs as explicit spatial measures administered in adulthood. Instead, implicit measures may rely on domain-general cognitive processing or assess developmentally distinct cognitive processes that are unrelated to later spatial thinking. Alternatively, the disparity in performance between infancy and early childhood could be the result of differences in task demands or methods of measurement (Frick, Möhring, & Newcombe, 2014), leaving open the question of continuity and specificity in the cognitive processes that underlie visuospatial reasoning across development.

Research examining the degree to which individual differences in spatial aptitude are stable across early childhood is of theoretical importance in understanding continuity in spatial development, the role of experiential factors in shaping visuospatial reasoning in early childhood, and the mechanisms that underlie the associations between spatial and mathematical cognition later in development (Mix & Cheng, 2012). Moreover, such research may have translational applications. Studies have demonstrated that spatial abilities are malleable (for meta-analyses, see Baenninger & Newcombe, 1989; Uttal et al., 2013) and that spatial training may foster math achievement in school-aged children (Cheng & Mix, 2014). Consequently, research documenting the developmental trajectory of individual differences in spatial aptitude across early childhood would have substantial implications for the timing of educational interventions aimed at promoting STEM success.

Current Study

In the current study, we investigated whether early visuospatial processes present in infancy were predictive of spatial and mathematical aptitude at preschool age. Infants completed a spatial change detection task designed to assess mental rotation abilities. For this task, the change detection paradigm developed by Ross-Sheehy and colleagues (2003) was modified to require the discrimination of mirror images presented in different orientations, similar to canonical mental rotation measures administered in adulthood (e.g., Shepard & Metzler, 1971). During the task, infants were simultaneously presented with two image streams. In one stream, a single Tetris-like shape was presented repeatedly and in different orientations, and in the other stream (the ‘mirror’ stream), the figure alternated between the Tetris-like shape and its mirror image (see Figure 1). Infants who detected the mirror reversal in the mirror stream were expected to exhibit longer looking towards this stream (Ross-Sheehy, Oakes, & Luck, 2003; Libertus & Brannon, 2010). Thus, greater proportional looking towards the mirror stream reflected greater mental rotation capacity. Individual differences in infants’ task performance were substantial (Lauer, Udelson, Jeon, & Lourenco, under review), rendering this measure ideal for use in a longitudinal investigation. At 4 years of age, children completed a battery of cognitive tasks, including measures of mental transformation skill, other aspects of spatial thinking, quantitative reasoning, and general cognitive ability (see Table 1 for full list).

Method

Participants

Fifty-three children (28 male) participated as infants (*M* = 10.35 m, *SD* = 1.79 m) and again as 4-year-olds (*M* = 51.97 m, *SD* = 3.36 m). Boys and girls did not differ in age in infancy or at preschool age (*p*s > .35).

Procedure

Between 6 and 13 months of age, infants visited the laboratory for a single testing session during which they completed a spatial change detection task designed to assess mental rotation processes. All infants completed four trials of the task except for four infants who completed two trials. These infants were part of a larger sample whose data are reported elsewhere (Lauer et al., under review).

At 4 years of age, children completed two 1-hr testing sessions within a 14-day period except for one child who did not return for the second session. The majority of children (n = 48) were tested individually in a university laboratory; five children were tested in their respective homes. All children were tested by the same experimenter. Across the two sessions, children completed 16 tasks designed to measure different aspects of spatial reasoning, quantitative ability, and general cognitive functioning (see Table 1 for a full list). These tasks included subtests from standardized cognitive assessment batteries and experimenter-designed measures. Some measures were administered on a touchscreen computer (58 cm diagonal); children sat approximately 40 cm from the computer screen. All computerized tasks were created using custom Visual Basic scripts (Microsoft). For ease of administration, a fixed order of tasks was used such that tasks requiring similar materials were administered consecutively, with computerized tasks preceding paper-and-pencil measures during both sessions (see Table 1 for task order). To maintain interest, tasks with varying response formats were interleaved throughout the sessions and children were given stickers and small toys between tasks. For non-standardized measures, reliability analyses were performed to ensure internal consistency within our sample; tasks yielding low reliability (split-half *r*s < .5) were not included in subsequent analyses (further details below). All standardized measures have high reported internal consistency (split-half *r*s > .6; see Appendix A).

Caregivers provided written informed consent on behalf of their children before each testing session and were compensated $75 for their participation at the conclusion of the second preschool session. The local ethics committee approved all procedures.

Infant spatial change detection task. Infants were presented with two image streams that appeared simultaneously on the left and right sides of a frontal screen. The two streams contained a 2-dimensional Tetris-like figure that was presented rapidly and in different orientations (see Figure 1). Within each 60-s trial, the orientation of the figure varied randomly within a range of 180° along the picture plane. The same figure appeared in the same orientation in both image streams with the exception that on every third presentation of the stimulus, the figure presented in one stream (the mirror stream) was the mirror image of the figure presented in the other (the non-mirror stream). The left/right position of the mirror stream alternated across trials, with side on first trial counterbalanced across infants (Lauer et al., under review).

To assess task performance we calculated spatial change preference scores that equaled the proportion of time spent looking to the mirror stream as a function of looking time to both streams [i.e., mirror stream/(mirror stream + non-mirror stream)] across trials. Spatial change preference scores above .50 correspond to greater proportional looking to the mirror stream, indicating that infants recognized the novelty of the mirror stimulus within the mirror stream. Thus, higher spatial preference scores indicated greater task performance (see also Ross-Sheehy, Oakes, & Luck, 2003; Libertus & Brannon, 2010).

Infants exhibited the expected pattern of performance on the task, looking significantly more towards the mirror stream ($M = .56$, $SD = .07$) than would be expected by the chance level of .50, $t(52) = 6.86$, $p < .0001$, $d = .94$, with the majority of infants (47/53) displaying a preference for the mirror stream (binomial test, $p < .0001$). Spatial change preference scores did not vary by age or sex (see Appendix B for details).

Preschool spatial measures. As the spatial change detection task was designed to assess early mental rotation processes, we were interested in assessing children's mental rotation skills at 4 years of age as well as other aspects of spatial reasoning. Consequently, children completed a widely used measure of early mental rotation abilities, namely the Children's Mental Transformation Task (CMTT; Levine *et al*., 1999), and a number of other spatial tasks.

CMTT. All children completed a computerized version of this task at the beginning of each preschool session. The task included two training trials with corrective feedback followed by 30 test trials without feedback (randomized order). The experimenter initiated each trial by touching a star presented centrally on screen. Children responded by touching one of the choice options. Response times (RTs) and accuracy were recorded. Data were excluded for trials in which RTs were less than 200 ms or above 2.5 SDs per participant mean on a given task.

During each trial, children were presented with two pieces of a 2-dimensional target shape divided symmetrically along the vertical axis and a 2 x 2 array of choice shapes. Children were directed to select the choice shape that would be formed by moving the two target pieces together (see Figure 2). Half of the 30 test items required mental translation (i.e., the target pieces were separated along the vertical and/or the horizontal axis) whereas the other half required mental rotation (i.e., the target pieces were rotated 60° from the vertical axis and separated along the vertical and/or horizontal axis). Children completed the CMTT during each session. Because one four-year-old did not return for the second preschool session, CMTT data collected during the first session were used in all analyses. This task yielded high internal consistency within our sample (split-half *r* = .726, adjusted using Spearman-Brown formula). See Appendix A for additional details.

Children completed a second mental rotation task (i.e., the Ghost Puzzle; Frick, Hansen, & Newcombe, 2013) and a search task designed to assess children's use of distance for reorientation within a navigable space (Lee, Sovrano, & Spelke, 2012; see Appendix A for additional details related to both tasks). Although the search task yielded high reliability (split-half *r* = .519, adjusted using Spearman-Brown formula), Ghost Puzzle data were not reliable (split-half *r* = .264, adjusted using Spearman-Brown formula) and thus not analyzed further.

Standardized spatial tasks. Children completed four standardized assessments of spatial reasoning, which included measures of spatial visualization and spatial short-term memory (see Table 1). See Appendix A for additional details.

Preschool quantitative measures. Children completed two measures of quantitative ability: the number discrimination task (NDT; Bonny & Lourenco, 2013) and a standardized math measure (WJ-Applied Problems; Woodcock, McGrew, & Mather, 2001). The NDT is a computerized task that assesses non-symbolic number processing by having children judge which of two visual displays contains the larger numerical quantity (see Appendix A for additional details). Internal consistency within our sample was high (split-half *r* = .584, adjusted using Spearman-Brown formula). The WJ-Applied Problems subtest includes a variety of items that require counting and simple mental arithmetic (See Appendix A for additional details).

Preschool general cognitive measures. Children also completed non-spatial and non-quantitative measures as controls for various general cognitive abilities, including working memory, verbal ability, and processing speed (see Table 1). Children additionally completed a computerized physical reasoning task, but this task yielded low reliability (split-half $r = .254$, adjusted using Spearman-Brown formula) and was not included in later analyses. See Appendix A for additional details.

