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Continuity and Change in Spatial Processing Between Infancy and Adulthood

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Continuity and Change in Spatial Processing Between Infancy and Adulthood

By

Jillian Lauer
M.A., Emory University, 2015

Advisor: Patricia J. Bauer, PhD

An abstract of
A dissertation submitted to the Faculty of the
James T. Laney School of Graduate Studies of Emory University
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Abstract

Developmental Continuity and Change in Spatial Processing Between Infancy and Adulthood
By Jillian Lauer

The ability to generate and transform mental representations of objects is a hallmark of spatial intelligence that facilitates problem solving in myriad contexts. This ability is often studied with mental rotation tasks thought to elicit mental processes analogous to physical rotation and to produce a robust male advantage in performance. Paradoxically, 4-year-olds display limited mental rotation skills when tested explicitly, yet infants perform above chance on implicit mental rotation tasks. Moreover, 4-year-old girls and boys perform similarly on explicit mental rotation tasks, whereas some studies have reported a male advantage in infants' implicit performance. Thus, it is unclear whether implicit and explicit mental rotation tasks elicit similar processes, whether such processes display developmental continuity between infancy and adulthood, and if so, when gender differences first emerge in ontogeny. The present dissertation addressed these questions through three studies. First, a novel pupillometry task was designed to compare the implicit mental rotation performance of adults (Study 1) and 4-year-olds (Study 2). In both age groups, participants' pupillary responses were consistent with analog mental rotation and were correlated with explicit mental rotation performance. Gender differences in pupillary responses were present at both time points, yet a male advantage in explicit performance was only found in adults. Study 3 further characterized the development of analog mental rotation by examining infants' performance on an implicit change-detection task. Infants' visual preferences were consistent with analog processes, but did not vary by gender. Together, these results suggest that analog mental rotation processes, as assessed via implicit mental rotation tasks, exhibit moderate developmental continuity between early childhood and adulthood, but gender differences in performance may undergo notable change across this period of development.

Continuity and Change in Spatial Processing

Between Infancy and Adulthood

By

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Introduction

The ability to generate and rotate mental representations of objects is an integral component of spatial intelligence that facilitates problem-solving in numerous academic domains (e.g., Golledge, 2002; Guillot et al., 2007; Hegarty & Waller, 2005). This ability, known as mental rotation, is particularly associated with academic success in science, technology, engineering, and mathematics (STEM) disciplines (Mix & Cheng, 2012; Uttal & Cohen, 2012), with recent longitudinal studies reporting that a predictive relation between mental rotation skills and STEM achievement emerges during childhood (e.g., Geer, Quinn, & Ganley, 2018; Gunderson, Ramirez, Beilock, & Levine, 2012) and perhaps within the first years of life (Lauer & Lourenco, 2016; Verdine et al., 2017). Evidence that early mental rotation skills relate to STEM success is particularly noteworthy given that there is a robust male advantage in mental rotation performance during childhood (Lauer, Yhang, & Lourenco, 2019) that has been shown to contribute to gender disparities in STEM achievement by adolescence (Casey et al., 1995; Ganley et al., 2014). These findings have incited considerable interest in the developmental origins of mental rotation abilities, as well as individual and gender differences therein. Nonetheless, research examining mental rotation across early childhood has thus far produced paradoxical results: whereas the findings of some studies suggest that mental rotation processes first emerge in infancy (e.g., Hespos & Rochat, 1997), other findings indicate that mental rotation skills are not manifest in children under 5 years of age (cf., Frick, Möhring, & Newcombe, 2014). These conflicting results leave open questions about the developmental origins and progression of mental rotation abilities across early childhood.

Despite evidence that early mental rotation skills have meaningful implications for later STEM achievement, much remains unknown about the mental rotation abilities of young children or the origins of individual and gender differences in mental rotation skills. Consequently, research elucidating the nature of mental rotation abilities early in ontogeny has the potential to be of significant theoretical and practical importance. In light of this, the present dissertation sought to advance our understanding of mental rotation processes across development and to identify factors that contribute to variability in mental rotation performance during the first years of life.

Evidence of Analog Mental Representations of Spatial Rotation

In adulthood, mental rotation abilities are commonly examined by tasks that require individuals to visualize the rotation of objects in three-dimensional space. For example, in the canonical mental rotation task developed by Shepard and Metzler (1971), adult participants are presented with pairs of line drawings that depict the same object rotated to two different orientations or an object and its mirrored image, also rotated into different orientations. Participants are then asked to indicate whether the line drawings portray the same object or two different objects. In a series of seminal studies, Shepard and colleagues reported that the amount of time adults required to perform these judgments varied as a function of the angular disparity between the two objects (e.g., Shepard & Cooper, 1986; Shepard & Metzler, 1971). These results suggested that adults imagined the two objects rotating into alignment in 'mental space' in a manner that adhered to the same spatiotemporal constraints as the rotation of the two objects in physical space. Thus, Shepard and colleagues interpreted their findings as evidence that their task elicited a mental process analogous to physical rotation.

Shepard and colleagues' findings proved to be groundbreaking in the study of human cognition and spurred extensive research into the cognitive and neural correlates of mental rotation. This research has demonstrated that the linear relation between angular disparity and mental rotation performance is highly robust. In fact, the psychophysical signature of mental rotation has been elicited across various paradigms that differ in experimental procedures (e.g., paired vs. sequential presentation of rotated stimuli), stimulus parameters (e.g., 2-D vs. 3-D; alphanumeric characters vs. abstract shapes), and measures of performance (e.g., response times, accuracy, subjective task difficulty; neural activity; e.g., Heil, 2002; Shepard & Cooper, 1986). Neuroimaging studies have provided further evidence that mental rotation tasks evoke analog mental rotation processes, reporting that activity in parietal cortex varies parametrically as a function of the angular disparity between two to-be-rotated stimuli (for meta-analysis, see Zacks, 2008). These findings indicate that the psychophysical signature of mental rotation can be elicited across paradigms and methods of measurement. However, the aforementioned studies focused disproportionately on college-aged samples, and it remains unclear whether children engage in analog mental rotation processes when presented with similar mental rotation tasks.

Prior Research on Analog Mental Rotation Processes during Development

In the first studies exploring mental rotation abilities in young children, Marmor (1975, 1977) administered a simplified version of Shepard and Metzler's (1971) task to preschool-aged participants. Marmor reported that children as young as 4 years of age exhibited the psychophysical signature of mental rotation, namely a positive relation between the degree of rotation performed and the time required to perform it. However, later studies failed to replicate these results using Marmor's experimental paradigm (Dean & Harvey, 1979; Platt & Cohen, 1981). More recent attempts to document analog mental rotation processes in young children have also had minimal success, typically reporting that children under 5 years of age are unable to discriminate between objects and their rotated mirrored images (e.g., Frick, Ferrara, & Newcombe, 2013; Frick, Hansen, & Newcombe, 2013; Hawes, LeFevre, Xu, & Bruce, 2015).

For example, Frick and colleagues (2013) developed a puzzle-game paradigm that required children to determine which of two asymmetrical puzzle pieces (i.e., a two-dimensional shape and its mirrored image) could be rotated to fit into another shape, completing the puzzle. Despite the familiarity of a puzzle task to young children, 3-year-olds did not perform above the level of chance, suggesting that children do not engage in mental rotation at this age. In contrast, the authors found that 5-year-olds exhibited the behavioral signature of mental rotation when given the same puzzle task (i.e., their response accuracy negatively related to the angular disparity between the puzzle pieces). These findings, *inter alia*, suggest that the capacity to engage in mental rotation may first emerge between 3 and 5 years of age.

The seemingly impoverished mental rotation abilities displayed by children younger than 5 years of age stand in contrast to findings from studies examining infant spatial development, calling into question the age at which mental rotation processes emerge in ontogeny. Specifically, a growing literature suggests that infants form predictions about the rotational motion of objects and detect mirror reversals in rotating shapes within the first year of life. In the first studies to explore these processes in infancy, Rochat and Hespos (1996) employed the violation-of-expectation (VOE) method to test infants' sensitivities to changes in the spatial configuration of a rotating object. Following an occlusion event, infants looked longer towards an object when one of its components had been mirror reversed during occlusion than when the objects configuration had not changed, suggesting that infants detected the unexpected change in the shape's orientation (see also Hespos & Rochat, 1997). Subsequent research utilizing VOE (e.g., Frick & Möhring, 2013), familiarization (Quinn & Liben, 2008), and habituation/dishabituation (Moore & Johnson, 2008; Schwarzer, Freitag, Buckel, & Lofruthe, 2013) paradigms has demonstrated that infants detect mirror reversals in the shape of rotating figures, a key component of mental rotation tasks administered in adulthood (e.g., Shepard & Metzler, 1971). Furthermore, a recent longitudinal study reported that infants' sensitivities to mirror reversals in a rotating shape, measured via performance on a preferential-looking change-detection task (Lauer, Udelson, Jeon, & Lourenco, 2015), predicted their later spatial reasoning abilities when tested at 4 years of age (Lauer & Lourenco, 2016). Taken together, these findings proffer the possibility that infant mental rotation tasks tap early emerging spatial processes that exhibit continuity throughout development.

As described above, prior findings from looking-time studies suggest that infants represent the rotational trajectories of objects and detect mirror reversals in rotating shapes. However, it remains unclear whether the looking-time tasks designed to assess infants' mental rotation abilities through implicit means evoke analog mental representations of spatial rotation similar to those elicited by explicit, mental rotation tasks administered in adulthood. That is, the extant literature has not addressed whether infant looking behavior is consistent with analog mental rotation processes (i.e., scales as a function of the angular disparity between rotated objects) or whether implicit mental rotation tasks tap similar mental processes at later points in development, including during the preschool years when children exhibit poor performance on explicit mental rotation tasks. Consequently, it is not known whether the seemingly disparate mental rotation abilities of infants and preschool-aged children can be attributed to true developmental discontinuity in spatial processing or differences between the implicit and explicit paradigms used to assess children's abilities across these two developmental time points.

Dissertation Objectives

As previously noted, the current literature on spatial development has not addressed whether the spatial processes elicited by implicit mental rotation measures have similar properties to those elicited by explicit mental rotation tasks that are administered in adulthood (e.g., Shepard & Cooper, 1986). The current dissertation aimed to bridge this gap in the literature by examining participants' performance on implicit mental rotation tasks at multiple time points in development, from infancy to adulthood. Paper 1 presents two studies that investigate similarities and differences in the implicit mental rotation processes exhibited by 4-year-olds and adults. Specifically, we designed a novel, implicit task, hereby referred to as the Spatial Oddball Task, to evoke implicit mental rotation processes. This task indexed participants' pupillary responses to changes in the orientation of a rotating stimulus and was administered with limited task instructions, limiting potential age-related variability in task performance that could arise from differences in task comprehension. We first examined the validity of the Spatial Oddball Task as a measure of analog mental rotation processes in adult participants, examining their performance as a function of angular disparity, gender, and mental rotation ability (as measured by an explicit mental rotation task). Then, we administered the same task to 4-year-olds, again examining their Spatial Oddball Task performance in relation to the angular disparity between stimuli, the children's gender, and their performance on an explicit spatial reasoning task. This paper provides the first direct developmental comparison of mental rotation processes between preschool-aged children and adults, allowing us to characterize developmental continuity and discontinuity in analog mental rotation processes between early childhood and adulthood.

In Paper 2, we further documented the extent to which analog mental rotation processes, when measured implicitly, display developmental continuity between early childhood and adulthood by examining these processes even earlier in development. Specifically, we investigated whether infants' performance on an implicit looking-time task was consistent with analog mental rotation processes during their first year of life. As in Paper 1, Paper 2 considered whether correlates (e.g., spatial memory) and factors (e.g., gender) shown to relate to explicit mental rotation performance later in development also account for variation in infants' performance on an implicit mental rotation task. Together, these two papers advance our current understanding of the ontogenetic origins and progression of mental rotation processes during early childhood, contributing insight into developmental continuity and change in spatial processing between infancy and adulthood.

