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Spatial Processing in Infancy Predicts Both Spatial and Mathematical Aptitude in Childhood

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Abstract

Despite considerable interest in the role of spatial intelligence in science, technology, engineering, and mathematics (STEM) achievement, little is known about the ontogenetic origins of individual differences in spatial aptitude or their relation to later accomplishments in STEM disciplines. The current study provides evidence that spatial processes present in infancy predict interindividual variation in both spatial and mathematical competence later in development. Using a longitudinal design, we found that children's performance on a brief visuospatial change-detection task administered between 6 and 13 months of age was related to their spatial aptitude (i.e., mental-transformation skill) and mastery of symbolic-math concepts at 4 years of age, even when we controlled for general cognitive abilities and spatial memory. These results suggest that nascent spatial processes present in the first year of life not only act as precursors to later spatial intelligence but also predict math achievement during childhood.

Keywords
spatial cognition, symbolic mathematics, cognitive development, mental-transformation skill

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Spatial intelligence is paramount to success in science, technology, engineering, and mathematics (STEM; Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009). Indeed, superior spatial aptitude at 13 years of age has been found to predict professional and creative accomplishments in STEM disciplines, including the number of scholarly works and patents produced, more than 30 years later (Kell, Lubinski, Benbow, & Steiger, 2013). A hallmark of spatial intelligence is the ability to transform and rotate objects in mental space (Frick, Möhring, & Newcombe, 2014; Hegarty & Waller, 2005). This ability to perform mental transformations is often assessed by tasks that require individuals to envision the alignment of two objects via their translation or rotation (e.g., Levine, Huttenlocher, Taylor, & Langrock, 1999; Shepard & Metzler, 1971). Although mental-transformation processes are refined throughout development (Frick et al., 2014), research using visual attention paradigms demonstrates that even infants detect mirror reversals in rotating figures (e.g., Frick & Möhring, 2013), which suggests that a sensitivity to spatial transformations emerges within the first months of life (see also Hespos & Rochat, 1997; Rochat & Hespos, 1996). Moreover, some studies have found that infants exhibit sex differences in their processing of rotational movement (Moore & Johnson, 2008; Quinn & Liben, 2008) that parallel sex differences found in adulthood (Linn & Petersen, 1985; Voyer, Voyer, & Bryden, 1995). Nevertheless, it remains unclear whether the spatial processes infants display during visual attention tasks represent precursors of the more complex spatial processes required by mental-transformation tasks administered in explicit contexts later in life (Frick et al., 2014) and, critically, whether individual differences in infants' spatial processing are predictive of later individual differences in children's STEM achievement.

Longitudinal studies have confirmed that visual attention tasks used with infants have predictive validity in

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other domains of cognition. Findings suggest that numerical, linguistic, and social processes exhibit developmental continuity between infancy and early childhood (Starr, Libertus, & Brannon, 2013; Tsao, Liu, & Kuhl, 2008; Wellman, Lopez-Duran, LaBounty, & Hamilton, 2008). If the mechanisms underlying mental-transformation abilities are similarly developmentally continuous, then infants' early sensitivities to rotational movement should predict their later spatial aptitude. Moreover, one could predict that spatial processes present in infancy, and specifically infants' ability to engage in mental transformations, would have meaningful implications for their later performance in STEM domains as well. Alternatively, if infants' early sensitivity to rotational movement relies on cognitive or perceptual processes that are distinct from those recruited for later spatial reasoning, spatial processes present in infancy could have no bearing on later mental-transformation ability or STEM competence. In this article, we present a longitudinal investigation of spatial development between infancy and preschool age. This study had two aims: (a) to characterize the extent of continuity in the processes associated with mental transformation across early childhood and (b) to determine whether spatial processing ability in infancy predicts mathematical aptitude at 4 years of age.

Method

Participants

Fifty-three children (25 females) participated as infants (mean age = 10.35 months, *SD* = 1.79 months) and again at preschool age (mean age = 51.94 months, *SD* = 3.30 months). Caregivers provided written informed consent on behalf of their children before each testing session and were compensated $75 for their participation. The local ethics committee approved all procedures.