Results

Performance on the spatial change detection task in infancy significantly predicted preschool CMTT performance, $r(51) = .47$, $p = .0004$ (see Figure 3), as well as performance on a number of standardized measures of spatial reasoning at 4 years of age (see Table 2). Infant spatial preference scores also predicted preschool performance on the standardized math task (WJ-Applied Problems), $r(51) = .42$, $p = .002$ (Figure 3), but did not predict performance on any of the general cognitive measures administered at preschool age (ps > .05). Importantly, when controlling for preschool performance on the general cognitive measures (see Table 1), infant spatial preferences scores remained significantly correlated with preschool performance on the mental transformation task (CMTT), $r_p(36) = .43$, $p = .007$, a standardized measure of spatial visualization ability (NEPSY-Block Construction), $r_p(36) = .37$, $p = .033$, and the standardized measure of math ability (WJ-Applied Problems), $r_p(36) = .37$, $p = .020$ (see Table 3; see Appendix B for partial regression plots). These findings suggest that infant visuospatial abilities are uniquely predictive of later spatial and mathematical competence.

As age was correlated with performance on a number of preschool measures (see Appendix B), we also controlled for the potential influence of children's age across tasks. When controlling for age in addition to performance on the general cognitive measures, infant spatial preference scores significantly predicted performance on the CMTT, $r_p(35)$

= .40, p = .014; NEPSY-Block Construction, $r_p(35) = .33$, p = .043; and WJ-Applied Problems, $r_p(35) = .36$, p = .029, as in the analysis above.

In an additional analysis, we examined the role of children's spatial short-term memory in the relationship between infant and preschool spatial abilities. Although heretofore we have characterized spatial short-term memory as an exclusively spatial construct, it is associated with domain-general working memory processes (Alloway, Gathercole, & Pickering, 2006; Miyake Friedman, Rettinger, Shah, & Hegarty, 2001) and has been shown to contribute to inter-individual variability in mental rotation abilities (Kaufman, 2007) and math performance (Alloway & Passolunghi, 2011; Bull, Espy, & Wiebe, 2008; Swanson & Kim, 2007). We thus conducted partial correlation analyses to rule out the potential effect of spatial short-term memory in the previously reported relationships. When controlling for performance on the spatial short-term memory task (KABC-Spatial Memory) in addition to the general cognitive measures and children's age, infant spatial preference scores remained a significant predictor of preschool performance on the CMTT, $r_p(34) = .40$, p = .016, and WJ-Applied Problems, $r_p(34) = .34$, p = .044 (for other measures, rs < .31, ps > . 05). Thus, individual differences in spatial short-term memory did not account for the reported relation between infant visuospatial ability and spatial and mathematical reasoning at age 4.

To ensure that the reported findings were not the result of outliers in performance on one or more measures, we reexamined the relationships reported above using non-parametric rank correlation analyses (Spearman's ρ). Infants' rank order on the spatial change detection task significantly predicted children's rank order on the CMTT, NEPSY-Block Construction, WJ-Spatial Relations, KABC-Spatial Memory, and WJ-

Applied Problems (Table 4), but was unrelated to any other measure (Spearman's ρs $< .26$, ps $> .05$). As in the analyses above, we again controlled for children's performance on the general cognitive measures as well as their age at preschool testing; infant spatial preference scores remained significantly correlated with preschool performance on the mental rotation measure [CMTT; $\rho(35) = .38$, $p = .020$] and the standardized math measure [WJ-Applied Problems, $\rho(35) = .41$, $p = .014$; see Appendix B]. When additionally controlling for spatial short-term memory, the correlations between infant spatial preference scores and preschool performance on the mental rotation task [CMTT; $\rho(34) = .43$, $p = .009$] and the standardized math measure [WJ-Applied Problems, $\rho(34) = .41$, $p = .014$] remained statistically significant (other correlations, ps $> .05$).

Although the above findings suggest that infant spatial preference scores uniquely predicted preschool performance on the CMTT and standardized math measure (WJ-Applied Problems), the CMTT was also correlated with WJ-Applied Problems at preschool age, $r(51) = .34$, $p = .012$. When controlling for children's CMTT performance, infant spatial preference scores remained significantly correlated with WJ-Applied Problems performance, $r(50) = .31$, $p = .025$. Similarly, when controlling for WJ-Applied Problems performance, infant spatial preference scores remained correlated with CMTT performance, $r(50) = .38$, $p = .006$. These findings suggest that infant spatial preference scores held significant incremental validity in predicting both mental rotation performance and math achievement beyond what could be attributed to the contemporaneous relation between the two cognitive abilities at preschool age.

Taken together, our findings suggest that there is a moderate degree of stability in mental rotation abilities between infancy and preschool age that cannot be accounted for by the common influence of general cognitive abilities or spatial memory capacities in performance across tasks. Moreover, our findings suggest that early visuospatial processes may serve as a precursor to mathematical reasoning later in development, as infant spatial preference scores also held unique incremental validity in predicting mathematical competence at preschool age.

Discussion

In the present study, we report that visuospatial abilities in infancy were uniquely predictive of spatial and mathematical aptitude at 4 years of age. The relation between infants' performance on an implicit mental rotation measure and later performance on an explicit mental transformation task at preschool age could not be accounted for by individual differences in general cognitive abilities or spatial memory capacities. Mental rotation performance in infancy was found to be similarly predictive of math ability at age 4. Together, these findings provide the first evidence that individual differences in mental transformation abilities are moderately stable between infancy and preschool age and that precursory mental rotation processes in infancy influence the development of spatial and mathematical reasoning in early childhood.

The presented findings contribute novel insight into the developmental origins of visuospatial thinking. Previous studies on mental transformation skills in early childhood have reported paradoxical results, with infants appearing to posses adult-like mental rotation processes (e.g., Frick & Möhring, 2013; Möhring & Frick, 2013), but young children showing poor performance on explicit mental transformation tasks (e.g., Frick, Hansen, & Newcombe, 2013; Kosslyn, Margolis, Barrett, Goldknopf, & Daly, 1990). These findings have led to questions of whether the two types of measures recruit similar cognitive operations (Frick, Möhring, & Newcombe, 2014). Our results not only indicate that similar cognitive processes underlie performance on implicit mental rotation measures in infancy and explicit measures of mental transformation ability in childhood, but also suggest continuity in these processes throughout early development. Although previous research has demonstrated that there are substantial individual differences in spatial aptitude (Hegarty & Waller, 2005), the sources of this inter-individual variation have remained elusive. Our findings shed light on these origins, indicating that precursors to mental transformation abilities present in infancy in part give rise to the individual differences in spatial competence that are pervasive later in life.

Our findings also point to specificity in the stability of visuospatial processes across early childhood. Although infants' performance on the spatial change detection task was associated with preschool performance on mental transformation and spatial visualization measures, there was no predictive relationship between visuospatial reasoning in infancy and spatial reorientation at preschool age. Moreover, preschool performance on the reorientation task was not associated with performance on concurrent measures of mental transformation ability or quantitative reasoning. These findings support previous research showing that small-scale spatial transformation abilities, such as object-based mental transformation skills, are at least partially dissociable from the large-scale spatial orientation abilities recruited during navigation (Hegarty & Waller, 2004; Kozhevnikov, Motes, Rasch, & Blajenkova, 2006) and give credence to suggestions that the cognitive processes underlying small-scale spatial transformations are uniquely associated with STEM learning (Newcombe & Frick, 2010).

In addition to documenting developmental continuity in spatial aptitude, our results provide further evidence of a close association between spatial and mathematical cognition early in development. Previous studies have demonstrated stability in mathematical reasoning from preschool into elementary school (Jordan, Kaplan, Ramineni, & Locuniak, 2009; Mazzocco & Thompson, 2005), suggesting that meaningful individual differences in math abilities arise prior to intensive math instruction. Recent research has suggested that early differences in non-symbolic number processing may underlie inter-individual variation in mathematical competence by elementary school (e.g., Lourenco, Bonny, Fernandez, & Rao, 2012; Mazzocco, Feigenson, & Halberda, 2011). Moreover, a recent longitudinal study reported that individual differences in infants' performance on a non-symbolic numerical discrimination task predicted both non-symbolic number processing and symbolic math ability at age 3 (Starr, Libertus, & Brannon, 2013), suggesting that domain-specific quantitative processes present in infancy may scaffold the acquisition of symbolic mathematical concepts later in childhood. In the present study, we also reported a relation between performance non-symbolic number discrimination task and performance on a contemporaneous measure of symbolic math achievement at preschool age. However, our findings suggest that early visuospatial processes present in infancy also serve as a precursor to symbolic mathematical competence at age 4, indicating that preverbal spatial processes play a unique role in facilitating the acquisition of symbolic mathematics.

How do visuospatial processes influence mathematical reasoning? Previous research has offered a number of potential explanations for the association between spatial and mathematical cognition. Neurobiologically, similar parietal structures underpin performance on both spatial and quantitative tasks (Hubbard, Piazza, Pinel, & Dehaene, 2005), and cognitively, we tend to represent quantitative information in spatial formats (Dehaene, Bossini, & Giraux, 1993; see Mix & Cheng, 2012). Moreover, there is evidence to suggest that spatial skills scaffold children's math learning by strengthening their spatial representations of numerical concepts. For instance, Gunderson and colleagues (2012) recently reported that mental transformation abilities at 5 years of age predicted symbolic math ability at age 8 via their influence on the precision of children's mental number lines. The present study extends our understanding of the predictive relation between spatial and mathematical reasoning and indicates that the association between spatial aptitude and math achievement has origins in visuospatial processes that are present in infancy.