Paper 1

Developmental continuity in spatial rotation processing: A pupillometry study

Abstract

Prior studies of infant spatial processing suggest that rudimentary mental rotation abilities may be present within the first year of life, at least when measured by implicit looking-time tasks. Yet children do not appear to engage in mental rotation on explicit behavioral tasks before 5 years of age (cf., Frick, Möhring, & Newcombe, 2014). Thus, it is unclear whether implicit mental rotation measures administered to infants elicit spatial processes comparable to those elicited by explicit mental rotation tasks later in development, clouding our understanding of their developmental trajectory between early childhood and adulthood. To address this gap in our knowledge on spatial development, the current research investigated whether 4-year-olds and adults perform similarly on implicit mental rotation measures and whether similar correlates of performance can be observed across these developmental time points. We designed a novel implicit task (i.e., the Spatial Oddball Task) that indexed participants' pupillary responses to changes in the orientation of a 2-D stimulus, a putative measure of mental rotation, and administered the task to adults ($N = 51$) and 4-year-olds ($N = 49$). Pupillary response patterns suggested that the Spatial Oddball Task elicited similar processes in both age groups. Moreover, performance on the Spatial Oddball Task was associated with explicit mental rotation task performance in both age groups, suggesting that the implicit and explicit mental rotation tasks may recruited similar underlying processes. In line with this conjecture, gender differences in Spatial Oddball Task performance were observed at age 4 and in adulthood. Taken together, these findings demonstrate that, like adults, preschool-aged children may engage in mental rotation when presented with implicit measures of spatial processing.

Keywords: Mental rotation, spatial processing, pupillometry, gender differences

Developmental differences in spatial rotation processing: A pupillometry study

The ability to generate and transform mental representations of objects is an integral component of spatial intelligence that facilitates problem-solving in myriad contexts (e.g., Hegarty & Waller, 2005; Uttal & Cohen, 2012). In adulthood, this ability is most often assessed via mental rotation tasks that require participants to determine whether a rotated object is identical to a second rotated object presented in a different orientation in space (Shepard & Metzler, 1971). Prior research on adults has demonstrated that the angular disparity between the two rotated objects linearly relates to various outcome measures, including reaction time, response accuracy, and neural activity (e.g., Shepard & Cooper, 1986; Zacks, 2008). This linear relation between angular disparity and participants' responses has been cited as evidence that adults mentally represent the rotation of objects in a manner that is analogous to the rotation of those objects in physical space (Shepard & Metzler, 1971). Given the robust linear relation between angular disparity and response outcomes observed across outcome measures, it is now well established that mental rotation tasks elicit analog mental rotation processes among adults. However, it remains unclear whether young children engage in analog mental rotation when presented with similar tasks in early childhood (Frick et al., 2014).

Previous studies on this topic have reported that preschool-aged children exhibit impoverished mental rotation abilities when tested via mental rotation measures similar to those administered in adulthood (e.g., Frick, Ferrara, & Newcombe, 2013; Frick, Hansen, & Newcombe, 2013; Frick, Hansen, & Newcombe, 2013; Hawes, LeFevre, Xu, & Bruce, 2015). Yet paradoxically, infants perform above chance on implicit looking-time measures that assess their ability to detect mirror reversals in rotating stimuli, a putative measure of implicit mental rotation processes (e.g., Lauer et al., 2015; Moore & Johnson, 2008; Quinn & Liben, 2008). There are a number of potential explanations for this apparent discrepancy in the mental rotation performance of infants and preschool-aged children. First, there may be developmental discontinuity in the spatial processes that underlie mental rotation performance between these two ages. A second, more parsimonious explanation is that the implicit tasks (i.e., looking time measures) used to assess mental rotation in infancy do not truly elicit analog mental rotation processes, instead recruiting cognitive or perceptual processes distinct from those recruited for explicit mental rotation task performance later in development. A third, alternative possibility is that preschool-aged children perform poorly on explicit mental rotation tasks because they have difficulty managing the task demands posed by explicit measures (e.g., task comprehension, response inhibition), not because they lack the processing capacities necessary to engage in mental rotation (cf. Frick et al., 2014). If this were the case, one would expect that preschool-aged children would exhibit evidence of engaging in mental rotation processes if they were presented with implicit measures of spatial processing similar to those administered to infants.

To adjudicate among these three possibilities, we developed a novel pupillometry task to assess spatial rotation processing and examined its validity as a measure of mental rotation processes in adults (Study 1) and preschool-aged children (Study 2). This experimental approach allowed us to accomplish three objectives: (1) to determine whether implicit tasks elicit patterns of performance consistent with analog mental rotation processes, (2) to investigate whether similar mental processes underlie performance on implicit and explicit mental rotation measures when administered concurrently, and (3) to characterize developmental similarities and differences in these processes and their correlates between early childhood and adulthood.

Inconsistent Findings of Mental Rotation in Preschool-Aged Children

As summarized above, prior research has produced robust evidence of a linear relation between angular disparity and adults' response times on canonical mental rotation tasks (e.g., Shepard & Metzler, 1971; Shepard & Cooper, 1986). This linear relation has been observed with other outcome measures as well: angular disparity linearly relates to subjective reports of task difficulty (Shepard & Cooper, 1986), event-related potentials (e.g., Heil, 2002), and functional activity in parietal cortex (for meta-analysis, see Zacks, 2008) when engaging in mental rotation. These findings indicate that the mental rotation of objects adheres to the same spatio-temporal constraints as the physical rotation of objects, representing a mental analog of physical object rotation in adulthood. Consequently, the linear relation between angular disparity and participants' responses is considered to be a signature of analog mental rotation processes.

Inconsistent results regarding the presence of analog mental rotation processes during early childhood can be traced to the first developmental studies of this ability. In two influential experiments, Marmor (1975, 1977) tested 4- and 5-year-olds' mental rotation abilities using a modified version of the canonical Shepard and Metzler (1971) mental rotation task. Children were presented with pairs of teddy bears, one of which was shown in its upright position and the other of which was rotated around the frontal plane, away from its upright position. Children were then tasked with determining whether the rotated teddy bear was the same object as its partner or whether it was the mirrored image of its partner. Marmor reported that preschool-aged children successfully discriminated between non-mirrored and mirrored teddy bears, and their facility in doing so linearly related to the angular disparity between the upright and rotated stimuli. Marmor's work was the first to document analog mental rotation processes during childhood and continues to be regarded as seminal work on these processes at any point in development, as it was published just shortly following Shepard and Metzler's first paper demonstrating these processes in adults. However, later attempts to replicate Marmor's results in 4- to 6-year-olds were unsuccessful (Dean & Harvey, 1979; Platt & Cohen, 1981). In combination with failures to replicate Marmor's early work, recent studies have found little evidence that young children engage in analog mental rotation prior to 5 to 6 years of age (e.g., Frick, Hansen, & Newcombe, 2013; Hawes et al., 2015). Together, these results cast doubt on arguments that young children possess the capacity to perform mental rotation.

The extant spatial development literature provides only limited evidence of analog mental rotation processes during the preschool years. However, this limited evidence may not necessarily reflect a lack of mental rotation processes within this age range. Studies that have administered standard forced-choice mental rotation tasks to preschool-aged children have often found dramatic developmental gains in children's accuracy on mental rotation tasks between 3 and 5 years of age (e.g., Frick, Ferrara, & Newcombe, 2013; Frick, Hansen, & Newcombe, 2013). Importantly, these gains may be attributable to several factors unrelated to the development of mental rotation processes specifically, such as increased task comprehension, response inhibition, and executive functioning. For instance, Cronin (1967) reported that preschool-aged children experience difficulty understanding that an object differs from its mirrored image, even when the object and its mirrored image are both presented in the same, upright orientation, meaning that no mental rotation should be necessary to determine that the two objects are different. Given this, it would be logical to assume that children may fail to comprehend mental rotation tasks that require them to state whether an object and its rotated mirrored image are the "same" or "different" objects. Because common paradigms currently used to assess young children's mental rotation performance rely on same-different judgments of mirrored images, prior studies may not have been well poised to evaluate mental rotation skills in preschool-aged children. In line with this possibility, mental transformation tasks that do not directly assess analog mental rotation processes but still require the mental rotation of object parts have produced clearer evidence of above-chance performance in young children. Most notably, Levine and colleagues (1999) created a task that requires children to mentally assemble shapes via the translation or rotation of their component parts, but does not require mirror discrimination. The authors reported that children as young as 4 years of age performed reliably above chance on the task with minimal instruction, suggesting that preschool-aged children may engage in mental rotation when it is not necessary that they discriminate between mirrored images.

Further consistent with the possibility that analog mental rotation processes emerge by preschool age, a growing body of literature on mental rotation in infancy suggests that, when tested via implicit looking-time tasks, infants appear to possess rudimentary mental rotation processes that display developmental continuity across early childhood. In one longitudinal study, Lauer and Lourenco (2016) administered an implicit mental rotation measure to children aged 6 to 13 months and later tested the explicit mental rotation skills of the same children when they reached 4 years of age. In infancy, the children were presented with an implicit change-detection task that evaluated their ability to detect mirror reversals in a rotating stimulus (Lauer et al., 2015). At 4 years of age, children completed the Children's Mental Transformation Task (CMTT) developed by Levine and colleagues (1999), an explicit measure of mental transformation abilities that does not require mirror-image discrimination. Infants who displayed greater sensitivity to the mirror reversals in the rotating stimuli, measured via their looking times, exhibited higher performance on the explicit mental transformation task at 4 years of age, even when accounting for individual differences in children's general cognitive functioning and spatial memory capacities. These results suggest specificity in the relation between infants' performance on Lauer and Lourenco's implicit looking-time task and their later spatial skills, as measured by an explicit mental transformation task. These findings of developmental continuity are consistent with the possibility that implicit mental rotation tasks administered to infants evoke spatial processes that are later used when solving explicit mental transformation tasks that require mental rotation.

In addition to evidence of longitudinal stability, the implicit task administered in Lauer and Lourenco's study has also been shown to detect gender differences in infant performance, such that boys appeared to display greater sensitivity to the mirror reversals of the rotating stimulus relative to girls (Lauer et al., 2015). This early-emerging gender difference parallels the robust male advantage in mental rotation performance found later in development (Lauer et al., 2019; Voyer, Voyer, & Bryden, 1995), further supporting the possibility that similar mental processes are recruited when performing both implicit and explicit mental rotation tasks across development. However, findings of gender differences in infants' performance on implicit mental rotation measures have been mixed, with some researchers documenting a male advantage in infancy (e.g., Moore & Johnson, 2008; Quinn & Liben, 2008), but others finding no evidence that performance varied between girls and boys during the first year of life (e.g., Erdmann et al., 2018; Möhring & Frick, 2013; Schwarzer et al., 2013). Moreover, a recent meta-analysis reported that the male advantage in children's performance on explicit mental rotation task does not emerge until the elementary-school years (Lauer et al., 2019), casting doubt on whether gender differences in infants' implicit mental rotation task performance, if present, should be considered evidence of developmental continuity in mental rotation processes between infancy and adulthood.