Participant recruitment occurred in two phases. As infants, 63 children were recruited for a single session from a pool of families who had previously expressed interest in research participation (data from that study have been reported elsewhere; see Lauer, Udelson, Jeon, & Lourenco, 2015). For the preschool portion of the study, we attempted to recruit all 63 children from the original sample; 84% of caregivers agreed to participate. Power analyses indicated that this sample size ($n = 53$) provided adequate power ($1 - \beta > .85$) to detect the hypothesized correlations between spatial performance in infancy and spatial and mathematical aptitude at preschool age. Population effect sizes for the longitudinal relations of interest were estimated in accordance with prior research suggesting moderate to large correlations among concurrently administered mental-transformation and symbolic-math measures (i.e., $\rho\text{s} \geq .4$, two-tailed; e.g., Gunderson, Ramirez, Beilock, & Levine, 2012; Hawes, Moss, Caswell, & Poliszczuk, 2015).

Procedure

Between 6 and 13 months of age, the infants were presented with a spatial change-detection task designed to assess their ability to engage in the mental transformation of a two-dimensional (2-D), Tetris-like shape. During this task, two image streams appeared simultaneously on opposing sides of a projection screen (see Fig. 1). In both image streams, static images of the 2-D shape were presented in succession for the duration of four 60-s trials; every image was presented for 500 ms and was followed by an interstimulus interval of 300 ms. The 2-D shape appeared in a different randomly selected orientation along the picture plane with each successive image presentation. It always appeared in the same orientation in both streams, but on every third presentation, the mirror image of the shape was presented in one stream (the *mirror* stream) while the original shape was presented in the other (the *nonmirror* stream; see Fig. 1). Thus, the critical manipulation in this paradigm was the inclusion of the mirrored shape in the mirror stream (see Detailed Task Descriptions, in the Supplemental Material available online, for additional details). Performance was measured as the proportion of total looking time during which the infants looked toward the mirror stream (i.e., mirror/(mirror + nonmirror)). Looking toward the mirror stream was measured relative to overall looking time in order to eliminate the influence of individual differences in the infants' general attention during the testing session (Ross-Sheehy, Oakes, & Luck, 2003).

When the children were 4 years of age, they returned for two 1-hr testing sessions during which they completed a battery of cognitive tasks (see Table 1 for a list of the tasks and Detailed Task Descriptions, in the Supplemental Material, for task descriptions). The spatial tasks included a mental-transformation measure, the Children's Mental Transformation Task (CMTT; Levine et al., 1999; see Fig. 1), as well as tasks that required visualization or reorientation within a navigable environment. The children also completed quantitative measures that assessed their symbolic-math achievement (e.g., counting, arithmetic) and nonsymbolic number processing. Nonspatial and nonquantitative tasks were administered as controls for general cognitive abilities (e.g., vocabulary, working memory). Internal consistency was analyzed for all nonstandardized measures; measures were not included in subsequent analyses if their reliabilities were deemed unacceptable (split-half $r < .5$; see Detailed Task Descriptions and Supplemental Method and Results, in the Supplemental Material, for further details).