Although our results are strongly suggestive of developmental stability in spatial aptitude and indicate that the association between spatial and mathematical competence arises prior to 4 years of age, there were limitations to the retrospective design of the current study. As infants were presented with a single cognitive measure, we were unable to account for individual differences in general cognitive abilities, such as working memory and speed of processing, in infancy, nor could we conclude that the observed relation between spatial and mathematical reasoning emerged before age 4. Consequently, future research should examine the association between spatial and numerical processing in infancy as well as the role of early individual differences in general cognitive abilities in predicting spatial and mathematical aptitude later in development. Additionally, longitudinal research utilizing a larger sample of children would extend the generalizability of our findings.

In summary, the present study provides the evidence that early visuospatial processes present in the first year of life serve as precursors to later spatial abilities and facilitate the acquisition of symbolic mathematics. Given the close relationship between spatial and mathematical abilities throughout development (Mix & Cheng, 2012) and the predictive role of childhood spatial abilities in STEM achievement in adulthood (e.g., Wai et al., 2009), the presented findings point to the importance of incorporating spatial education into early interventions aimed at promoting STEM success.

Table 1

Tasks Analyzed at Preschool Age

Domain	Construct	Task	Measure
Spatial	Mental rotation	CMTT[a]	Accuracy
	Spatial visualization	NEPSY-Block Construction[c]	Standard score
		WJ-Spatial Relations[d]	Standard score
	Spatial short-term memory	KABC-Spatial Memory[e]	Raw score
	Reorientation	Search task	Accuracy
	Visuospatial analysis	NEPSY-Geometric Puzzles	Raw score
Quantitative	Mathematical reasoning	WJ-Applied Problems	Standard score
	Non-symbolic number	NDT[f]	Accuracy
General	Expressive vocabulary	WJ-Picture Vocabulary	Standard score
	Processing speed	WJ-Visual Matching	Standard score
	Relational language	TRC[g]	Standard score
	Sensorimotor functioning	NEPSY-Visuomotor Precision	Standard score
	Sequential reasoning	WJ-Planning	Standard score
	Working Memory	WJ-Auditory Working Memory	Standard score

Note. Children additionally completed the Ghost Puzzle and a physical reasoning task, which were not analyzed due to low task reliability within our sample (see Method). Tasks were administered in the following order: (i) CMTT and Ghost Puzzle (order counterbalanced), (ii) NDT, (iii) NEPSY-Block Construction, (iv) WJ-Spatial Relations, (v) WJ-Auditory Working Memory, (vi) NEPSY-Visuomotor Precision, (vii) WJ-Applied Problems, (viii) WJ-Picture Vocabulary, (ix) KABC-Spatial Memory. During the second session, tasks were administered in the following order: (i) CMTT and Ghost Puzzle (order counterbalanced), (ii) Physical reasoning task, (iii) NEPSY-Geometric Puzzles, (iv) WJ-Visual Matching, (v) WJ-Planning, (vi) TRC, (vii) Search task.

[a] CMTT: Children's Mental Transformation Task (Levine *et al*., 1999)
[b] Modified from Frick, Hansen, & Newcombe (2013)
[c] NEPSY: A Developmental NEuroPSYchological Assessment-II (Korkman, Kirk & Kemp, 2007)
[d] WJ: Woodcock-Johnson-III Tests of Achievement, Tests of Cognitive Abilities (Woodcock, McGrew, & Mather, 2001)
[e] KABC: Kaufman Assessment Battery for Children (Kaufman & Kaufman, 1983)
[f] NDT: Number Discrimination Task (Bonny & Lourenco, 2013; see also Halberda & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2011)
[g] TRC: Test of Relational Concepts (Edmonston & Litchfield Thane, 1988)

Table 2

Zero-order Correlations between Infant Spatial Preference Scores and Preschool Task Performance

Task	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***
Infancy									
1. Change detection task	-	.47***	.30*	.31*	.31*	-.23	.08	.42**	-.07
Preschool									
2. CMTT		-	.43**	.32*	.32*	.05	.11	.34*	.12
3. NEPSY-Block Const.			-	.13	.41**	.38*	.23	.41**	.26
4. WJ-Spatial Relations				-	.46***	-.11	.38**	.45***	.27
5. KABC-Spatial Memory					-	.21	.14	.40**	.40**
6. Search task						-	-.03	-.11	.27
7. NEPSY-Geo. Puzzles							-	.19	.23
8. WJ-Applied Problems								-	.30*
9. NDT									-

$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Note. n = 53 on all measures except for Search Task (n = 46) and NEPSY-Geometric Puzzles (n = 52). Cases with missing values were deleted pairwise.

Table 3

Partial Correlations between Infant Spatial Preference Scores and Preschool Task Performance when Controlling for General Cognitive Abilities

Task	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***
Infancy									
1. Change detection task	-	.43**	.37*	.20	.24	-.16	.09	.37*	-.17
Preschool									
2. CMTT		-	.46**	.22	.25	.11	.03	.08	.00
3. NEPSY-Block Const.			-	.12	.38*	.37*	.17	.45**	.18
4. WJ-Spatial Relations				-	.35*	-.06	.39*	.27	.18
5. KABC-Spatial Memory					-	.27	.03	.23	.28
6. Search task						-	-.06	-.09	.29
7. NEPSY-Geo. Puzzles							-	.05	.15
8. WJ-Applied Problems								-	.13
9. NDT									-

$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Note. n = 45. The intercorrelations among scores on the general cognitive measures did not indicate statistical collinearity (tolerances > .5; VIFs < 1.9). General cognitive abilities were measured by performance on the following tasks: NESPY-Visuomotor Precision, TRC, WJ-Auditory Working Memory, WJ-Picture Vocabulary, WJ-Planning, and WJ-Visual Matching. See Table 1 for more information.

Table 4

Rank Correlations (Spearman's ρ*) between Infant Spatial Preference Scores and Preschool Task Performance*

Task	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***
Infancy									
1. Change detection task	-	.41**	.28*	.38**	.31*	-.19	.05	.44**	-.02
Preschool									
2. CMTT		-	.32*	.20	.11	.03	.13	.22	.06
3. NEPSY-Block Const.			-	.11	.23	.34*	.24	.38**	.18
4. WJ-Spatial Relations				-	.47***	-.12	.37**	.42***	.29*
5. KABC-Spatial Memory					-	.20	.16	.30**	.42**
6. Search task						-	-.11	-.09	.24
7. NEPSY-Geo. Puzzles							-	.22	.17
8. WJ-Applied Problems								-	.27*
9. NDT									-

$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Note. n = 53 on all measures except for the search task (n = 46) and NEPSY-Geometric Puzzles (n = 52). Cases with missing values were deleted pairwise.

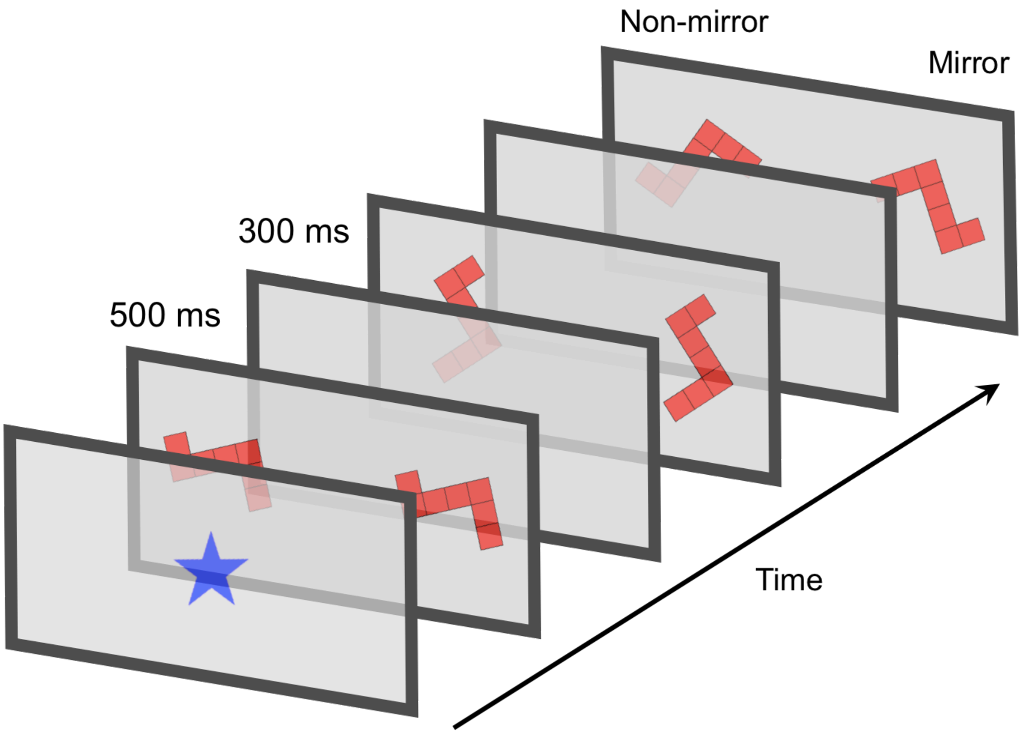

Figure 1. Spatial change detection paradigm used to assess mental rotation in infancy. Infants viewed two image streams containing a figure that was presented rapidly in different orientations throughout each trial. The two image streams were identical with the exception that on every third stimulus presentation, the figure in the mirror stream (left) was the mirror image of the stimulus in the non-mirror stream (right). Stimuli were presented for 500 ms followed by a blank screen of 300 ms. *Note.* Figure not to scale.