As detailed above, results of previous infant studies suggest that implicit looking-time tasks may elicit mental rotation processes in infancy, and these processes exhibit developmental stability in terms of both individual (Lauer & Lourenco, 2016) and gender differences (Lauer et al. 2015; Moore & Johnson, 2008; Quinn & Liben, 2008). Contradicting this supposition, prior research on older children has indicated that analog mental rotation processes do not manifest in children until 5 years of age (Frick et al., 2014). Furthermore, gender differences in explicit mental rotation task performance do not emerge until at least 6 years of age (for meta-analysis, see Lauer et al., 2019), countering the notion that the male advantage in mental rotation is developmentally continuous between infancy and adulthood. At first glance, evidence of fairly sophisticated mental rotation processes in infancy is difficult to reconcile with studies documenting impoverished mental rotation skills in preschool-aged children. However, implicit mental rotation tasks administered to infants differ from explicit mental rotation tasks administered to preschool-aged children in a number of important ways, including various stimulus parameters and differing outcome measures (i.e., looking time vs. response accuracy). Thus, apparent discrepancies in the mental rotation abilities of infants and children, as well as gender differences therein, could be attributable to paradigmatic differences in the tasks used to measure these abilities across development. If this were the case, it is possible that preschool-aged children would engage in analog mental rotation processes and exhibit gender differences in their facility in doing so if presented with implicit tasks. No prior research has addressed this possibility, as implicit mental rotation tasks have not been administered to participants older than 2 years of age. As a result, our current understanding of the development of mental rotation processes between childhood and adulthood remains limited.

Present Research

In the present research, we conducted two studies to address the following questions: (1) do implicit mental rotation tasks recruit the same underlying mental processes as those recruited during explicit mental rotation tasks; and (2) if so, is there developmental continuity in these mental processes and their correlates between early childhood and adulthood? To answer these questions, we developed the Spatial Oddball Task, an implicit measure designed to evoke analog mental rotation processes in a silent-viewing context. Importantly, the silent-viewing aspect of this task places limited demands on young children, contrary to explicit mental rotation measures that require children to comprehend task instructions, coordinate verbal and/or motor responses, and so on. Thus, the implicit Spatial Oddball Task afforded us the novel opportunity to compare the performance of young children and adults via an identical experimental procedure.

We modeled the Spatial Oddball Task after the visual-oddball paradigm traditionally used to examine novelty detection in infancy. In our task, participants are presented with a single 2-dimensional stimulus that appears in various orientations within a 180° arc (i.e., the stimulus rotates around the picture plane within a trajectory of 180°). At random intervals, the stimulus appears to rotate outside of its expected 180° arc (i.e., the "oddball" rotation). Our task indexes pupillary responses to the oddball stimulus, reflecting the extent to which participants' pupil size changes in response to changes in the orientation of the rotating stimulus.

Pupillometry provided an optimal implicit measure of mental processing during our task for a number of reasons. First, it is well established that pupil dilation serves as a physiological marker of novelty detection across development (for reviews, see Einhäuser, 2017; Hepach & Westermann, 2016; Laeng, Sirois, & Gredebäck, 2012; Nieuwenhuis, De Geus, & Aston-Jones, 2011). That is, pupils dilate in response to novel (more surprising) stimuli, an effect referred to as the task-evoked pupillary response (Laeng et al., 2012; Nieuwenhuis et al., 2011). Such task-evoked pupil dilation is the result of increased activity in neurons in the locus coeruleus-norephinephrine (LC-NE) system, a neural system involved in various mental functions critical to novelty detection, such as visual attention and cognitive control (see Benarroch, 2009; Laeng et al., 2012). Consequently, task-evoked pupillary responses are considered to be involuntary measures of neural activity, providing an implicit measure of mental processing outside of participants' conscious control. Given that novel events evoke pupil dilation beginning in infancy, pupillometry allows for the direct comparison of pupillary responses to novel stimuli across multiple time points in development (see Hepach & Westermann, 2016). We capitalized on this feature of pupillometry in the current research to develop a novel, implicit measure of mental rotation processes suitable for use across disparate developmental populations. Specifically, we examined participants' pupil dilation in response to novel orientations in a rotating stimulus (i.e., a putative measure of spatial rotation processing) during the preschool years and in early adulthood, allowing for the first direct developmental comparison of implicit mental rotation processes across development.

Secondly, pupillary responses represent an outcome measure that scale incrementally with task demands, akin to the continuous dependent measures previously used to demonstrate analog mental rotation processes in explicit contexts (e.g., reaction time, ERPs, subjective difficulty; Heil, 2002; Shepard & Cooper, 1986; Shepard & Metzler, 1971). As previously mentioned, prior research suggests that task-evoked increases in pupil size (i.e., pupil dilation) correspond with increases in attention (Kahneman, 1973), cognitive load (Beatty, 1982), mental effort (Ahern & Beatty, 1979), and task engagement (Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010) that are associated with novelty detection. Importantly, studies on children and adults suggest that pupil dilation scales incrementally with these constructs (e.g., Cabestrero, Crespo, & Quiros, 2009; Gilzenrat et al., 2010; Kahneman & Beatty, 1966). For example, Johnson and colleagues (2014) reported that pupil size during a working memory task was positively related to the number of items held in working memory, both for children and adults. The authors found that pupil size incrementally scaled with the number of to-be-recalled items (i.e., a proxy for cognitive demand) until the number of items outpaced the participants' working memory capacity, at which time pupils began to constrict. Given that the magnitude of the task-evoked pupillary response scales with task demands, pupillometry can reveal how cognitive processing is influenced by specific task parameters.

Considerable empirical evidence indicates that our pupils dilate when we encounter a novel stimulus, reflecting the greater processing demands posed by such stimuli relative to familiar ones (Beatty, 1982; Hepach & Westermann, 2016; Laeng et al. 2012; Sirois & Brisson, 2014). As described above, the magnitude of these processing demands incrementally relates to the magnitude of the evoked pupillary response. Consequently, pupillometry afforded us the opportunity to quantify participants' responses to unexpected orientations of a rotating stimulus as a function of the angular disparity between the expected and unexpected stimuli. If the Spatial Oddball Task elicits analog mental rotation processes, we would expect participants' pupillary responses to linearly relate to the angular disparity between the expected and unexpected/test stimuli. That is, we would predict that larger angular disparities between the expected and unexpected stimuli would result in greater changes in pupil size (i.e., more pupil dilation).

In Study 1, we administered the Spatial Oddball Task to adult participants. We also administered a standard explicit measure of mental rotation performance in order to determine the extent to which adults' pupillary response during the Spatial Oddball Task exhibited patterns consistent with engaging in mental rotation processes. Specifically, we examined whether participants' pupillary responses to the rotation of novel stimuli varied as a function of the angular disparity between rotating objects, as would be expected if the task recruited implicit mental rotation processes. To provide further insight into the underlying cognitive processes employed during implicit mental rotation tasks, we also characterized the relation between adults' pupillary response patterns during the Spatial Oddball Task and their explicit mental rotation performance. Lastly, we assessed whether adults' pupillary responses to differing angular disparities related to their gender, given substantial evidence of a male advantage in explicit mental rotation across development (Lauer et al., 2019). If the silent-viewing Spatial Oddball Task elicits mental rotation processes, one would expect that adults' performance on this task would relate to their explicit mental rotation task performance as well as their gender.

In Study 2, we administered our Spatial Oddball Task to 4-year-old participants to shed light on developmental continuity in implicit mental rotation processes. We studied 4-year-olds given that children do not appear to exhibit analog mental rotation processes when administered explicit tasks until at least 5 years of age (Frick et al., 2014), meaning that children in this age range are thought to possess limited mental rotation capacities. However, relative to younger children, 4-year-olds do perform at above chance levels on simplified mental transformation tasks (e.g., Levine et al., 1999), allowing us to correlate their implicit and explicit mental transformation performance. As in Study 1, 4-year-olds also completed an explicit measure of mental rotation performance, namely the Children's Mental Transformation Task (CMTT; Levine et al., 1999). This explicit task was chosen because it is the most commonly used measure of mental transformation abilities in preschool-aged children and is often considered a simplified measure of basic mental rotation skills in this age range (see Lauer et al., 2019). Moreover, children's performance on implicit mental rotation measures administered in infancy relates to their CMTT performance at 4 years of age (Lauer & Lourenco, 2016), suggesting that the CMTT may tap similar underlying mental processes as implicit mental rotation tasks.

The experimental approach of the present research allowed us to address a number of open questions. First, administering the Spatial Oddball Task to 4-year-olds allowed us to determine whether analog mental rotation processes are detectable in preschool-aged children when measured via implicit paradigms, shedding light on the age-related discrepancies previously observed in the mental rotation abilities of infants and preschool-aged children. Beyond addressing these discrepancies, our study design provided the opportunity to examine developmental continuity and discontinuity in analog mental rotation processes (and gender differences therein) beyond early childhood by directly comparing the mental rotation performance of young children and adults using the same experimental paradigm and identical testing procedures. This direct developmental comparison will contribute insight into the developmental emergence and trajectory of mental rotation processes between early childhood and adulthood. Furthermore, the Spatial Oddball Task developed for the present study provided us with the novel opportunity to explore whether implicit mental rotation tasks recruit the same underlying mental processes as explicit mental rotation tasks at multiple developmental time points. Thus, this work has the potential to shed light on the nature of spatial processes elicited by implicit mental rotation measures across development.

Study 1

Method

Participants

Participants were 51 undergraduate students (29 female, 22 male) between 18 and 29 years of age (*M* = 19.64 y, *SD* = 1.84 y) who attended a private university in the southeastern United States. Participants were recruited to participate in the study through an undergraduate participant pool and received course credit for their participation. At the beginning of the testing session, participants provided written informed consent and completed a brief demographics questionnaire that asked them to identify their sex, race, and ethnicity. This questionnaire indicated that participants were primarily Asian (45%) or White/Caucasian (41%), with a minority of participants identifying as Black/African-American (5%) or biracial (4%); 2 additional participants did not report their race. 13% of participants also identified as Hispanic and/or Latinx (13%). The Emory Institutional Review Board approved all study procedures.

Stimuli and Procedure

Participants visited the lab for a 30-minute testing session conducted by one of two female experimenters, including the author. After completing the consent process and the brief demographics questionnaire, participants were asked to complete two tasks (order counterbalanced across participants). The first task was the passive-viewing Spatial Oddball Task designed to assess implicit mental rotation processes, which was administered on a Tobii T120 eye-tracker. This task required approximately 10 minutes to complete. The second task was the redrawn Vandenberg Mental Rotation Task (MRT) published by Peters and colleagues (1995). This task required approximately 12 minutes to complete. Both tasks are described in greater detail below.

Implicit mental rotation measure. Participants were presented with a Spatial Oddball Task designed to elicit mental rotation processes. The Spatial Oddball Task created for our study was designed to assess whether participants' ability to discriminate between expected and unexpected orientations in a rotating stimulus varied as a function of the angular disparity between these two types of rotation (see Figure 1). In the task, adults were presented with four to six adaptation trials during which a single stimulus appeared in different orientations around the picture plane, constrained to an arc of 180°. Each trial lasted for 2000 ms. The inter-trial interval consisted of a blank screen with a central fixation cross, which was presented for a duration of 750 to 1750 ms (duration jittered). Following each adaptation sequence, participants were presented with a single test trial. For each test trial, the stimulus was presented in an orientation that was unexpected given its previous 180° rotational trajectory. The degree to which the test stimulus differed from the expected rotational trajectory varied across three disparity conditions, with the test stimulus differing by an average of 15°, 45°, and 75°.

The Spatial Oddball Task was administered on a Tobii T120 eye-tracker with a 17 in screen. Prior to beginning the task, participants completed a 9-point calibration sequence provided by Tobii Studio (*v*. 3.4.8). Before the task began, participants were told that they would watch short videos (< 60s) of a shape and that they should attend to the screen throughout the duration of each video. In total, participants were presented with 8 videos corresponding to 8 unique test blocks, which consisted of 3 adaptation and test sequences each, resulting in a total of 8 trials per disparity condition. Each test block lasted approximately 40 s. Prior to the beginning of each adaptation sequence, a central audiovisual attractor was presented on the screen to orient participants' attention towards the screen. Participants were given brief breaks in between blocks to rest their eyes, and participants were reminded at this time to attend to the stimuli on screen as much as possible. The order of test blocks was randomized across participants.