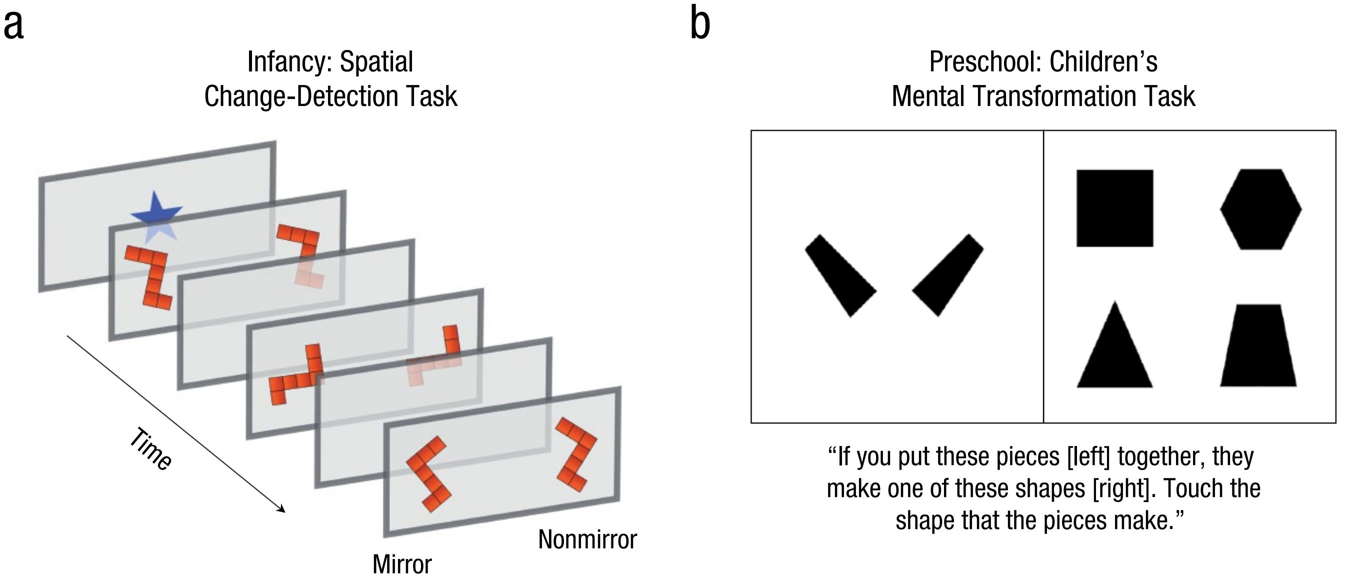

Fig. 1. Illustration of the spatial change-detection paradigm used to assess mental-transformation ability in infancy (left; Lauer, Udelson, Jeon, & Lourenco, 2015) and an item from the Children's Mental Transformation Task (CMTT; Levine, Huttenlocher, Taylor, & Langrock, 1999), which was administered when the children were 4 years of age (right). In the change-detection task, the infants were presented with two simultaneous image streams, one of which contained the mirror-reversal of the original image on every third presentation. Performance was measured by the duration of the infants' looking toward the stream with the mirror stimulus relative to their overall looking time during the task (chance performance = .50). In the CMTT, the children were presented with two pieces of a target shape (shown here on the left) and four choice shapes (shown here on the right) and were directed to select the choice shape that the target pieces could be combined to make. Performance was measured by the proportion of items answered correctly (chance performance = .25). Note that the figure is not drawn to scale.

Results

Two-tailed tests ($\alpha = .05$) were implemented for all statistical analyses reported in this article (including the power analyses reported earlier).

Infants' spatial change-detection performance

The infants' looking patterns were consistent with the findings of previous studies employing change-detection paradigms. Specifically, the infants exhibited greater looking toward the image stream that contained greater novelty (i.e., the mirror stream). The vast majority of infants (47 of 53) displayed a preference for the mirror stream (binomial test, $p < .001$), and the infants' scores indicated that, as a group, they looked toward the mirror stream significantly more ($M = .56$, $SE = .01$, 95% confidence interval, CI = [.55, .58]) than would be expected by chance (i.e., .50), $t(52) = 6.86$, $p < .001$, $d = 0.94$. This mirror-stream preference suggests that the infants in our sample recognized that the mirror reversal within the mirror stream was unexpected given the shape's previous orientations along the picture plane (see also Lauer et al., 2015).