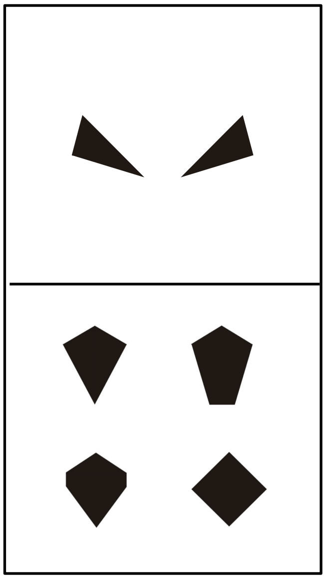

Figure 2. Item from the Children's Mental Transformation Task (CMTT; Levine et al., 1999) administered at 4 years of age. Children were presented with two pieces of a target shape (top) and four choice shapes (bottom). During the training trials, the experimenter gestured to the relevant shapes and instructed children to "Look at these pieces. Now look at these shapes. If you put these pieces together, they will make one of these shapes. Touch the shape that the pieces make." On test trials, children were directed to "Touch the shape that the pieces make."

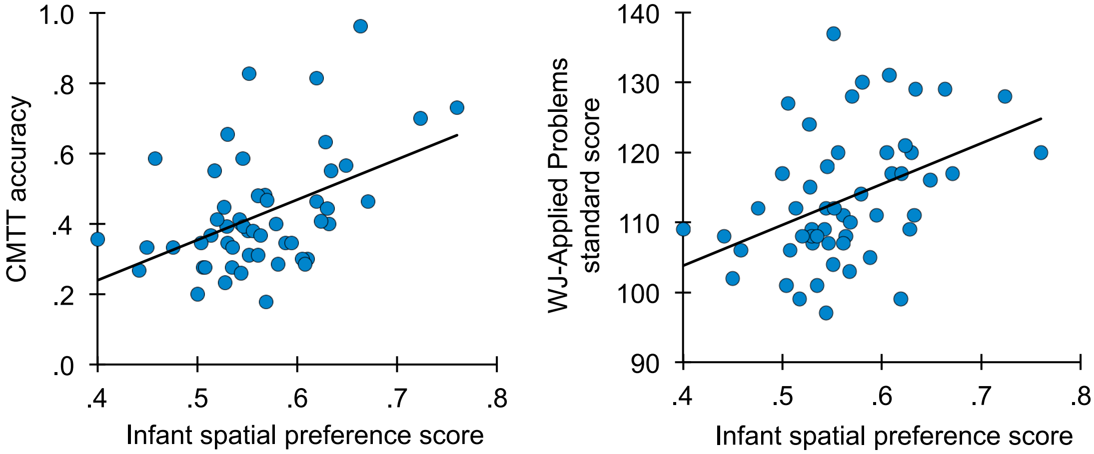

*Figure 3. S*catterplots showing that infants' spatial preference scores (chance performance = .50) predicted preschool performance on a mental transformation task (measured as proportion correct, chance = .25), *r*(51) = .47, *p* < .001 (left) and a standardized measure of mathematical aptitude, *r*(51) = .42, *p* = .002 (right). All correlations remain significant when removing outliers (2.5 SDs +/- mean; *r*s > .32, *p*s < .025). See Appendix B for scatterplots showing other significant zero-order correlations between spatial preference scores and spatial task performance at 4 years of age.

References

Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visuospatial short-term and working memory in children: Are they separable?. *Child Development*, *77*(6), 1698-1716. doi: 10.1111/j.1467-8624.2006.00968.x

Alloway, T. P., & Passolunghi, M. C. (2011). The relationship between working memory, IQ, and mathematical skills in children. *Learning and Individual Differences*, *21*(1), 133-137. doi: 10.1016/j.lindif.2010.09.013

Baenninger, M., & Newcombe, N. (1989). The role of experience in spatial test performance: A meta-analysis. *Sex Roles*, *20*(5-6), 327-344. doi: 10.1007/BF00287729

Benbow, C. P., Lubinski, D., Shea, D. L., & Eftekhari-Sanjani, H. (2000). Sex differences in mathematical reasoning ability at age 13: Their status 20 years later. *Psychological Science*, *11*(6), 474-480. doi: 10.1111/1467-9280.00291

Bonny, J. W., & Lourenco, S. F. (2013). The approximate number system and its relation to early math achievement: Evidence from the preschool years. *Journal of Experimental Child Psychology*, *114*(3), 375-388. doi: 10.1016/j.jecp.2012.09.015

Bull, R., Espy, K. A., & Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Developmental Neuropsychology*, *33*(3), 205-228. doi: 10.1080/87565640801982312

Carroll, J. B. (1993). *Human cognitive abilities: A survey of factor-analytic studies*. Cambridge: Cambridge University Press.

Casey, M. B., Nuttall, R., 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*(4), 697-705. doi:10.1037/0012-1649.31.4.697

Cheng, Y. L., & Mix, K. S. (2014). Spatial training improves children's mathematics ability.*Journal of Cognition and Development*, *15*(1), 2-11. doi: 10.1080/15248372.2012.725186

De Soto, C. B., London, M., & Handel, S. (1965). Social reasoning and spatial paralogic. *Journal of Personality and Social Psychology*, *2*(4), 513-521. doi: 10.1037/h0022492

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, *122*(3), 371-396. doi:10.1037/0096-3445.122.3.371

Edmonston, N. K., & Litchfield Thane, N. (1988). *TRC: Test of relational concepts*. Austin, TX: Pro-Ed.

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., & Newcombe, N. S. (2013). Development of mental rotation in 3- to 5-year-old children. *Cognitive Development*, *28*(4), 386-399. doi: 10.1016/j.cogdev.2013.06.002

Frick, A., & Möhring, W. (2013). Mental object rotation and motor development in 8-and 10-month-old infants. *Journal of Experimental Child Psychology*, *115*(4), 708-720. doi:10.1016/j.jecp.2013.04.001

Frick, A., Möhring, W., & Newcombe, N. S. (2014). Development of mental transformation abilities. *Trends in Cognitive Sciences*, *18*(10), 536-542. doi: 10.1016/j.tics.2014.05.011

Ganley, C. M., Vasilyeva, M., & Dulaney, A. (2014). Spatial ability mediates the gender difference in middle school students' science performance. *Child Development*, *85*(4), 1419-1432. doi: 10.1111/cdev.12230

Golledge, R. G. (2002). The nature of geographic knowledge. *Annals of the Association of American Geographers*, *92*(1), 1-14. doi: 10.1111/1467-8306.00276

Guillot, A., Champley, S., Batier, C., Thiriet, P., & Collet, C. (2007). Relationship between spatial abilities, mental rotation and functional anatomy learning. *Advances in Health Sciences Education*, *12*(4), 491-507. doi:10.1007/ s10459-006-9021-7

Gunderson, E. A., Ramirez, G., Beilock, S. L., & Levine, S. C. (2012). The relation between spatial skill and early number knowledge: The role of the linear number line. *Developmental Psychology*, *48*(5), 1229-1241. doi: 10.1037/a0027433

Hamrick, J., Battaglia, P., & Tenenbaum, J. B. (2011). Internal physics models guide probabilistic judgments about object dynamics. In *Proceedings of the 33rd annual conference of the cognitive science society* (pp. 1545-1550). Austin, TX: Cognitive Science Society.

Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence*, *32*(2), 175-191. doi: 10.1016/j.intell.2003.12.001

Hegarty, M. & Waller, D. (2005). Individual differences in spatial abilities. In P. Shah &

A., Miyake (Eds.), *Handbook of higher-level visuospatial thinking* (121-169). New York: Cambridge University Press.

Hespos, S. J., & Rochat, P. (1997). Dynamic mental representation in infancy. *Cognition*, *64*(2), 153-188. doi: 10.1016/S0010-0277(97)00029-2

Halberda, J., & Feigenson, L. (2008). Developmental change in the acuity of the "Number Sense": The Approximate Number System in 3-, 4-, 5-, and 6-year-olds and adults. *Developmental Psychology*, *44*(5), 1457-1465. doi: 10.1037/a0012682.