To assess changes in participants' pupillary responses between expected and unexpected orientations, we first computed participants' mean pupil size across each 2000 ms trial. Then, we compared mean pupil size on each test trial to the mean pupil size on the adaptation trial that immediately preceded it (hereby referred to as the "control" trial). For each participant, we then averaged their mean pupil size across all test trials and across control trials for each disparity condition. We also calculated the percent change in pupil size between the test and control trial means for each disparity condition [% change in pupil size = (*M* pupil size during test trial/*M* pupil size during control trial) – 1], allowing for further comparisons of the effects of condition on performance.

In addition to the 51 adults in the current sample, 5 other adults were recruited to participate in the study but were ultimately excluded from analyses due to poor data quality. To be included in the present study, participants must have exhibited adequate looking, which we defined as mean looking times greater than 500 ms across the 8 trials for each combination of the 3 disparity conditions and 2 trial types. Only five potential participants provided looking time data that did not reach this criterion, suggesting that most participants were able to maintain attention throughout the testing session.

Explicit mental rotation measure. Participants completed 24 items of the Vandenberg Mental Rotation Task (MRT; Peters et al., 1995). In this task, participants are presented with a figure containing a 3-dimensional target stimulus alongside four response options. Two of the response options depict the same object as the one presented in the target figure, rotated to a different orientation in 3-dimensional space. The other two response options depict the mirrored image of the object in the target figure, also rotated to a different orientation. Participants are asked to mark the two response options that depict the same object as shown in the target figure. The task was administered according to standard procedures. Specifically, participants first completed four practice items with corrective feedback. Then they were given 5 min to complete 12 test items with no feedback; participants were aware of the time limit. After the first 12 test items, participants were given a short break before they were asked to complete another 12 test items, again with no feedback and with a time limit of 5 min. Test items were scored such that participants were required to identify both of the correct response options to receive 1 point for the item. Thus, all participants could receive a maximum score of 24 on the MRT. A reliability analysis indicated that the test yielded high reliability within our sample (Gutmann's λ = .95).

Analytic Approach

In an initial analysis on adults' pupillary responses during the implicit mental rotation task, we found that adults' mean pupil sizes across control trials did not vary by disparity condition [$F(2, 100) = 1.99$, $p = .147$], indicating that control trials were suitable as a baseline measure of adults' pupillary responses to an expected rotation of the stimulus. Thus, we calculated the mean percent change in pupil size between test and control trials [% change in pupil size = 100*(*M* pupil size during test trial/*M* pupil size during control trial) – 1)] for use as the dependent variable in all further analyses. Specifically, we first examined whether adults' pupillary responses varied by disparity condition and as a function of gender via analyses of variance. Then, we examined the association between performance on the Spatial Oddball Task and explicit mental rotation task performance, again considering the potential effect of gender on this relation.

Results

To address two of the central questions of the current research, we conducted a mixed-model ANOVA with disparity condition (*15°*, *45°*, *75°*) as a within-subjects factor and gender (*female*, *male*) as a between-subjects factor. As shown in Figure 2, the relation between the mean percent change in pupil size and disparity condition varied significantly by gender (see Table 1 for statistics). Post-hoc polynomial contrasts revealed a significant linear component that also varied by gender [$F(1, 49) = 5.51$, $p = .023$, $\eta^2_p = 0.10$], such that the linear relation between mean percent change in pupil size and disparity condition was significantly greater for males (η^2_p = 0.16) than for females (η^2_p = 0.04; Figure 2).

We next calculated the slope of the relation between disparity condition and the corresponding percent change in pupil size for each participant to quantify the linearity of the relation between angular disparity and the outcome measure using a single continuous measure. As expected given the results presented above, the slope of this relation differed by gender: $t(49) = -2.35$, $p = .023$, $d = -0.66$. For male participants, this slope was significantly greater than 0 on average [M percent change in pupil size = 0.99%, SD = 2.30%; $t(21) = -2.08$, $p = .029$], suggesting that men exhibited greater pupil dilation in response to greater angular disparities, as would be expected if the Spatial Oddball Task evoked mental rotation processes. In contrast, slopes did not differ significantly from 0 for female participants [M percent change in pupil size = -0.33%, SD = 1.71%; $t(28) = -1.06$, $p = .149$]. Together, these results indicate that men, but not women, displayed pupillary response patterns consistent with analog mental rotation processes (i.e., a linear relation between angular disparity and change in pupil size).

In addition to the significant gender difference in slope on the Spatial Oddball Task, we found the expected male advantage in participants' performance on the explicit mental rotation task: $t(49) = -4.15$, $p < .001$, $d = -1.17$ (see Figure 3). Thus, the gender difference in mental rotation was present when measured by both implicit and explicit task performance in adulthood.

Next, we directly examined whether performance on the implicit Spatial Oddball Task was associated with explicit mental rotation task performance. Participants' slopes on the Spatial Oddball Task were positively correlated with their explicit mental rotation performance in the expected direction [$r(49) = .27$, $p = .051$], such that the greater the relation between angular disparity and participants' percent change in pupil size, the higher their explicit mental rotation performance (see Figure 4). Despite the significant gender difference in slope, the magnitude of the positive correlation between slope and explicit mental rotation task performance did not differ by gender (Fisher's $Z = -0.83$, $p = .407$), suggesting that participants with greater slopes tended to have higher explicit mental rotation performance regardless of their gender.

Summary and Discussion

The findings detailed above suggest that implicit mental rotation processes, as measured by the Spatial Oddball Task, may display similar properties to the analog mental rotation processes evoked by explicit mental rotation tasks in adulthood. That is, there was a linear relation between angular disparity and percent change in pupil size that was congruent with analog mental rotation processes among male participants, but not female participants. This gender difference paralleled the male advantage in participants' performance on the explicit mental rotation measure, a male advantage that would be expected given previous findings of a robust male advantage in adults' performance on standard mental rotation tasks (Voyer et al., 1995). Together, these findings validate the Spatial Oddball Task as an implicit, indirect measure of analog mental rotation processes in adulthood and indicate that such processes relate to both within- and between-gender variability in adults' explicit mental rotation task performance.

Study 2

After validating our Spatial Oddball Task in our study of adults, we next used this task to address questions regarding the development of analog mental rotation processes during early childhood. In Study 2, we administered the Spatial Oddball Task to a sample of 4-year-olds, taking an identical experimental approach to assessing implicit mental rotation task performance as taken in Study 1. Using the same procedure to examine implicit mental rotation performance in adults (Study 1) and 4-year-olds (Study 2) allowed for the direct comparison of mental rotation processes between early childhood and adulthood, a developmental comparison not yet available in the extant literature. Therefore, the results of Study 1 and Study 2 provide us with the first opportunity to examine developmental continuity in analog mental rotation processes when assessed via the same mental rotation measure across disparate developmental time points.

In Study 1, we found a gender difference in adults' performance on our Spatial Oddball Task as well as a standard explicit mental rotation task, consistent with the male advantage in mental rotation that is well established in adulthood (Voyer et al., 1995). In Study 2, we explored the potential origins of this male advantage by examining whether either mental rotation task produced gender differences in 4-year-olds' performance. Recent meta-analytic findings suggest that explicit mental rotation tasks do not yield a reliable male advantage in performance until middle childhood (Lauer et al., 2019). Yet some studies have documented gender differences in infants' performance on looking-time tasks designed to assess mental rotation skills (e.g., Lauer et al., 2015; Moore & Johnson, 2008; Quinn & Liben, 2008), introducing the possibility that implicit mental rotation measures may be better suited for detecting gender differences in early childhood (for discussion, see Lauer et al., 2019). Administering both an implicit and explicit mental rotation task to 4-year-olds in Study 2 allowed us to address this possibility, advancing our understanding of the developmental trajectory of the male advantage in mental rotation.

Lastly, as in our study of adults, we also investigated the relations between 4-year-olds' Spatial Oddball Task performance and their explicit mental rotation abilities. Prior research on explicit mental rotation abilities during early childhood has commonly relied on tasks that require 4-year-olds to discriminate between rotated mirrored objects, as in Marmor's (1975; 1977) seminal work on this topic. However, preschool-aged children often display chance levels of performance on such tasks until 5 years of age, calling into question whether they truly possess a limited capacity for engaging in mental rotation or instead struggle with mirror discrimination (cf. Frick et al., 2014), as summarized in the Introduction. To circumvent this issue, we assessed 4-year-olds' mental rotation performance with the Children's Mental Transformation Task (CMTT; Levine et al., 1999), a spatial measure that does not require mirror discrimination and that is widely used as an age-appropriate measure of young children's mental rotation abilities (see Lauer et al., 2019). In addition to the CMTT, we also administered other cognitive assessments to 4-year-olds to evaluate other aspects of their cognitive functioning, including spatial working memory, verbal ability, and math achievement. These additional cognitive assessments allowed us to address the extent to which the implicit Spatial Oddball Task tapped cognitive processes that were specific to mental rotation ability or whether individual differences in Spatial Oddball Task performance were rather driven by more general cognitive capacities, such as spatial working memory or general intelligence. Finally, we included a math achievement measure in our cognitive assessment battery at age 4 given the well-established relation between mental rotation and math performance that has been documented across development (for review, see Mix & Cheng, 2012). Moreover, Lauer and Lourenco (2016) found that infants' looking behavior during an implicit mental rotation task uniquely predicted their later performance on a symbolic math task at age 4, suggesting that individual differences in implicit mental rotation task performance could continue to account for individual differences in math competence later in development. To address this possibility, we contemporaneously measured children's implicit mental rotation performance via our Spatial Oddball Task and their symbolic math ability at age 4.

Method

Participants

Forty-nine children (27 female, 22 male) participated in a single session study at 4 years of age (M = 4.41 y, SD = 0.31 y). The sample was recruited via an existing database containing contact information for families who previously expressed interest in participating in child development research. Parents reported their children's racial backgrounds as White/Caucasian (60%), biracial (21%), Black/African-American (15%), and Asian (4%). In addition, 10% of parents also identified their children as being Hispanic or Latinx. Parents reported that their children's primary caregivers were highly educated: 52% possessed a graduate degree, 44% possessed a Bachelor's degree, and the remaining 4% had completed at least some college coursework.

Parents provided written informed consent on behalf of their children before testing. At the end of the testing session, participants were given a $5 gift card and a small toy as a token of appreciation. The Emory Institutional Review Board approved all procedures.

Stimuli and Procedure

Children completed a 1-hr testing session. All children were tested by one of two female experimenters, including the author. During the testing session, children completed the Spatial Oddball Task presented in Study 1 and five age-appropriate explicit tasks used to measure different aspects of spatial reasoning (i.e., mental transformation ability, spatial working memory), symbolic math ability, and general cognitive abilities (i.e., verbal working memory, vocabulary).

Implicit measure. Participants were presented with the Spatial Oddball Task using the exact materials and procedure as described in Study 1. Children completed the Spatial Oddball Task either at the beginning of the testing session, prior to completing any explicit tasks, or at the end of the testing session, after completing all 5 of the explicit tasks. Children were required to complete the Spatial Oddball Task to be included in our analyses. In addition to the 49 children reported in the current paper, another 9 children participated in the study but were unable to complete the Spatial Oddball Task due to fatigue at the end of the testing session. These children were not considered in any of the analyses reported in this paper.