Longitudinal relations

Table 2 presents zero-order correlations and partial correlations (controlling for general cognitive abilities) between the children's scores on the change-detection task in infancy and their performance on the spatial and quantitative tasks administered at preschool age. The infants' scores on the spatial change-detection task significantly predicted their preschool performance on the CMTT, $r(51) = .47$, $p < .001$, 95% CI = [.23, .66], $\log_{10}$ Bayes factor (BF) = 48.56 (see Fig. 2), a longitudinal relation that would be expected if the two tasks relied on similar mental-transformation processes. This correlation remained significant when we corrected for the number of longitudinal relations analyzed (i.e., 14 zero-order correlation analyses; Bonferroni-adjusted $\alpha = .004$), and the estimated BF provided very strong evidence for a predictive association between change-detection performance in infancy and CMTT performance at age 4 (see Wetzels & Wagenmakers, 2012, for details regarding computation and interpretation of BFs for correlation analyses). Change-detection scores in infancy also significantly predicted preschool performance on three additional spatial measures (see Table 2), but these correlations did not withstand correction (ps > .02, $\log_{10}$ BFs < 2). An additional correlational analysis revealed that change-detection scores in infancy significantly predicted preschool performance on the symbolic-math test (Woodcock-Johnson III, or WJ: Applied Problems; Woodcock, McGrew, & Mather, 2001), $r(51) = .42$, $p = .002$, 95% CI = [.17, .62], $\log_{10}$ BF = 13.17 (Fig. 2). Taken together, these findings suggest that the predictive value of infants' mental-transformation performance has

Table 1. Preschool Tasks Included in the Analyses

Domain and construct	Task
Spatial	
Mental transformation	Children's Mental Transformation Task (Levine, Huttenlocher, Taylor, & Langrock, 1999)
Reorientation	Search task (Lee, Sovrano, & Spelke, 2012)
Spatial relations	A Developmental NEuroPSYchological Assessment-II (NEPSY; Korkman, Kirk, & Kemp, 2007): Geometric Puzzles; Woodcock-Johnson III (WJ; Woodcock, McGrew, & Mather, 2001): Spatial Relations
Spatial short-term memory	Kaufman Assessment Battery for Children (A. S. Kaufman & Kaufman, 1983): Spatial Memory
Spatial visualization	NEPSY: Block Construction
Quantitative	
Mathematical reasoning	WJ: Applied Problems
Nonsymbolic number processing	Number Discrimination Task (Bonny & Lourenco, 2013)
General	
Expressive vocabulary	WJ: Picture Vocabulary
Processing speed	WJ: Visual Matching
Relational language	Test of Relational Concepts (Edmonston & Litchfield Thane, 1988)
Sensorimotor functioning	NEPSY: Visuomotor Precision
Sequential reasoning	WJ: Planning
Verbal working memory	WJ: Auditory Working Memory

Note: The children completed two tasks not listed here (a mental rotation task and a physical-reasoning task), but the data from these tasks were not analyzed because of low internal consistency within our sample. See Detailed Task Descriptions and Supplemental Method and Results, in the Supplemental Material, for further details.

specificity within the spatial domain but also extends to the domain of math.

Scores on the spatial change-detection task did not significantly predict performance on any general cognitive measure administered at age 4 (ps > .05, $\log_{10}$ BFs < 0.70; see Table S2 in Supplemental Method and Results in the Supplemental Material), but significant intercorrelations among the spatial and quantitative measures at preschool age (Table 2) suggested a potential influence of general cognitive abilities (e.g., working memory, processing speed) on the children's performance on the spatial and mathematical tasks. Thus, it was critical to determine whether spatial performance in infancy predicted later spatial and mathematical aptitude specifically or later cognitive abilities more generally. Controlling for performance on the six measures of general cognitive functioning (see Table 1), we found that change-detection scores in infancy remained significantly correlated with preschool performance on both the CMTT, partial $r(36) = .43$, $p = .007$, $\log_{10}$ BF = 13.65, and the WJ Applied Problems test, partial $r(36) = .37$, $p = .020$, $\log_{10}$ BF = 4.40 (see Fig. S1 in Supplemental Method and Results for partial-regression plots). In contrast, when we controlled for performance on the CMTT or the WJ Applied Problems test, change-detection scores were not significantly correlated with preschool performance on any general cognitive measure, partial rs < .19, ps ≥ .20, $\log_{10}$ BFs < 1.5. Together, these results indicate that the predictive value of early spatial processes is specific to the domains of spatial and mathematical aptitude.