Halberda, J., Mazzocco, M. M., & Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature*, *455*(7213), 665-668. doi: 10.1038/nature07246

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews Neuroscience*, *6*(6), 435–448. doi: 10.1038/nrn1684

Kaufman, S. B. (2007). Sex differences in mental rotation and spatial visualization ability: Can they be accounted for by differences in working memory capacity?. *Intelligence*, *35*(3), 211-223. doi:10.1016/j.intell.2006.07.009

Kaufman, A. S., & Kaufman, N. L. (1983). *Kaufman Assessment Battery for Children: Administration and scoring manual*. Circle Pines, MN: American Guidance Service.

Kell, H. J., Lubinski, D., Benbow, C. P., & Steiger, J. H. (2013). Creativity and technical innovation spatial ability's unique role. *Psychological Science*, *24*(9), 1831-1836. doi: 10.1177/0956797613478615

Kozhevnikov, M., Motes, M. A., Rasch, B., & Blajenkova, O. (2006). Perspective-taking vs. mental rotation transformations and how they predict spatial navigation performance. *Applied Cognitive Psychology*, *20*(3), 397-417. doi: 10.1002/acp.1192

Kozhevnikov, M., Motes, M. A., & Hegarty, M. (2007). Spatial visualization in physics problem solving. *Cognitive Science*, *31*(4), 549-579. doi: 0.1080/15326900701399897

Korkman, M., Kirk, U., & Kemp, S. (2007). *NEPSY-II*. San Antonio, TX: Pearson.

Kosslyn, S. M., Margolis, J. A., Barrett, A. M., Goldknopf, E. J., & Daly, P. F. (1990). Age differences in imagery abilities. *Child Development*, *61*(4), 995-1010. doi: 10.1111/j.1467-8624.1990.tb02837.x

Jordan, N. C., Kaplan, D., Ramineni, C., & Locuniak, M. N. (2009). Early math matters: Kindergarten number competence and later mathematics outcomes. *Developmental Psychology*, *45*(3), 850-867. doi: 10.1037/a0014939

Lee, S. A., Sovrano, V. A., & Spelke, E. S. (2012). Navigation as a source of geometric knowledge: Young children's use of length, angle, distance, and direction in a reorientation task. *Cognition*, *123*(1), 144-161. doi: 10.1016/j.cognition.2011.12.015

Levine, S. C., Huttenlocher, J., Taylor, A., & Langrock, A. (1999). Early sex differences in spatial skill. *Developmental Psychology*, *35*(4), 940-949. doi: 10.1037/0012-1649.35.4.940

Levine, S. C., Ratliff, K. R., Huttenlocher, J., & Cannon, J. (2012). Early puzzle play: A predictor of preschoolers' spatial transformation skill. *Developmental Psychology*, *48*(2), 530-542. doi: 10.1037/a0025913

Libertus, M. E., & Brannon, E. M. (2010). Stable individual differences in number discrimination in infancy. *Developmental Science*, *13*(6), 900-906. doi: 10.1111/j.1467-7687.2009.00948.x

Lohman, D. F. (1996). Spatial ability and g. In Dennis, I., & Tapsfield, P. (Eds.), *Human abilities: Their nature and measurement* (97-116). Mahwah, NJ: Lawrence Erlbaum Associates.

Lourenco, S. F., Bonny, J. W., Fernandez, E. P., & Rao, S. (2012). Nonsymbolic number and cumulative area representations contribute shared and unique variance to symbolic math competence. *Proceedings of the National Academy of Sciences*, *109*(46), 18737-18742. doi: 10.1073/pnas.1207212109

Mazzocco, M. M., & Thompson, R. E. (2005). Kindergarten predictors of math learning disability. *Learning Disabilities Research & Practice*, *20*(3), 142-155. doi: 10.1111/j.1540-5826.2005.00129.x.

Mazzocco, M. M., Feigenson, L., & Halberda, J. (2011). Preschoolers' precision of the approximate number system predicts later school mathematics performance. *PLoS One*, *6*(9), e23749. doi: 10.1371/journal.pone.0023749

McGrew, K. S., Schrank, F. A., Woodcock, R. W. (2007). *Woodcock–Johnson III normative update*. Rolling Meadows, IL: Riverside.

Mix, K. S., & Cheng, Y. L. (2012). The relation between space and math: Developmental and educational implications. In J. Benson (Ed.), *Advances in child development and behavior* (pp. 179–243). New York, NY: Elsevier.

Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology: General*, *130*(4), 621-640. doi: 10.1037/0096-3445.130.4.621

Möhring, W., & Frick, A. (2013). Touching up mental rotation: Effects of manual experience on 6-month-old infants' mental object rotation. *Child Development*, *84*(5), 1554-1565. doi: 10.1111/cdev.12065

Moore, D. S., & Johnson, S. P. (2008). Mental rotation in human infants: A sex difference. *Psychological Science*, *19*(11), 1063-1066. doi: 10.1111/j.1467-9280.2008.02200.x

Moore, D. S., & Johnson, S. P. (2011). Mental rotation of dynamic, three-dimensional stimuli by 3-month-old infants. *Infancy*, *16*(4), 435-445. doi: 10.1111/j.1532-7078.2010.00058.x

National Research Council (US). Committee on Support for Thinking Spatially, & Downs, R. M. (2006). *Learning to think spatially*. National Academies Press.

Newcombe, N. S., & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain, and Education*, *4*(3), 102-111. doi: 10.1111/j.1751-228X.2010.01089.x

Quinn P. C., & Liben L. S. (2008). A sex difference in mental rotation in young infants. *Psychological Science*, *19*(11), 1067-1070. doi: 10.1111/j.1467-9280.2008.02201.x

Quinn, P. C., & Liben, L. S. (2014). A sex difference in mental rotation in infants: Convergent evidence. *Infancy*, *19*(1), 103-116. doi: 10.1111/infa.12033

Rochat, P., & Hespos, S. J. (1996). Tracking and anticipation of invisible spatial transformations by 4- to 8-month old infants. *Cognitive Development*, *11*(1), 3-17. doi: 10.1016/S0885-2014(96)90025-8

Ross-Sheehy, S., Oakes, L. M., & Luck, S. J. (2003). The development of visual short-term memory capacity in infants. *Child Development*, *74*(6), 1807-1822. doi: 10.1046/j.1467-8624.2003.00639.x

Schwarzer, G., Freitag, C., Buckel, R., & Lofruthe, A. (2013). Crawling is associated with mental rotation ability by 9-month-old infants. *Infancy*, *18*(3), 432-441. doi: 10.1111/j.1532-7078.2012.00132.x

Shea, D. L., Lubinski, D., & Benbow, C. P. (2001). Importance of assessing spatial ability in intellectually talented young adolescents: A 20-year longitudinal study. *Journal of Educational Psychology*, *93*(3), 604-614. doi:10.1037//0022-0663.93.3.604

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

Starr, A., Libertus, M. E., & Brannon, E. M. (2013). Number sense in infancy predicts mathematical abilities in childhood. *Proceedings of the National Academy of Sciences*, *110*(45), 18116-18120. doi: 10.1073/pnas.1302751110

Stieff, M. (2007). Mental rotation and diagrammatic reasoning in science. *Learning and Instruction*, *17*(2), 219-234. doi:10.1016/j.learninstruc.2007.01.012

Swanson, L., & Kim, K. (2007). Working memory, short-term memory, and naming speed as predictors of children's mathematical performance. *Intelligence*, *35*(2), 151-168. doi: 10.1016/j.intell.2006.07.001

Terlecki, M. S., Newcombe, N. S., & Little, M. (2008). Durable and generalized effects of spatial experience on mental rotation: Gender differences in growth patterns. *Applied Cognitive Psychology*, *22*(7), 996-1013. doi: 10.1002/acp.1420

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*(2), 352-402. doi: 10.1037/a0028446

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*(2), 250-270. doi: 10.1037/0033-2909.117.2.250

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over fifty years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, *101*(4), 817-835. doi: 10.1037/a0016127

Watson, J. D., & Crick, F. H. (1953). Molecular structure of nucleic acids. *Nature*, *171*(4356), 737-738.

Woodcock, R. W., McGrew, K. S., & Mather, N. (2001). *Woodcock-Johnson III*. Itasca, IL: Riverside Publishing.

Appendix A

Experimenter-Designed Tasks at Preschool Age

Reliability coefficients for the following tasks can be found in Table S1.

CMTT. We presented children with a computerized version of the paper-and-pencil task developed by Levine and colleagues (1999) and widely used to assess children's ability to engage in mental transformations (e.g., Gunderson et al., 2012; Levine, Ratliff, Huttenlocher, & Cannon, 2012). To allow for computer administration, the stimuli were scaled to 90% of their original size and arranged vertically, with a black line separating the target pieces and choice shapes (Figure 2). As in the paper version, the location of the correct choice shape within the 2 x 2 array was counterbalanced across trials. To maintain interest, children were periodically presented with brief animations throughout the task.

Children completed two forms of the CMTT (Forms A and B), one during each session (order counterbalanced across children). The two forms contained identical target pieces and choice shapes, but the configuration of the target pieces (e.g., horizontally translated, diagonally rotated) varied by form. All children completed both forms except for one child who did not return for the second preschool session.