Explicit measures. Explicit tasks included subtests from a standardized cognitive assessment battery, namely the Woodcock Johnson (WJ) Tests of Achievement and Cognitive Abilities-III (Woodcock, McGrew, & Mather, 2001), and experimenter-designed measures. Both of the explicit spatial tasks were created using custom Visual Basic scripts (Microsoft) and administered on a touchscreen computer (58 cm diagonal). Children sat approximately 30 cm from the computer screen. For ease of administration, a fixed order of tasks was used such that tasks requiring similar testing materials were administered consecutively, with computerized tasks following paper-based tasks (see Table 2 for task order). Tasks were administered in the following order: vocabulary (WJ-Picture Vocabulary), symbolic math ability (WJ-Applied Problems), verbal working memory (WJ-Numbers Reversed), mental transformation ability (the Children's Mental Transformation Task; Levine et al., 1999), and an experimenter-designed spatial working memory task. Children were given stickers between tasks to maintain interest.

Explicit spatial tasks. Children completed a computerized version of the Children's Mental Transformation Task (CMTT; Levine et al., 1999), a widely used measure of mental rotation skills in preschool-aged children. Children also completed an experimenter-designed measure of spatial working memory, as described below.

CMTT. At the beginning of this task, children were presented with two training trials and received corrective feedback on their performance. Children then completed 16 test trials, presented in a randomized order, during which they received no feedback. On each trial, children were directed to look at a 2-dimensional target shape that had been divided symmetrically along the vertical axis, creating two separate pieces of the target shape. A 2 × 2 array of response options, one of which corresponded to the target shape, was also shown directly below the two pieces of the target shape. Children were asked to touch the response option that corresponded to the shape that would be formed by moving the two target pieces together. For half of the 16 test items, the target pieces were separated and translated along the vertical and/or the horizontal axis, and in the other half of the test items, the target pieces were rotated 60° from the vertical axis and translated vertically and/or horizontally.

The experimenter initiated each trial, and children responded by touching one of the response options. Their response accuracy was recorded, and the sum of the number of items answered correctly was used to evaluate a given child's task performance.

Location Working Memory Task. Children completed the Location Working Memory Task, designed to assess their spatial working memory. This task was modeled after the standard Corsi-Backwards assessment but modified for administration to 4-year-olds. In this task, children were presented with four closed doors on a touchscreen computer. The doors were shown randomly located within a 6 in × 4 in rectangle. At the beginning of each trial, two doors opened to reveal a picture of an animated dog for 1000 ms. The doors opened in a sequential order such that only one door was open at a time. Children were instructed to touch the doors that opened in backwards order. Children completed 3 practice trials with corrective feedback and then 8 test trails without corrective feedback. Given the age and limited working memory capacities of our participants, only two doors opened during each trial. Performance was evaluated by summing the number of trials in which children touched the doors that opened in the correct backwards order from which they were presented (max score = 8).

Other explicit tasks. Children completed three standardized assessments designed to assess general, verbal, and mathematical abilities. These measures were subtests of the

Woodcock et al. (2001) Tests of Achievement and Cognitive Abilities-III and were administered according to standard protocols. First, children completed WJ-Picture Vocabulary, an expressive vocabulary task in which children are presented with drawings of various objects and asked the object's name. Then, children completed the WJ-Applied Problems, a measure of symbolic math abilities (e.g., counting, basic arithmetic). Finally, children completed the WJ-Numbers Reversed, a standard assessment of verbal working memory.

Analytic Approach

In this study, we adopted the same analytic approach as in Study 1, allowing us to directly compare patterns of Spatial Oddball Task performance and their correlates in 4-year-olds and adults. In a preliminary analysis, we first ensured that 4-year-olds' pupillary responses during control trials did not vary by disparity condition [$F(2, 96) = 0.20$, $p = .818$], indicating that control trials served as an adequate baseline measure of children's pupillary responses to an expected rotation of the stimulus. As in Study 1, we computed the mean percent change in pupil size between test and control trials [% change in pupil size = ((*M* pupil size during test trial/*M* pupil size during control trial) – 1)*100] for use as the dependent variable in all analyses reported below. Then, we examined the relation between disparity condition and percent change in pupil size as a function of gender to determine if children display the same pattern of pupillary responses during the Spatial Oddball Task as were observed in adults in Study 1, and if so, if this pattern varies between girls and boys. Next, we analyzed the association between children's performance on the Spatial Oddball Task and their performance on the CMTT, an explicit measure of mental rotation ability, as well as their performance on explicit measures of other cognitive skills (e.g., spatial working memory, symbolic math).

Results

We first conducted a mixed-model ANOVA, with disparity condition (*15°*, *45°*, *75°*) as a within-subjects factor and gender (*female*, *male*) as a between-subjects factor. As shown in Table 3 below, the relation between the mean percent change in pupil size and disparity condition varied significantly by gender, as observed in adults in Study 1. Post-hoc polynomial contrasts revealed a significant linear component that also varied by gender [$F(1, 47) = 8.45$, $p = .006$, $\eta^2_p = 0.15$]. Similar to the findings of Study 1, the linear relation between mean percent change in pupil size and disparity condition was significantly larger for males ($\eta^2_p = 0.11$) than for females ($\eta^2_p = 0.08$; see Figure 5). These results suggest that boys exhibited greater pupil dilation in response to larger angular disparities in comparison to girls.

We next calculated the slope of the linear relation between disparity condition and percent change in pupil size for each participant. Paralleling the gender differences observed in adulthood, the slope of this relation differed by gender [$t(47) = -2.95$, $p = .005$, $d = -0.85$], with boys displaying significantly greater slopes ($M = 1.30\%$, $SD = 3.20\%$) than girls ($M = -1.20\%$, $SD = 2.70\%$). These results suggest that boys exhibited greater pupil dilation in response to greater angular disparities in comparison to girls, mirroring the gender differences previously found in adulthood (see Figure 6). In combination with findings from Study 1, these results indicate that pupillary responses during the Spatial Oddball Task are more consistent with analog mental rotation processes among males than among females across development.

In Study 1, we found that the significant gender difference in adults' slopes on the Spatial Oddball Task corresponded to a male advantage in their performance on the explicit mental rotation task. Thus, we next examined whether 4-year-olds' displayed a gender difference in their explicit mental rotation performance, as measured by the CMTT. As reported in Table 4, girls and boys performed similarly on the CMTT [$t(47) = 0.28$, $p = .257$, $d = 0.08$]. In fact, the only gender difference found at 4 years of age on any task was in boys' relatively greater slopes on the Spatial Oddball Task (Table 4). These results introduce the possibility that even though a male advantage in implicit mental rotation performance showed continuity across the two developmental time points we examined, this gender difference may only relate to a male advantage in explicit mental rotation performance during adulthood.

Why did 4-year-olds exhibit gender differences in their slopes on the Spatial Oddball Task but no gender difference in their explicit mental rotation task performance? One possibility is that children's explicit mental rotation performance may not rely on the same cognitive processes as those recruited during the Spatial Oddball Task. To evaluate this possibility, we examined the relation between participants' slopes on the Spatial Oddball Task and their performance on the explicit measure of mental rotation ability (i.e., the CMTT). As in adulthood, Spatial Oddball Task slopes were positively associated with explicit mental rotation task performance [$r(47) = .33$, $p = .021$; Figure 7) That is, children whose pupillary responses were consistent with engaging in analog mental rotation (i.e., greater pupil dilation in response to larger angular disparities) displayed higher explicit mental rotation performance relative to their peers. A Fisher's r-to-z test indicated that the magnitude of the correlation between Spatial Oddball Task slope and explicit mental rotation performance did not differ between girls ($r = .46$) and boys ($r = .22$); $Z = -0.89$, $p = .374$. Therefore, regardless of gender, the greater the relation between disparity condition and percent change in pupil size, the higher children's explicit mental rotation performance.

Finally, in a set of exploratory analyses, we considered whether 4-year-olds' performance on the implicit mental rotation task displayed specificity in its association with their explicit mental rotation performance. At the zero-order level, children's slopes on the Spatial Oddball Task were significantly related to their explicit mental rotation scores and to their symbolic math task performance (see Table 5), but not to their performance on any other measure of cognitive functioning (Table 5). These results parallel the longitudinal findings of Lauer and Lourenco (2016), who reported that individual differences in infants' performance on an implicit mental rotation task was associated with individual differences in their later performance on explicit mental rotation and symbolic math tasks at preschool age.

We next examined whether individual differences in children's implicit mental rotation performance continued to be uniquely related to their explicit mental rotation performance when measured concurrently during the preschool years. These analyses were aimed at characterizing the specificity of individual differences in children's implicit Spatial Oddball Task, addressing whether individual differences in implicit performance were uniquely attributable to children's mental rotation abilities (as measured by a standard, explicit mental rotation task) or instead were reflected inter-individual variability in more general cognitive processes recruited for both implicit and explicit mental rotation tasks (e.g., spatial working memory). To this end, we conducted a regression analysis with explicit mental rotation, spatial working memory, verbal working memory, and vocabulary performance as predictors of Spatial Oddball Task slope. Gender was also included as a covariate in the regression analysis given its significant relation to Spatial Oddball Task performance. All four of the explicit cognitive assessments administered to children were included as predictors of implicit Spatial Oddball Task performance in the same model because doing so represented the most stringent test for examining specificity in the relation between implicit and explicit mental rotation performance. Although including four predictor variables in the same regression model reduced our power to detect significant effects, we opted to take this conservative approach in order to ensure that we adequately controlled for individual differences in general cognitive abilities (e.g., working memory) that could have produced an apparent relation between implicit and explicit mental rotation performance.

The results of this regression are presented in Table 6. As shown in the table, explicit mental rotation performance was positively, but not significantly, related to Spatial Oddball Task slope (p = .079) when controlling for our measures of general cognitive ability. Children's performance on the remaining cognitive tasks did not relate to Spatial Oddball Task slope (see Table 6). These results demonstrate that individual differences in children's performance on the Spatial Oddball Task could not be accounted for by domain-general cognitive capacities or spatial working memory, and they leave open the possibility that they are instead driven specifically by individual differences in children's mental rotation skills. Conducting this regression analysis with a large sample of participants in the future will provide greater power for detecting significant effects and thus will have the potential to elucidate the specificity of the relation between implicit and explicit mental rotation performance.

Summary and Discussion

The results of Study 2 indicate that preschool-aged children's performance on our implicit Spatial Oddball Task was consistent with the task eliciting analog mental rotation processes. Specifically, we found that there was a linear relation between angular disparity and percent change in pupil size, a pattern congruent with analog mental rotation processes. As in adulthood, the linear effect of disparity condition on pupillary responses was greater for boys than for girls, and greater linearity was associated with explicit mental rotation task performance. However, unlike in Study 1, female and male participants performed similarly on the explicit mental rotation task at 4 years of age, in line with the findings of Lauer and colleagues' (2019) meta-analysis indicating that the male advantage in explicit mental rotation task performance does not emerge until middle childhood. With the findings of Study 1, these results suggest that the Spatial Oddball Task may similarly elicit implicit analog mental rotation processes in early childhood and adulthood.

General Discussion

The present study is the first to use an implicit pupillometry measure to directly compare analog mental rotation processes in young children and adults. Validating our novel adaptation of the oddball paradigm, our results were consistent with the Spatial Oddball Task eliciting analog mental rotation processes in adulthood, as adults' pupillary responses varied by disparity condition, particularly among male participants and participants with higher explicit mental rotation abilities. Our findings also indicated that the Spatial Oddball Task may elicit similar analog mental rotation processes in preschool-aged children, who displayed similar pupillary response patterns as adults across disparity conditions and between genders. Thus, our results demonstrate developmental continuity in analog mental rotation processes, as assessed via an implicit pupillometry measure, between early childhood and adulthood and suggest that similar underlying processes may be recruited when completing implicit and explicit mental rotation tasks across development. Despite some evidence of developmental continuity, we also found that the male advantage in explicit mental rotation task performance was not consistent between our two age groups. These findings indicate some degree of discontinuity in the relations between implicit and explicit task performance across the two developmental time points examined, as gender differences in 4-year-olds' implicit Spatial Oddball Task performance did not map onto a male advantage in their explicit mental rotation performance. Below, we discuss these findings within the context of prior research and offer recommendations for future research.