Age at preschool testing was significantly correlated with performance on some preschool measures (see Supplemental Method and Results, in the Supplemental Material, for details), which raises the concern that the common influence of age across measures could have driven the reported findings. However, scores on the spatial change-detection task remained significantly correlated with performance on the CMTT, partial $r(35) = .41$, $p = .011$, $\log_{10}$ BF = 8.50, and the WJ Applied Problems test, partial $r(35) = .36$, $p = .028$, $\log_{10}$ BF = 3.61, when we controlled for age in addition to performance on the general cognitive tasks.

Could another factor have accounted for the relation between change-detection performance in infancy and spatial and mathematical aptitude at age 4? Thus far, spatial short-term memory (STM) has been considered a spatial measure and was not included as a control in the partial correlations reported. However, spatial STM has been found to contribute to interindividual variability in both mental-rotation (S. B. Kaufman, 2007) and math (Bull, Espy, & Wiebe, 2008) performance, and within our sample, performance on the spatial STM task at preschool age was correlated with concurrent performance on both spatial and quantitative tasks (see Table 2). We thus conducted

Table 2. Correlations Among the Scores on the Infant Change-Detection Task and Preschool Spatial and Quantitative Measures

Age, domain, and task	1	2	3	4	5	6	7	8	9
Infancy									
Spatial									
1. Change-detection task		.47***	−.23	.08	.31*	.31*	.30*	.42**	−.07
Preschool									
Spatial									
2. Children's Mental Transformation Task (Levine, Huttenlocher, Taylor, & Langrock, 1999)	.43**		.05	.11	.32*	.32*	.43***	.34*	.12
3. Search task (Lee, Sovrano, & Spelke, 2012)	−.16	.11		−.03	−.11	.21	.38*	−.11	.27
4. A Developmental NEuroPSYchological Assessment-II (NEPSY; Korkman, Kirk, & Kemp, 2007): Geometric Puzzles	.09	.03	−.06		.38**	.14	.23	.19	.23
5. Woodcock-Johnson III (WJ; Woodcock, McGrew, & Mather, 2001): Spatial Relations	.20	.22	−.06	.39*		.46***	.13	.45***	.27
6. Kaufman Assessment Battery for Children (A. S. Kaufman & Kaufman, 1983): Spatial Memory	.24	.26	.26	.03	.35*		.41**	.40**	.40**
7. NEPSY: Block Construction	.37*[a]	.46**	.36*	.17	.12	.38*		.41**	.26
Quantitative									
8. WJ: Applied Problems	.37*	.08	−.09	.05	.27	.23	.45**		.30*
9. Number Discrimination Task (Bonny & Lourenco, 2013)	−.17	.00	.29	.15	.18	.28	.18	.13	

Note: Zero-order correlations are above the diagonal. Partial correlations (controlling for general cognitive abilities) are below the diagonal. Reported p values are uncorrected. Bayes factors for all zero-order correlations are provided in Table S1 in Supplemental Method and Results, in the Supplemental Material.

[a] Although this correlation was significant, the zero-order correlation between change-detection performance and NEPSY Block Construction performance was not significant after correction for the number of longitudinal analyses.

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

an additional analysis to control for its potential influence across measures. When we controlled for the children's performance on the spatial STM task in addition to the general cognitive measures and age, scores on the spatial change-detection task remained a significant predictor of CMTT performance, partial $r(34) = .41$, $p = .013$, $\log_{10}$ BF = 7.97, and performance on the WJ Applied Problems test, partial $r(34) = .34$, $p = .044$, $\log_{10}$ BF = 2.56. These results indicate that individual differences in spatial STM did not account for the predictive relation between infants' spatial processing and their spatial and mathematical aptitude at 4 years of age.