Ghost Puzzle. This task was developed by Frick, Hansen, and Newcombe (2013) to assess mental rotation abilities in preschool-aged children. We modified the task so that the two mental transformation tasks used in this study (CMTT and Ghost Puzzle) were similar in trial structure and layout. Modifications included decreasing the number of training trials (from 6 to 2), increasing the number of test trials (from 21 to 30), increasing the angular disparity between test stimuli (from 30° to 45°), and rearranging the position of the stimuli such that the target ghost was presented above the choice shapes (the target ghost and its mirror image). The stimuli were scaled to 90% of their original size to allow for computer administration; the outline of the target ghosts was 9 cm in diameter and ghost stimuli varied in size (6 to 8 cm in height and width). Ghosts were rotated in 45° increments between 0° and 180° in both the clockwise and counterclockwise directions, with each orientation appearing in an equal number of trials (6 trials). Order of test items was randomized, and the location of the target ghost (left/right) was counterbalanced across trials. To maintain interest, children were periodically presented with brief animations throughout the task.

All children completed the Ghost Puzzle during both sessions with the exception of one child who did not return for the second preschool session.

Number Discrimination Task. This task was an abbreviated version of the number discrimination task (NDT) employed by Bonny and Lourenco (2013) to measure non-symbolic number processing in preschool-aged children. During the task, children were asked to judge which of two simultaneously-presented arrays contained the greater number of rectangles. The numerical ratio between the numbers of elements in each array was 2.00, 1.50, 1.33, or 1.17 (larger array divided by smaller array), with an equal number of trials for each ratio. The task included 2 training trials with corrective feedback and 24 test trials without feedback (randomized order). During training trials, children were presented with arrays that varied by a 3.00 ratio and that remained onscreen until a touch response was provided. During test trials, arrays were presented for 600 ms before children were prompted to touch the side that had contained the greater number of rectangles.

The arrays were presented side-by-side and were framed by a 10.5 × 8 cm border. The number of rectangles within each array varied between 5 and 12. As in other studies, the size and position of the rectangles differed across trials to control for differences in cumulative area; in 12 trials the numerically greater array was larger in cumulative area in the other 12 trials the numerically greater array was smaller in cumulative area. Color of arrays varied across trials but was constant within trial. The side (left/right) of the numerically greater array was counterbalanced across trials. For additional procedural details, see Bonny and Lourenco (2013).

The experimenter initiated each trial by touching a star. Children responded by touching one of the two arrays. Response times (RT) and accuracy were recorded, and data were excluded for trials in which RTs were less than 200 ms or greater than 2.5 standard deviations above the participant’s mean.

Search Task. This task measures children’s use of geometric information, namely distance, to locate a hidden object following disorientation. The task took place in a circular room (3.68 m diameter) with curtained walls concealing the entrance. At the center of the room, four freestanding walls of equal height (47 cm) and length (76 cm) were arranged to form a rectangular array with an aspect ratio of 3:2. Two walls were positioned parallel to one another at a distance of 116 cm and sat perpendicular to the remaining two walls, which were positioned in parallel and 175 cm apart, forming a disjointed rectangular space in the room’s center. Small containers were placed in the empty spaces at the corners of the rectangular space. During the task, children stood in the center of the array and watched as the experimenter hid a toy in one of the containers. Then, the experimenter spun the child 4-5 revolutions as the child covered his or her eyes.

Disorientation concluded with the child facing one freestanding wall (chosen randomly), and the child searched for the hidden toy until he or she located it. The experimenter moved around the space so as not to serve as a reliable cue to the target's location, leaving only geometric information to localize the target. An overhead surveillance camera recorded the procedure for later offline coding of search locations.

Children completed 8 trials. The hiding location was counterbalanced across participants but was constant within participant. Task performance equaled the proportion of times the child initially searched at one of the two geometrically-correct corners across all trials. Seven children did not complete this task because they were tested in their home (5), did not return for a second session (1), or refused to complete all trials (1).

Physical Reasoning Task. This computerized task was a modified version of the task developed by Hamrick, Battaglia, and Tenenbaum (2011) to measure reasoning about the physical properties of objects. Children viewed videos of 3-dimensional towers with varying degrees of stability and heights. Towers were composed of 10 colored blocks positioned on a circular platform that was divided into halves by color (red and green). Each tower was presented for 7 seconds during which the video frame rotated in one revolution around the tower, such that it was presented from all sides. Children were instructed to state the side of the platform (red or green) on which the towers would fall.

The task included 2 training trials and 16 test trials. During the 2 training trials, children received feedback regarding their response by passively viewing the tower falling to the correct side of the platform. No feedback was given on test trials. Test trials included 2 catch trials in which the direction of the tower's fall was unambiguous (i.e., 9 of 10 blocks were positioned on one side of the platform).

As in the other computerized tasks, the experimenter initiated each trial. However, in this task participants' provided verbal responses that were recorded by the experimenter. Task performance was measured as proportion of items answered correctly across all test trials.

Standardized Measures at Preschool Age

At 4 years of age, children completed subtests from the Kaufman Assessment Battery for Children (KABC; Kaufman & Kaufman, 1983), the NEPSY-II (Korkman, Kirk & Kemp, 2007), and the Woodcock-Johnson III (WJ) Tests of Achievement and Tests of Cognitive Abilities (Woodcock, McGrew, & Mather, 2001). Children also completed The Test of Relational Concepts (TRC; Edmonston & Litchfield Thane, 1988). These measures have been used to assess cognitive abilities across various domains for clinical, educational, and research purposes. An experienced experimenter adhered to standard protocols for administration and scoring of each subtest unless otherwise noted. Brief descriptions of each subtest are provided below.

KABC. Children completed the Spatial Memory subtest of the first edition of the KABC, which is normed on a sample of 2,000 children between the ages of 2.5 and 12.5 years.

KABC-Spatial Memory. The Spatial Memory subtest assesses children's spatial short-term memory. Children are presented with an array of pictures for 5 s and subsequently indicate the location of the pictures on an empty grid. The number of elements in the array and the size of the grid increase throughout the test. The test is discontinued after 4 incorrect responses.

Due to the age of our sample, standard scores could not be computed for this subtest. Instead, raw scores (total number of correct responses) were used in all analyses. Reported reliability for the subtest is high in children 5 years of age and older (split-half procedure, $r = 0.80$; Kaufman & Kaufman, 1983).

NEPSY. Children completed three NEPSY-II subtests that assessed visuospatial aptitude and visuomotor competence. The NEPSY-II is normed on a sample of 1,200 children between the ages of 3 and 16. Standardized scores were computed for each subtest ($M = 10$, $SD = 3$) unless otherwise noted.

NEPSY-Block Construction. The Block Construction subtest measures spatial visualization and visuomotor abilities. Children use blocks to construct 3-dimensional objects that correspond to two-dimensional figures presented on a page. Children must complete each construction within 30 to 60 seconds, depending on item difficulty. The test consists of a total of 19 items and is discontinued after 4 incorrect responses. Reported reliability is estimated as $r = 0.75$ using a split-half procedure (Korkman, Kirk, & Kemp, 2007).

NEPSY-Visuomotor Precision. The Visuomotor Precision subtest measures visuomotor speed and accuracy. Children draw lines inside tracks as quickly and as accurately as possible. Children under 5 years of age complete 5 items that vary in difficulty and have differing time constraints (60-180 seconds). Completion times and error rates are used to evaluate performance. Reported reliability is estimated as $r = 0.89$ using a split-half procedure (Korkman, Kirk, & Kemp, 2007).

NEPSY-Geometric Puzzles. The Geometric Puzzles subtest measures visuospatial analysis and attention to detail. Children are asked to match two target shapes to two shapes in a large grid containing the two target shapes as well as several distractor shapes. All children under age 6 complete 12 items and are given either 30 or 60 seconds to respond to each item, depending on item difficulty. Reported reliability is estimated as $r = 0.75$ using a split-half procedure (Korkman, Kirk, & Kemp, 2007).

Standardized scores are not available on this subtest for 4-year-olds; we thus used raw scores (total number of correct responses) in all analyses. One child was not given this subtest because she did not complete the second preschool session.

TRC. The TRC measures children's understanding of various relational concepts. It is normed on a sample of 1,000 children between the ages of 3 and 8 years. Standard scores are available for this test ($M = 50$, $SD = 10$). Reported reliability is estimated as $r = 0.93$ using a split-half procedure (Edmondston & Litchfield Thane, 1988).

Children are presented with pictures and asked to point to a target item within the picture. Items assess understanding of five relational concepts including spatial (e.g., above/below, near/far, middle), dimensional (e.g., tall/short, thin/thick), temporal (e.g., first/last, next), quantitative (e.g., many/few, most/least), and other (e.g., same/different) concepts. The TRC consists of 56 items. Children are required to complete all items. There are no time constraints.

One child did was not given this subtest because she did not complete the second preschool session.