Similar to our findings in adulthood, 4-year-olds' pupillary responses were consistent with engaging in analog mental rotation processes, particular among boys. This significant effect of disparity condition on children's pupillary responses was more pronounced for participants who showed greater performance on the explicit mental rotation measure relative to their peers, congruent with the results observed in adulthood. Previous studies have reported that 4-year-olds' display chance-level performance on explicit measures of analog mental rotation processes that require children to discriminate between rotated mirrored images (e.g., Frick et al., 2013; Hawes et al., 2015), unlike the mental transformation task administered in the current research. Our results suggest that 4-year-olds' poor performance on explicit measures requiring the discrimination of rotated mirror images may be due to the challenging nature of the explicit task instructions (cf. Frick et al., 2014), rather than the absence of analog mental rotation processes in this age group. Therefore, the apparent age-related discrepancies in infants' performance on implicit mental rotation measures and preschool-aged children's performance on explicit measures of analog mental rotation processes are likely attributable to differences in the paradigms used to assess these abilities across these two time points. Future research examining infants' performance on the Spatial Oddball Task would allow us to directly assess the possibility.

Our findings were largely consistent with developmental continuity in the presence of analog mental rotation processes between early childhood and adulthood and in the relation between implicit and explicit mental rotation task performance. However, there was one notable difference in the pattern of findings between Study 1 and Study 2. In adulthood, we found significant effects of gender on implicit Spatial Oddball Task performance ($d = 0.66$) as well as explicit mental rotation task performance ($d = 1.17$), consistent with the robust male advantage previously documented in the prior literature (*d*s ~ 0.59-1.25; Linn & Petersen, 1985; Maeda & Yoon, 2013; Voyer et al., 1995). In line with these results, we also found that gender moderated the effect of disparity condition on 4-year-olds' Spatial Oddball Task performance ($d = 0.85$), such that boys' pupillary responses across disparity conditions were more consistent with analog mental rotation processes than were girls'. However, we found no gender difference in 4-year-olds' explicit mental rotation task performance ($d = -0.03$), as would be expected previous studies examining gender differences in young children's explicit mental rotation performance (for meta-analysis, see Lauer et al., 2019). These results may indicate that implicit mental rotation tasks are better suited for detecting gender differences in young children's mental rotation performance, as posited by Lauer and colleagues (2019). Alternatively, it is possible that the explicit mental rotation task administered to 4-year-olds was more easily solved via spatial strategies that do not require mental rotation (such as feature matching), allowing children to achieve high performance on the task through multiple means. Future research administering the Spatial Oddball Task to slightly older children, who exhibit greater performance on explicit mental rotation tasks requiring mirror discrimination, could therefore be useful in documenting the age at which gender differences in implicit task performance first map on to a male advantage in explicit performance. Similarly, research administering the Spatial Oddball Task to children younger than 4 years of age would have the potential to inform the developmental trajectory of the male advantage in mental rotation abilities.

To conclude, the present research introduced a novel implicit measure for assessing developmentally continuous analog mental rotation processes across disparate periods of development. The current studies represent the first attempt at using an implicit pupillometry measure to directly compare mental rotation abilities between early childhood and adulthood, finding substantial similarities in the implicit task performance of 4-year-olds and adults as well as its relation to participants' explicit mental rotation skills. Lastly, our results provide initial evidence that gender differences in implicit mental rotation processing may be present by preschool age and persist throughout development, suggesting that the well-established male advantage in explicit mental rotation task performance observed in adulthood may have origins in early-emerging mental rotation processes.

Paper 2

Spatial transformation processes in infancy

Abstract

The present study examined spatial processing and its correlates in 61 infants between 6 and 12 months of age. Infants were presented with two change-detection tasks designed to assess different facets of spatial processing, namely early mental rotation processing and spatial short-term memory. One of these tasks, the Rotation Change-Detection Task, was modeled after the standard forced-choice mental rotation paradigm developed by Shepard and Metzler (1971) to examine mental transformation processes in adulthood. The Rotation Change-Detection Task designed for the present study specifically assessed infants' ability to discriminate between a two-dimensional, Tetris-like shape and its rotated mirrored image as a function of the angular disparity between the non-mirrored and mirrored versions of the shape, providing an implicit measure of mental rotation processes. In addition, infants were presented with the Location Change-Detection Task developed by Oakes and colleagues (2011) to evaluate their spatial short-term memory. Performance on the Rotation Change-Detection Task indicated that infants successfully discriminated between a shape and its rotated mirrored image, but only when the angular disparity between the two stimuli was minimal. Infants' Rotation Change-Detection Task performance was not correlated with their Location Change-Detection Task performance, suggesting that individual differences in infants' spatial rotation processing may not depend upon spatial short-term memory capacity within the age range tested. Lastly, infants' performance on the two spatial change-detection tasks did not vary by gender, age, or motor experience. These findings are consistent with the possibility that implicit mental rotation tasks elicit analog mental representations of spatial rotation in infancy, but highlight the need for future research that characterizes these early spatial processes and their correlates during the first year of life.

Keywords: mental rotation, spatial reasoning, infancy, short-term memory

Spatial transformation processes in infancy

The ability to generate and transform mental representations of objects and spatial layouts is a critical component of human intelligence (Carroll, 1993) that is essential for many of our most mundane activities as well as more complex problem-solving. For example, we rely on our ability to transform mental representations of objects to predict their potential future locations and orientations within our environments, facilitating navigation and tool use. Moreover, mental transformation abilities appear to scaffold abstract reasoning in a number of academic domains, including science, technology, engineering, and math (STEM) fields (for reviews, see Mix & Cheng, 2012; Uttal & Cohen, 2013). Given the importance of mental transformation in both curricular and extracurricular contexts, these spatial abilities have garnered significant interest among cognitive psychologists and have been extensively studied in adulthood. However, less is known about the developmental emergence and trajectory of these abilities during the first years of life. The current study sought to address this gap in the literature by characterizing mental rotation processes in infancy.

In adulthood, mental transformation abilities are most commonly studied through the use of mental rotation tasks, which require participants to imagine two 3-dimensional figures rotating into alignment in mental space. The two figures either depict the same object rotated to two different orientations in space or depict an object and its mirrored image, also rotated to two different orientations. Participants must determine whether the two figures contain the exact same object or two different objects (i.e., an object and its mirrored image). In seminal work on this topic, Shepard and colleagues reported that adult participants' mean response times varied as a function of the angular disparity between the two figures (e.g., Shepard & Cooper, 1986; Shepard & Metzler, 1971). These results demonstrated that the rotation of objects in 'mental space' adheres to the same spatiotemporal constraints as the rotation of objects in physical space, providing evidence of mental analog to the perception of spatial rotation. Subsequent research confirmed that the linear relation between angular disparity and mental rotation performance, the "signature" of mental rotation, is highly robust, and can be elicited across diverse paradigms with differing measures of performance in adulthood (e.g., response times, accuracy, subjective rating of task difficulty; see e.g., Shepard & Cooper, 1986). Despite clear evidence of analog mental rotation processes in adults, we do not yet known when these processes first manifest during development (Frick et al., 2014).

Accumulating evidence suggests that mental rotation processes akin to those observed in adulthood may first emerge in infancy. Specifically, research using looking-time paradigms to assess infant spatial processing has demonstrated that infants are sensitive to mirror reversals in the shape of a rotating figure (e.g., Frick & Möhring, 2013; Möhring & Frick, 2013; Schwarzer, Freitag, Buckel, & Lofruthe, 2013), suggesting that infants discriminate between objects and their rotated mirrored images. Given that discriminating between rotated mirrored objects is a key component of mental rotation tasks administered to adults (e.g., Shepard & Metzler, 1971), these findings have been taken as evidence that infants may possess rudimentary mental rotation abilities. In support of this contention, infants' ability to discriminate between rotated mirrored images, as measured by their looking behavior on an implicit spatial change-detection task (Lauer et al., 2015), has been shown to predict their later performance on an explicit spatial reasoning task at 4 years of age (Lauer & Lourenco, 2016). These longitudinal results indicate that looking-time paradigms may assess precursory mental transformation abilities that represent the developmental origins of mental rotation skills observed later in development. In line with this possibility, some studies have reported a gender difference in infants' performance on looking-time tasks designed to elicit mental rotation processes (Lauer et al., 2015; Moore & Johnson, 2008; 2011; Quinn & Liben, 2008; 2014), and this gender difference parallels the well-established male advantage in mental rotation performance found on explicit tasks administered to older children and adults (Lauer et al., 2019; Voyer, Voyer, & Bryden, 1995). Furthermore, some recent studies have found a link between infants' motor development and their performance on implicit mental rotation tasks (e.g., Gerhard & Schwarzer, 2016; Schwarzer et al., 2013), mirroring the association between motor processes and mental rotation performance that has been observed later in development (e.g., Funk, Brugger, & Wilkening, 2005; Wexler, Kosslyn, & Berthoz, 1998). Together, these findings provide promising evidence that spatial processes present in infancy could serve as developmental precursors to later mental rotation skills. However, a more in-depth exploration of the infant spatial literature brings attention to several findings that are incongruent with this assumption, as detailed in the following section.

Review of Infant Mental Rotation Literature

Hespos and Rochat (1997) were the first to provide putative evidence of early mental transformation processes in infancy (see also Rochat & Hespos, 1996). In a series of experiments, the authors utilized a violation-of-expectation paradigm to examine 4- to 8-month-olds' expectations regarding the rotational movement of a T-shaped object. During each trial, the T-shaped object rotated 180° from the top to the bottom of a screen, except for a brief period in which the object was occluded from the view of the infant. When the object emerged after occlusion, it appeared either in an orientation that was expected given its previous rotational trajectory or in an orientation that was unexpected given its trajectory (i.e., the mirrored image of the object in its expected orientation). Infants exhibited longer looking to the object when it was presented in its unexpected, mirrored orientation than when it was presented in its expected, non-mirrored orientation. These results revealed that infants formed predictions about the future orientation of a rotating object, suggesting that rudimentary mental transformation processes emerge in infancy. Subsequent findings have provided some support for this conjecture, with a number of studies reporting that infants' performance on implicit mental rotation tasks varies according to different factors that are known to moderate adults' mental rotation abilities (e.g., gender; Voyer et al., 1995). However, subsequent studies have also left open a number of questions regarding the extent to which spatial processes elicited by infant mental rotation tasks exhibit similar properties as those recruited for explicit mental rotation tasks in adulthood.

Initial evidence of analog mental rotation processes in infancy. In assessing mental rotation processes in infancy, prior research has generally relied on implicit looking-time paradigms modeled after standard explicit mental rotation tasks administered to adults. However, only one published study has investigated the extent to which infants' performance on such tasks parallels response patterns observed during mental rotation tasks in adulthood (i.e., a linear relation between angular disparity and response outcomes). Specifically, Gerhard and Schwazer (2018) administered a habituation task to 9-month-old infants that was modeled after the habituation paradigm developed by Schwarzer and colleagues (2013) to assess infants' mental rotation skills. During the task, infants were first habituated to a 3-dimensional object rotating around an arc of 180°. Then, infants were presented with two types of test trials. In "familiar" test trials, infants viewed the object seen during habituation rotating around a 90° arc. In "novel" test trials, infants also viewed the mirrored image of the habituation object, also rotating around a previously unseen 90° arc. Across two test conditions, the initial orientation of the object's differed from the end of object's arc during habituation by either 0° or 54° (Figure 2). Therefore, this procedure allowed the authors to examine whether infants' ability to discriminate between the non-mirrored and mirrored stimulus following habituation varied as a function of the angular disparity between the habituation and test arcs, similar to the linear relation between angular disparity and adults' response times found on explicit mental rotation tasks.