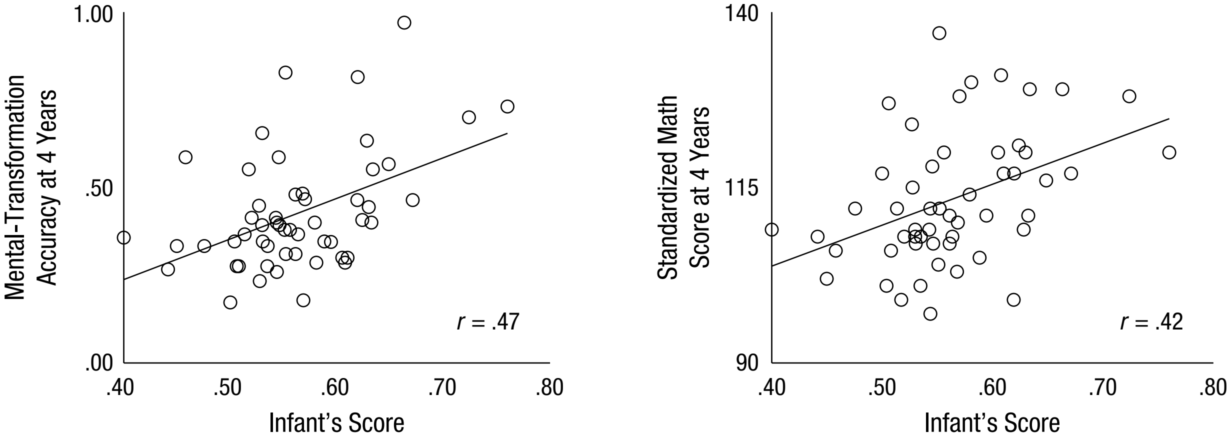

Fig. 2. Scatterplots (with best-fitting regression lines) depicting the relation between task performance in infancy and at preschool age. The graph on the left shows proportion correct on the Children's Mental Transformation Task (Levine, Huttenlocher, Taylor, & Langrock, 1999; chance performance = .25) at age 4 as a function of performance on the spatial change-detection task (chance performance = .50) in infancy. The graph on the right shows standardized score on the symbolic-math test (Woodcock-Johnson III: Applied Problems; Woodcock, McGrew, & Mather, 2001) at age 4 as a function of score on the spatial change-detection task in infancy.

General Discussion

Our findings demonstrate considerable stability in spatial aptitude across early development: Children who exhibited better spatial performance in infancy possessed greater spatial competence at 4 years of age even when we accounted for general cognitive abilities. Although individual differences in spatial aptitude are pervasive by adulthood (Hegarty & Waller, 2005), the sources of this variability have been elusive (Frick et al., 2014). The results of the present study indicate that individual differences in mental-transformation abilities emerge within the first year of life and reliably predict later spatial intelligence.

Our findings also suggest specificity in spatial processing during early childhood. Infants' mental-transformation performance did not predict their later ability to reorient within a navigable environment, which is consistent with extant research suggesting that the spatial processes recruited when reasoning about small-scale structures, as in object-based mental-transformation tasks, may be dissociable from those recruited when reasoning about large-scale layouts, as in navigation (Kozhevnikov & Hegarty, 2001). Moreover, infants' mental-transformation performance did not consistently predict their preschool spatial-relations, spatial visualization, or spatial STM performance when we controlled for domain-general cognitive abilities (see Table 2). These findings may reflect a dissociation between the processing of static and dynamic visuospatial information, which other researchers have argued is a critical dissociation in spatial processing (Uttal et al., 2013). Specifically, our change-detection measure required the processing of dynamic visuospatial information, whereas many of the preschool spatial measures, such as those assessing spatial STM and spatial relations, arguably required processing of static visuospatial information. Taken together, our findings are consistent with prior claims of heterogeneity within the spatial domain and suggest that specificity of spatial processing may be present from early in development.

Our findings also provide evidence that individual differences in children's math achievement relate to individual differences in spatial processing that arise in infancy. Despite a well-established association between spatial and mathematical aptitude later in development (Mix & Cheng, 2012), the nature and origins of this association have been largely unexplored. The current study documents, to our knowledge, the developmentally earliest predictive relation known to occur between spatial processing and mathematical aptitude.