WJ. Children completed six WJ-III subtests measuring spatial, mathematical, verbal, and general cognitive abilities. The WJ-III is normed on a sample of 8,782 individuals between the ages of 2 and 80+ years. Standard scores can be computed for each subtest ($M = 100$, $SD = 15$) and were computed for all children unless otherwise noted.

WJ-Spatial Relations. The Spatial Relations subtest assesses the ability to engage in spatial visualization. Individuals are presented with a target shape and asked to determine which items from a set of pieces form the target shape. Unlimited time is given on each item. The test consists of 33 items total divided into four sections. Participants must obtain a minimum score on each section to advance to the subsequent section. Reported reliability is estimated as $r = 0.92$ using a split-half procedure (McGrew, Schrank, & Woodcock, 2007).

WJ-Auditory Working Memory. The Auditory Working Memory subtest measures working memory capacity. Children must recall and reorder a series of numbers and words that contain 2 to 7 elements. All stimuli are presented aurally. There are no time constraints, and children are encouraged to attempt to answer each item before advancing to the next question. The test consists of 21 items and is discontinued after three consecutive errors. Reported reliability is estimated as $r = 0.96$ using a split-half procedure (McGrew, Schrank, & Woodcock, 2007).

One child did not complete this task because of a failure to follow instructions.

WJ-Applied Problems. The Applied Problems subtest measures mathematical reasoning. At preschool age, questions relate to counting, basic arithmetic, and abstract quantitative information such as reading time on an analog clock and identifying coins. Each item is read aloud by the experimenter and refers to visual figures presented on a page. There are no time constraints, and children are encouraged to attempt to answer each item before advancing to the next item. The test consists of 63 problems and is discontinued after six consecutive errors. Reported reliability is estimated as $r = 0.92$

using a split-half procedure (McGrew, Schrank, & Woodcock, 2007).

WJ-Picture Vocabulary. The Picture Vocabulary subtest measures lexical knowledge. Children are asked to verbally identify objects presented in visual figures. There are no time constraints, and children are encouraged to attempt to answer the problem before advancing to the next item. The test consists of 39 items and is discontinued after six consecutive errors. Reported reliability is estimated as $r = 0.81$ using a split-half procedure (McGrew, Schrank, & Woodcock, 2007).

WJ-Visual Matching. The Visual Matching subtest measures processing speed. Participants completed the first of two versions of the subtest, as is standard procedure for preschool-age children. Children are asked to identify which two shapes in an array of differing shapes are identical. The test consists of 26 items, and children are given 2 minutes to complete as many items as possible. Reported reliability is estimated as $r = 0.87$ using a split-half procedure (McGrew, Schrank, & Woodcock, 2007).

Due to high performance within our sample, standard scores could not computed on the first version of this subtest for many children (39/52). Consequently, raw scores (number of items completed within the time limit) were used to measure performance. One child was not given this subtest because she did not complete the second testing session at preschool age.

WJ-Planning. The Planning subtest measures sequential reasoning and executive functioning. In this paper-and-pencil task, participants must trace figures without lifting their pencils or retracing segments that were previously traced. Reported reliability is estimated as $r = 0.64$ using a split-half procedure (McGrew, Schrank, & Woodcock, 2007).

Standard scores could not be computed for 6 children due to excessively low performance. One child was not given this subtest because she did not complete the second preschool session.

Table A1.

Split-half Reliability Coefficients for Experimenter-Designed Tasks Administered at Preschool Age

Task	**n**	**Number of Test Items**	**Split-half $r^{\dagger}$**
CMTT			
Session 1	53	30	.726
Session 2	52	30	.794
Ghost Puzzle			
Session 1	53	30	.264
Session 2	52	30	.544
NDT	53	24	.584
Search task	47	8	.519
Physical reasoning task	52	16	.254

†Adjusted using the Spearman-Brown formula

Note. CMTT performance was highly correlated across the two testing sessions, $r(50) = .706$, $p < .0001$. Ghost Puzzle performance was also correlated across the two testing sessions, $r(50) = .594$, $p < .0001$.

Appendix B

Infant Spatial Change Detection Task Performance

Infants' spatial preference scores were not related to their age at time of infant testing, *r*(51) = .049, *p* = .729, or to their age at time of preschool testing *r*(51) = .169, *p* = .226. Within this sample, performance on the spatial change detection task did not vary between boys (*M* = .574, *SD* = .062) and girls (*M* = .551, *SD* = .071), *t*(51) = 1.250, *p* = .217, *d* = .35.

Preschool Task Performance

Children's age at preschool testing, measured by mean age across the two preschool testing sessions, was significantly correlated with performance on a number of experimenter-designed and standardized measures (see Table S2 for correlation coefficients). Boys and girls did not significantly differ in performance on any task administered at preschool age with the exception of WJ-Applied Problems, in which boys significantly outperformed girls, *t*(49) = 2.035, *p* = .047, corrected for unequal variance between groups, and KABC-Spatial Memory, in which boys marginally outperformed girls, *t*(51) = 1.953, *p* = .056 (see Table S3). Regression analyses revealed that when controlling for the effect of age, sex was not significantly related to WJ-Applied Problems [*t*(50) = 1.749, *p* = .086] or KABC-Spatial Memory [*t*(50) = 1.415, *p* = .163].

Although the two reported sex differences were small, there are well-established sex differences in spatial and mathematical reasoning (Benbow, Lubinski, Shea, & Eftekhari-Sanjani, 2000; Voyer, Voyer, & Bryden, 1995). To examine whether sex influenced the relationship between infant spatial preference score and preschool task performance, we conducted partial correlation analyses controlling for the effect of sex and found that the significance of the correlations reported in Table 2 were not affected. Furthermore, we used Fisher *r*-to-*z* tests to examine whether the relationships between children's performance in infancy and at preschool age differed for boys and girls. The zero-order correlation coefficients for any of the relationships between infant and preschool performance did not vary by sex, zs < 1.60, ps > .10. These findings suggest that the reported relationships between spatial preference scores in infancy and spatial and mathematical aptitude at preschool age were comparable for boys and girls.

Table B1.

Zero-order Correlations between Preschool Task Performance and Average Age (in Months) across Preschool Testing Sessions

Task	**Measure**	***r***
CMTT	Accuracy	$.410^{*}$
KABC-Spatial Memory	Raw score	$.502^{*}$
NDT	Accuracy	$.357^{*}$
NEPSY-Block Construction	Standard score	$.446^{*}$
NEPSY-Geometric Puzzles	Raw score	.004
NEPSY-Visuomotor Precision	Standard score	-.061
Search Task	Accuracy	.273
TRC	Standard score	.077
WJ-Applied Problems	Standard score	.201
WJ-Auditory Working Memory	Standard score	.038
WJ-Picture Vocabulary	Standard score	-.069
WJ-Planning	Standard score	.158
WJ-Spatial Relations	Standard score	.074
WJ-Visual Matching	Raw score	$.287^{*}$

$^{*}p < .05$

Table B2.

Descriptive Statistics on Preschool Task Performance Overall and by Sex

		All	**Male**	**Female**	***t***	***p***
CMTT	*M* (*SD*)	.43 (.17)	.45 (.19)	.40 (.14)	1.09	.28
	n	53	28	25		
KABC-Spatial	*M* (*SD*)	4.34 (2.67)	5.00 (2.99)	3.60 (2.08)	1.95	.06
Memory	n	53	28	25		
NDT	*M* (*SD*)	.70 (.15)	.71 (.16)	.70 (.14)	0.31	.76
	n	53	28	25		
NEPSY-Block	*M* (*SD*)	8.62 (3.43)	9.11 (3.69)	8.08 (3.10)	1.09	.28
Construction	n	53	28	25		
NEPSY-Geometric	*M* (*SD*)	15.25 (2.94)	15.25 (2.77)	15.25 (3.18)	.00	1.00
Puzzles	n	52	28	24		
NEPSY-	*M* (*SD*)	9.60 (2.58)	9.11 (2.49)	10.16 (2.63)	-1.50	.14
VM Precision	n	53	28	24		
Search task	*M* (*SD*)	.55 (.22)	.59 (.21)	.51 (.24)	1.15	.26
	n	46	23	23		
TRC	*M* (*SD*)	52.75 (9.30)	53.32 (8.98)	52.08 (9.82)	0.48	.64
	n	52	28	24		
WJ-Applied	*M* (*SD*)	113.32 (9.40)	115.68 (10.35)	110.68 (7.43)	2.04	.05*
Problems	n	53	28	25		
WJ-Auditory	*M* (*SD*)	110.06 (14.35)	111.00 (14.56)	109.04 (14.34)	0.49	.63
Working Memory	n	52	27	25		
WJ-Picture	*M* (*SD*)	111.74 (9.33)	112.11 (7.99)	111.32 (10.79)	0.30	.76
Vocabulary	n	53	28	25		
WJ-Planning	*M* (*SD*)	116.22 (8.57)	117.92 (8.20)	114.29 (8.76)	1.44	.16
	n	45	24	21		
WJ-Spatial	*M* (*SD*)	113.83 (8.48)	115.64 (7.43)	111.80 (9.26)	1.67	.10
Relations	n	53	28	25		
WJ-Visual	*M* (*SD*)	22.21 (4.76)	21.75 (5.05)	22.75 (4.45)	0.35	.46
Matching	n	52	28	24		

*$p < .05$ when using the Welch–Satterthwaite approach to correct for unequal variance between groups, as indicated by Levene's Test for Equality of Variance (uncorrected $p = .051$)

Table B3.