Gerhard and Schwarzer (2018) found that infants' visual preference for the non-mirrored object relative to the mirrored object differed as a function of test condition: infants showed greater looking to the non-mirrored test stimulus relative to the mirrored test stimulus when there was a 54° disparity between its arc and the arc of the habituation stimulus, but the inverse pattern of looking behavior was observed when there was no difference between the arcs of the test and habituation stimuli. That is, as the angle of rotation required to align the two stimuli increased, infants switched from displaying a novelty preference (i.e., looking longer toward the mirrored habituation stimulus than toward the non-mirrored stimulus) to a familiarity preference (i.e., looking longer toward the non-mirrored habituation stimulus than toward the mirrored habituation stimulus). These results provide initial evidence that infants' ability to discriminate between rotating objects and their mirrored images may depend on the amount of rotation necessary to align the two objects in space, consistent with engaging in mental rotation. However, only two test conditions were used in Gerhard and Schwarzer's work, and it remains unclear whether the transition from a novelty to a familiarity preference across the two conditions reflects increasing or decreasing difficulty across the two conditions. Thus, research with more than two test conditions is the logical next step to evaluating the extent to which infants' looking behavior relies on the angular disparity between a rotating object and its mirrored image.

Relations between motor development and mental rotation in infancy. In addition to significant condition differences, Gerhard and Schwarzer (2018) also reported an effect of crawling experience on infants' mental rotation performance. That is, a significant effect of angular disparity condition on infants' visual preferences at test was only present among infants who were considered "crawlers." These results align with those obtained from other studies examining the relation between infants' performance on implicit mental rotation tasks and their motor development. In particular, two studies conducted by Schwarzer and colleagues (2013a, 2013b) using a similar habituation procedure as Gerhard and Schwarzer reported a relation between infants' self-locomotion experience and their mental rotation performance. Evidence that motor development (e.g., facility with self-locomotion) may be a critical force driving the development of infant spatial processing has been found via other looking time paradigms as well (e.g., Möhring & Frick, 2013). Findings of a link between infants' motor experience and their performance on implicit mental rotation measures provides further evidence that infant looking-time tasks may capture some aspect of spatial processing that exhibits continuity across development given evidence that motor processes are recruited during explicit mental rotation task performance throughout development (e.g., Funk et al., 2005; Wexler et al., 1998; Zacks et al., 2008). Nonetheless, Erdmann and colleagues (2018) recently examined the role of motor development on implicit mental rotation performance in a large, longitudinal sample of infants aged 5 to 9 months, finding no association between motor development and infants' mental rotation performance. These results emphasize the need for further research on the importance of motor development, and particularly self-locomotion, in mental rotation during infancy.

Gender differences in infants' performance on mental rotation tasks. Other studies that have explored the extent of continuity in mental rotation processes have focused on the presence of gender differences in infant mental rotation performance. Explicit mental rotation tasks produce one of the most robust gender differences in cognitive performance in adulthood (Miller & Halpern, 2014). On average, men tend to outperform women on explicit measures of mental rotation abilities (*d* = 0.66; Voyer, Voyer, & Bryden, 1995), a male advantage that emerges by middle childhood (Lauer et al., 2019; Voyer et al., 1995). Interestingly, there is some evidence that infants display a similar gender difference in their performance on various implicit, looking-time tasks designed to assess mental rotation abilities (e.g., Lauer et al., 2015; Moore & Johnson, 2008; Quinn & Liben, 2008). The presence of a male advantage in both infant and adult mental rotation performance supports the contention that the spatial processes tapped by implicit mental rotation tasks in infancy are developmentally continuous across childhood and into adulthood. However, not all studies on infant mental rotation have reported significant gender differences (see Table 7), warranting further consideration of the empirical evidence on this topic.

In the first study to report a gender difference in infant mental rotation performance, Quinn & Liben (2008) examined spatial processing in 3- to 4-month-old infants using a familiarization paradigm. During their task, infants were first familiarized to a pair of 2-dimensional stimuli (i.e., the Arabic numeral "1") presented in multiple orientations rotated around the picture plane. Following familiarization, infants completed two test trials in which one of the pair of stimuli shown were mirrored images of one another (i.e., the number 1 and its mirrored image). Quinn and Liben found that boys exhibited significantly longer looking to the novel, mirrored stimulus relative to the familiar, non-mirrored stimulus during the test trials, suggesting that boys represented the rotational constraints of the stimulus and discriminated between rotated mirrored images, signaling potential mental rotation processes. In contrast, girls displayed no significant visual preference for either stimulus. This gender difference in infants' preferential looking toward the mirrored stimulus amounted to a large male advantage in task performance (*d* = 1.38). In a later study utilizing the same paradigm, Quinn and Liben (2014) replicated these results in infants aged 3 to 10 months, reporting that the gender difference in infants' mental rotation performance was stable in size across the first year of life. These findings coalesce with those obtained via violation-of-expectation paradigms (e.g., Hespos & Rochat, 1997; Möhring & Frick, 2013) to provide converging evidence that infants engage in the mental transformation of objects, and they further suggest that boys may have an advantage in performing this process.

In another study, Lauer and colleagues (2015) employed an alternative looking-time paradigm to examine mental rotation in infancy, namely a spatial change-detection task. Their change-detection task was designed to evaluate whether infants detect mirror reversals in a rotating 2-dimensional shape, an indirect measure of infants' ability to discriminate between objects and their rotated mirror images. During the task, infants were presented with two peripheral image streams. Both image streams contained the same static 2-dimensional shape appearing in different rotations along the picture plane (see Figure 8). The image streams were identical except that in one stream (the "mirror" stream), the shape variably rotated into its mirrored orientation. In the other image stream (the "non-mirror" stream), the shape remained in its non-mirrored orientation throughout each trial. The authors found that 6- to 13-month-old infants looked relatively more toward the mirror stream across trials, indicating that infants detected the unexpected mirror shape in that stream, as would be expected if the task elicited mental rotation processes. Lauer and colleagues also reported that boys displayed greater relative looking to the mirror stream in comparison to girls ($d = 0.50$). These results corroborated those of Quinn and Liben (2008, 2014), indicating that infants not only detected mirror reversals in the orientation of a rotating stimulus but also display gender differences in their tendency to do so.

As described above, previous studies employing the familiarization and change-detection paradigms to assess infant mental rotation processes have reported a significant gender difference in infants' task performance; however, only three published studies have employed these two tasks. Most prior research on this topic has instead relied on habituation/dishabituation procedures, which have resulted in discordant findings regarding the role of gender in infant performance and, more generally, regarding infants' abilities to discriminate between objects and their rotated mirrored images. In the first study to use such a procedure, Moore and Johnson (2008) habituated 5-month-old infants to a 3-D object rotating in depth along a 240° arc. Then, they presented infants with test trials in which the same object or its mirror image rotated through a novel 120° arc. Boys exhibited greater looking towards the mirrored object relative to the non-mirrored object across test trials, suggesting that they represented the shape of the rotating object and detected its mirror reversal. Similar to the findings of Quinn and Liben (2008; 2014), girls did not display a visual preference for either of the two test objects. Although the gender difference observed by Moore and Johnson (2008) paralleled other findings of a male advantage in infant implicit task performance, later research has revealed considerable inconsistencies in infants' visual preferences on their habituation task both between and within genders. For example, two studies have reported that only boys appear to discriminate between the mirrored and non-mirrored test stimuli (Constantinescu et al., 2018; Moore & Johnson, 2011), whereas other studies on infants of similar ages have not found gender differences in infants' performance on the same habituation task (Christodoulou et al., 2016; Erdmann et al., 2018) or reported that infants reliably discriminate between the two types of test stimuli, regardless of their gender (Slone, Moore, & Johnson, 2018).

Building upon conflicting findings of gender differences, studies evaluating infants' mental rotation performance via Moore and Johnson's (2008) habituation paradigm suggest that infants of both genders may not reliably display novelty preferences on their task. Whereas

Moore and Johnson (2008) originally reported that 5-month-old boys looked significantly longer at the mirrored test object than at the non-mirrored object, they later found that 3-month-old boys displayed greater looking to the familiar, *non-mirrored* test object (Moore & Johnson, 2011), whereas girls displayed no preference for either of type of stimulus across both studies. Later results obtained via the same habituation procedure were similarly conflicted in the directionality of infants' visual preferences for non-mirrored and mirrored stimuli (see Table 1). In some studies, infants exhibited greater looking toward the novel/mirrored object at test (Constantinescu et al., 2018), but in other studies, infants showed greater looking to the familiar/non-mirrored object (Christodoulou et al., 2016; Erdmann et al., 2018) or displayed no clear visual preference for either stimulus (Erdmann et al., 2018; Slone et al., 2018). Significant novelty and familiarity preferences have been taken as equal evidence that infants successfully discriminated between the two types of test stimuli, as is typical in the infant literature (Rose et al., 1982), but the source of these differences infants' visual preferences for the non-mirrored and mirrored stimuli remains unaddressed (see Christodoulou et al., 2016). The habituation task developed by Moore and Johnson (2008) was later modified by Schwarzer and colleagues (2013a) and is now the most commonly administered task in the infant mental rotation literature. Consequently, this issue clouds our current understanding of infants' mental rotation performance and the processes that underlie it. Thus, research examining gender differences in infancy via other looking-time paradigms holds promise for providing converging evidence of a male advantage in infant performance.

Correlates of individual differences in infant mental rotation performance. As described above, Lauer and colleagues (2015) documented a significant gender difference in infants' performance on their spatial change-detection task, designed to assess infant mental rotation abilities (Figure 8). However, the authors also noted considerable inter-individual variability in infants' task performance. In subsequent research, Lauer and Lourenco (2016) examined the developmental stability of these individual differences by conducting a longitudinal study. Specifically, the authors recruited children who completed their spatial change-detection task as infants to participate in a follow-up study at four years of age in order to examine individual difference factors related to children's earlier implicit mental rotation task performance. Lauer and Lourenco found that greater looking towards the mirror stream in infancy, suggesting greater sensitivity to mirror reversals in a rotating stimulus, was associated with higher performance on an explicit mental transformation task at age 4 years, even when controlling for general cognitive abilities (e.g., processing speed, verbal working memory). These results indicate that the implicit spatial change-detection task developed by Lauer et al. may tap the same cognitive constructs as explicit mental rotation measures. However, the authors also reported that infants' change-detection task performance was associated with their later performance on other measures of spatial reasoning at age 4, including a spatial short-term memory task. These findings introduce the possibility that the implicit change-detection task did not elicit mental rotation processes *per se*, but rather recruited a general spatial processing capacity, such as spatial short-term memory, and this general capacity accounted for individual differences in children's performance across tasks in infancy and at age 4. Nevertheless, these findings suggest that implicit mental rotation tasks may assess individual differences in spatial processes that have meaningful consequences for later mental rotation skills.

What could account for individual differences in infants' mental rotation task performance? Lauer and Lourenco (2016) were the first to correlate infants' performance on a mental rotation measure with their later cognitive abilities, reporting that individual differences in infant mental rotation may relate to broader spatial processing capacities, such as spatial memory. However, other attempts to characterize correlates of infant mental rotation performance when measured contemporaneously in infancy have also proven useful. For instance, as previously discussed, a number of studies have found that individual differences in infant motor development account for variability in implicit task performance (e.g., Frick & Möhring, 2013; Möhring & Frick, 2013; Schwarzer et al., 2013). Like the findings of Lauer and Lourenco, results from studies on the association between motor and spatial development have provided further support to the contention that infant mental rotation tasks elicit developmentally continuous spatial processes, given evidence that motor processes are critical in explicit mental rotation performance (e.g., Funk et al. 2005; Wezler et al., 1998). Together, these results call for further consideration of possible correlates of infants' performance on implicit mental rotation tasks that may contribute insight into the extent of developmental continuity in spatial processing between infancy and adulthood.