How might early spatial processes relate to later math achievement? Prior behavioral and neural findings suggest that abstract quantitative concepts acquire perceptible meaning when grounded in sensorimotor experience (Lakoff & Núñez, 2000) or instantiated in spatial metaphors, such as the mental number line (Dehaene, 2011). Individuals also benefit from employing spatial strategies to solve arithmetic problems specifically (Cheng & Mix, 2014) and logic problems generally (Glenberg & Robertson, 2000; Huttenlocher, 1968). Building on extant research, our findings suggest that superior spatial processing early in life may play a role in scaffolding math development by providing children with grounded representations of numerical concepts (Gunderson et al., 2012) and by promoting the use of mental models for arithmetic computation (Knops, Thirion, Hubbard, Michel, & Dehaene, 2009).

A recent longitudinal study provided evidence that early numerical processing is predictive of later math ability. Specifically, infants' performance on a nonsymbolic numerical discrimination task was reported to predict their symbolic-math ability at 3 years of age (Starr et al., 2013). In the present study, we found no association between nonsymbolic number processing at age 4 and mental-transformation skill in infancy or at age 4 (see Table 2). Together, these findings suggest that early spatial and numerical processing may play unique roles in the development of symbolic-math skills. However, infants' numerical processing was not assessed in the present study, and it remains unknown whether spatial and numerical processes are related prior to preschool age. An important area for future research will be to determine the respective contributions of early spatial and numerical processing in mathematical development, as well as the degree to which spatial abilities uniquely predict, and potentially influence, STEM achievement beyond childhood.

A limitation of the design of the present study is that, although a battery of spatial, quantitative, and general cognitive measures was administered to the children at preschool age, only a single measure was administered in infancy. Thus, we cannot definitively rule out the possibility that the infant change-detection task assessed domain-general processes such as attention. Nevertheless, we would argue that individual differences in attention are unlikely to account for the current findings for two reasons. First, the measure of performance in infancy accounted for overall looking time, so that this score was not affected by interindividual variability in attention to the task. Second, the predictive validity of performance in infancy was specific to spatial and mathematical aptitude at preschool age. The infants' scores did not significantly predict their preschool performance on any general cognitive measure, as would be expected if nonspecific processing in infancy accounted for the reported longitudinal correlations with spatial and mathematical aptitude. Moreover, the infants' change-detection scores and their general cognitive performance at preschool age remained uncorrelated when we controlled for preschool mental-transformation and symbolic-math performance, whereas the significant correlations between the infants' change-detection scores and their preschool mental-transformation and symbolic-math performance remained moderate in size when we controlled for all general cognitive measures, age, and even spatial memory.

Another possibility is that individual differences in visual pattern recognition during infancy predict spatial and mathematical aptitude at preschool age. We have argued that the change-detection task administered to the infants in the present study assessed spatial processing and specifically the ability to engage in mental transformation. However, performance on this task could instead primarily reflect visual processes that support viewpoint-invariant object recognition and intolerance to mirrored images of objects (cf. Kourtzi & Kanwisher, 2000), which would allow tracking of the nonmirrored shape regardless of its changing orientation and facilitate detection of the mirrored shape in the mirror stream. If these visual processes are also relevant to tasks such as the CMTT and the WJ Applied Problems test, then an alternative account of our findings is that early individual differences in visual recognition, rather than spatial processing, predict both spatial and mathematical aptitude later in life. We cannot rule out this possibility, and indeed, the finding that the vast majority of the infants looked longer toward the mirror stream than toward the nonmirror stream during the change-detection task seems consistent with the recruitment of basic visual processes. Thus, the role of visual recognition processes in spatial and mathematical development is an important area for future research.

We conclude by considering our results within the context of existing research demonstrating substantial malleability in spatial aptitude (Uttal et al., 2013) and suggesting that interventions involving mental-rotation training may improve children's arithmetic performance (Cheng & Mix, 2014; but see Hawes et al., 2015). In this light, our findings suggest that interventions designed to promote visuospatial processing early in development may benefit some types of later spatial and mathematical competence.

Action Editor

Brian P. Ackerman served as action editor for this article.

Author Contributions

S. F. Lourenco developed the study concept. Both authors contributed to designing the study, analyzing the data, and writing the manuscript. Both authors approved the final version of the manuscript.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Supplemental Material

Additional supporting information can be found at http://pss.sagepub.com/content/by/supplemental-data

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