Rank Correlations (Spearman's ρ) between Infant Spatial Preference Scores and Preschool Task Performance when Controlling for General Cognitive Abilities and Age

Task	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***
Infancy									
1. Change Detection task	-	.38*	.28	.31	.15	-.15	.05	.41*	-.15
Preschool									
2. CMTT		-	.23	.12	-.22	-.10	.07	.03	-.18
3. NEPSY-Block Const.			-	.06	-.04	.26	.22	.48**	.00
4. WJ-Spatial Relations				-	.44**	-.07	.32*	.20	.20
5. KABC-Spatial Memory					-	.20	.10	.07	.20
6. Search task						-	-.11	-.05	.23
7. NEPSY-Geo. Puzzles							-	.08	.09
8. WJ-Applied Problems								-	.08
9. NDT									-

$^{*}p \leq .05$, $^{**}p < .01$

Note. Cases with missing values were deleted pairwise. General cognitive abilities were measured by the following standardized tests: NESPY-Visuomotor Precision, TRC, WJ-Auditory Working Memory, WJ-Picture Vocabulary, WJ-Planning, and WJ-Visual Matching. See Table 1 for more information.

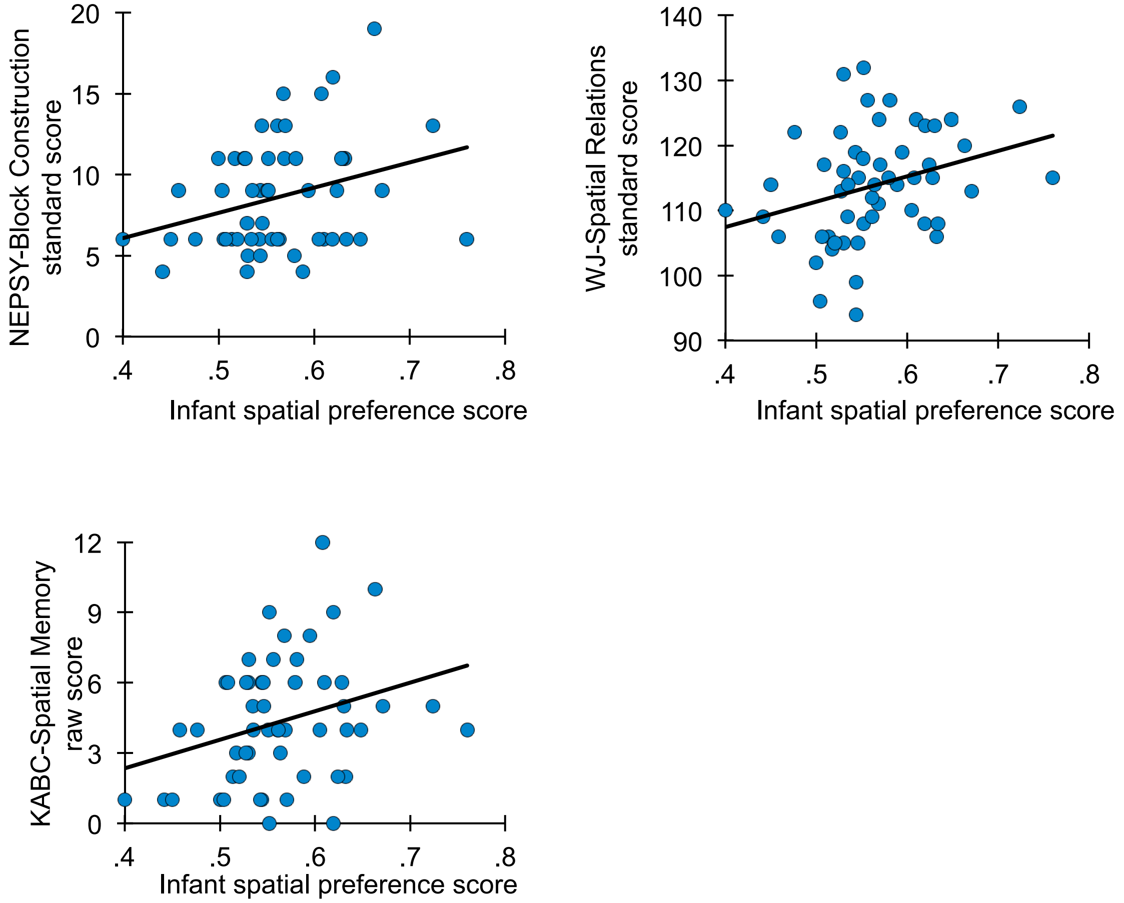

Figure B1. Scatterplots showing that infant spatial preference scores (chance performance = .50) are correlated with preschool spatial visualization abilities as measured by performance on NEPSY-Block Construction (upper left), $r(51) = .30$, $p = .03$, and WJ-Spatial Relations (upper right), $r(51) = .31$, $p = .03$, and with preschool spatial short-term memory as measured by KABC-Spatial Memory (bottom left), $r(51) = .31$, $p = .026$. All correlations remain significant when removing outliers (based on 2.5 SDs +/- mean; rs > .30, *p*s < .05).

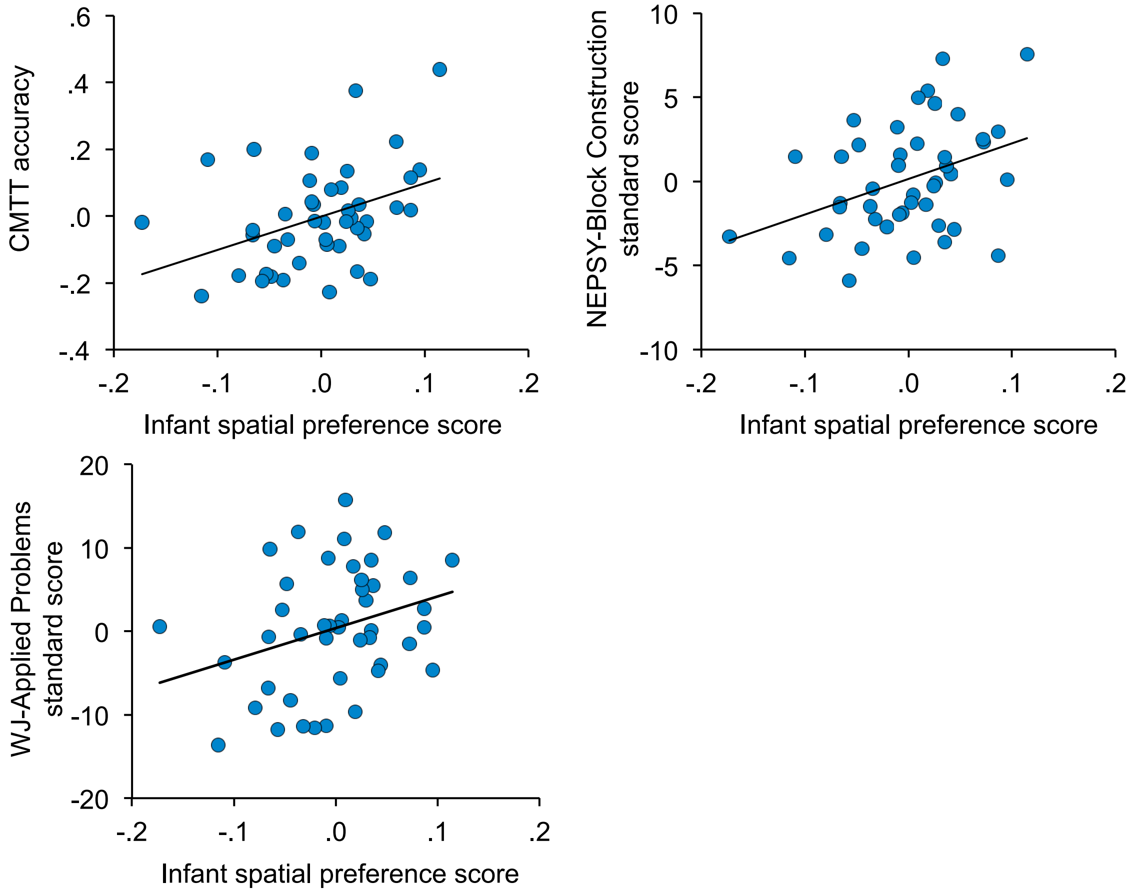

Figure B2. Partial regression plots showing that when controlling for general cognitive abilities (see Table 1 for list of measures), infant spatial preference scores predicted mental transformation ability (upper left), *r*(36) = .431, *p* = .007, spatial visualization ability (upper right), *r*(36) = .371, *p* = .022, and mathematical competence (bottom left), *r*(36) = .375, *p* = .020. All partial correlations remain significant when removing outliers (based on 2.5 SDs +/- mean; rs > .32, *p*s < .04).