Present Research

As summarized above, findings from the infant spatial cognition literature proffer the possibility that mental rotation processes emerge early in life and display developmental continuity between infancy and adulthood. However, several open questions must be addressed to evaluate the validity of this conjecture. First, it remains unclear whether infants' performance on implicit mental rotation tasks indeed relies on analog mental representations of spatial rotation, as seen in adulthood (cf. Frick et al., 2014). Second, do infants display gender differences in their implicit mental rotation performance, and if so, are they of a similar magnitude to the robust male advantage in explicit mental rotation performance observed later in development (e.g., Lauer et al., 2019; Voyer et al., 1995)? Lastly, what accounts for the considerable inter-individual variability in infants' performance on implicit measures of mental rotation ability? Prior research has pointed to roles for general spatial processing abilities (Lauer & Lourenco, 2016) and motor development (e.g., Gerhard & Schwarzer, 2016; Schwarzer et al., 2013), but the relative importance of these variables in accounting for individual differences in infant performance has not been addressed.

In the present study, we addressed the aforementioned questions by examining whether infants' looking behavior during an implicit mental rotation task is consistent with mental rotation processes (i.e., analog spatial representations of object rotation). To accomplish this, we designed a change-detection paradigm that indexes infants' ability to discriminate between an object and its rotated mirrored image as a function of their angular disparity, akin to standard tasks used to study mental rotation processes in adulthood (e.g., Shepard & Metzler, 1971). This paradigm was modeled from the spatial change-detection task developed by Lauer and colleagues (2015) to evaluate infants' ability to detect intermittent changes in the mirror orientation of a rotating stimulus. The change-detection task administered in the present study, hereby referred to as the Rotation Change-Detection Task, differed from the procedure employed by Lauer et al. in that we manipulated the angular disparity between the stimulus and its rotated mirrored image across trials. This experimental manipulation allowed us to assess whether infants' looking behavior parametrically related to the angular disparity of two rotated stimuli. If infant performance on implicit mental rotation measures indeed relies on analog mental representations of spatial rotation, then it would be expected to increase monotonically as a function of the angular disparity between the mirrored and non-mirrored stimuli, as found in adulthood. In contrast, if infant performance on implicit mental rotation measures instead relies on broader visuospatial and/or domain-general cognitive processes, then one would expect that infants' performance on the Rotation Change-Detection Task would not vary as a function of angular disparity.

In addition to characterizing early-emerging mental rotation processes, the present research considered a series of factors hypothesized to account for variability in infant spatial processing. As previously discussed, prior research has demonstrated a role for both gender and motor processing in mental rotation performance in adulthood, with preliminary evidence indicating that these factors may also be relevant to spatial processing in infancy. Thus, we examined gender and motor skill development as potential moderators of infants' performance on a mental rotation task. Lastly, the current research explored whether implicit measures designed to elicit mental rotation processes in infancy may actually recruit more domain-general processes, such as short-term memory or visual pattern recognition. To this end, we presented infants with additional change-detection tasks designed to assess various spatial and visual processes, including the Location Change-Detection Task developed by Oakes and colleagues (2011) to evaluate individual differences in infants' spatial short-term memory.

Method

Participants

Participants were 61 infants (30 female) aged 6 to 12 months (M = 8.14 mo, SD = 1.62 mo) who completed two testing sessions scheduled 5 to 9 days apart. At the beginning of the first testing session, parents provided written informed consent on behalf of their infants and completed questionnaires regarding family demographics. According to parent report, all infants were born full term (M gestational age = 39.45 weeks, SD = 1.21 weeks). The sample was racially diverse: 63% of parents identified their infants as white/Caucasian, 23% as black/African American, 10% as multiracial, and 2% as Asian American; 3% of parents did not report their infant's race. In addition, 13% of infants were identified as Hispanic or Latino. Participants' primary caregivers were highly educated: 51% possessed a graduate degree, 39% held a Bachelor's degree, and the remaining 10% had completed high school or its equivalent.

As noted above, 49% of infants were identified as female by their parents; the remaining 51% of infants were identified as male. When describing gender differences in the broader psychological literature, the term "sex" is often used to refer to biological differences between female and male individuals (e.g., behaviors mediated by sex steroid hormones), whereas the term "gender" is often used to refer to differences thought to arise from the social constraints imposed on women/girls and men/boys within their cultural environments (Siann, 2013). We did not differentiate between these two terms of the demographics questionnaire, meaning that parents indicated their child's "gender" as either "female" or "male". Therefore, we have chosen to refer to any distinctions between female and male infants as "gender" differences, but acknowledge that our research was not designed to address the causal origins of such differences (i.e., biologically vs. culturally mediated).

An additional 24 infants participated in at least one testing session but were excluded from the sample above because they failed to complete both testing sessions due to fussiness (7 infants), did not return for the second testing session (9 infants), did not provide sufficient looking-time data for inclusion across the two sessions (4 infants; see details below), or could not be calibrated to the eye-tracker (2 infants). These 24 infants did not differ in age (p = .101) or gender (p = .861) from the infants included in our analyses.

Procedure

Each testing session took placed in a dimly lit room that was equipped with a 17-in Tobii T120 eye-tracker. Infants were seated in a caregiver's lap or in a high chair, and they were positioned such that their eyes were approximately 60 cm from the center of the eye-tracker's presentation screen. A webcam fixed to the top of the presentation screen allowed the experimenter to monitor the session via a live videofeed from an adjoining space. Caregivers were instructed to keep their eyes closed during the testing session and to refrain from interacting with their infants except to sooth them if they became distressed. Prior to testing, the eye-tracker was calibrated using the 5-point infant calibration sequence provided by Tobii Studio 3.4.6, and Tobii Studio was used to record infants' gaze locations throughout the testing session (Tobii Technology, Stockholm, Sweden).

During each of the two testing sessions, infants were presented with two change-detection tasks: (1) the Rotation Change-Detection Task, designed to assess mental rotation processes, and (2) the Location Change-Detection Task, designed to assess spatial short-term memory. The order of these two tasks was counterbalanced across infants and between testing sessions. Following these two tasks, infants completed two trials of one of two control tasks, as described in the following section. Consequently, infants were presented with eight trials during each testing session.

At the conclusion of the first testing session, parents were given an abbreviated form of the Ages and Stages Questionnaire (ASQ) to complete at home and return during the second session; 90% of parents returned the questionnaire ($N = 55$). Infants were given a small toy or a t-shirt at the end of each testing session, and caregivers were given a $20 gift card at the conclusion of the second testing session. All procedures were approved by the Emory University Institutional Review Board.

Change-Detection Tasks

All change-detection tasks consisted of four 60-s trials, with two trials during each of the two testing sessions. At the beginning of each trial, a central audiovisual attractor appeared onscreen; the trial began after the infant fixated on the attractor for 2 s without looking away from the screen. All trials were presented for 60 s regardless of whether infants maintained their attention towards the screen, and no efforts were made to redirect infants' attention once a trial began. The changing stream was on the left side of the screen for one half of the trials for a given task and on the right side of the screen for the remaining trials. Left-right order of the changing stream was counterbalanced within and across infants for each task.

Infants were required to fixate on both image streams at least once during a given trial for the trial to be included in analyses. Moreover, infants were required to complete both trials presented during one or both of the study sessions to be included in the analyses.

Rotation Change-Detection Task. In the Rotation Change-Detection Task, infants were simultaneously presented with two image streams on opposite sides (i.e., left/right) of the eye-tracker's presentation screen. Both image streams consisted of the repeated presentation of a single static stimulus, namely a red 2-dimensional Tetris-like shape, on a gray background for the duration of each 60-s trial (see Figure 9). With each stimulus presentation, the shape appeared in one novel orientation along the picture plane for 500 ms. Each stimulus presentation was followed by a blank screen for 300 ms. Throughout each trial, the novel orientation of the shape was constrained within a range of 180° in both image streams except that with every third stimulus presentation, the shape in the changing stream rotated outside of the expected range along the *x*-axis and was horizontally reflected into its mirrored orientation (Figure 9). The expected range of 180° remained constant within each testing session for each infant, but was randomly selected from one of four arcs: 0-180°, 90-270°, 180-360°, or 270-90°. The orientation of the mirrored shape varied as a function of condition, as described in the following section. To measure infants' detection of the unexpected mirrored orientation in the changing stream, we calculated their relative visual preference for that image stream within a given trial [change-detection score = looking towards the changing stream/(looking towards the changing stream + the constant stream)].

The study design featured three conditions, illustrated in Figure 10. In the *small disparity* condition, the unexpected stimulus in the changing stream was rotated by an average of 15° (i.e., 0-30°) from the expected rotational trajectory before it was mirror reversed (i.e., reflected around the *y*-axis). In the *medium disparity* and *large disparity* conditions, the unexpected rotation was created by rotating the stimulus on average by 45° (i.e., 30-60°) and 75° (i.e., 60-90°), respectively, before it was mirror reversed.

All infants were presented with four trials of the *large disparity* condition and with four trials of either the *small disparity* or the *medium disparity* condition. Thus, there were two groups of infants, each of which completed two conditions. One group, namely the small-large group (N = 27; 14 females) completed the *small disparity* condition and the *large disparity* condition. The other group, namely the medium-large group (N = 34; 16 females) completed the *medium disparity* condition and the *large disparity* condition. Infants were randomly assigned to these groups prior to testing. Both groups completed the *large disparity* condition so that we could establish baseline performance across the two groups while limiting the number of trials presented to each infant.

The majority of infants included in the analyses completed four trials of both Rotation Change-Detection Task conditions, but infants who only successfully completed two trials of one of the conditions were also included in the analyses. Four of the 27 infants (15%) in the small-large group only completed two trials of one of the two conditions, and 7 of the 34 infants (21%)

in the medium-large group completed only two trials in one of their two conditions. Excluding infants who only completed two trials in one of the conditions did not affect the significance of any of the analyses reported in the Results section, so all infants who provided adequate looking data for two trials within each condition were retained for analyses.

Location Change-Detection Task. Infants also completed the Location Change-Detection Task designed by Oakes and colleagues (2011) to assess infants' spatial short-term memory (see Figure 11). The procedure for the Location Change-Detection Task was identical to the Rotation Change-Detection Task; only the stimuli included in the changing and constant streams were different. In the Location Change-Detection Task, both image streams contain three dots of different colors, which were presented within 16 in^2 gray squares on a black background. In the constant stream, the three dots remained in the same location within the gray square for the duration of each 60-s trial. In the changing stream, one of the three dots relocated to a new position in the gray square each time the stimuli appeared on screen. The novel location of the moving dot was randomly selected, and the dot that moved location was randomly selected among the three options in the changing stream.

Infants completed two trials of the Location Change-Detection Task during each of the two testing sessions. The side of the changing stream (left/right) was counterbalanced across trials for each infant, and the side of the changing stream on the initial Location Change-Detection Task trial was counterbalanced across infants. To measure performance, we again calculated change-detection scores that quantified infants' preferential looking towards the changing stream [change-detection score = looking towards the changing stream/(looking towards the changing stream + the constant stream)].

As previously discussed, infants were required to provide adequate looking data (i.e., to fixate on both the changing and constant stream) for both Location Change-Detection trials within at least one of the testing sessions to be included in the analyses reported in the Results section. The majority of infants included in the sample (85%) provided adequate looking data during all four trials of the Location Change-Detection Task, meaning that their performance for all four trials was averaged to compute their mean location change-detection score. For the remaining 15% of infants, data from only two trials were used to compute their mean location change-detection score. Excluding infants who only completed two trials of the Location Change-Detection Task did not affect the significance of the analyses reported in the Results.

Control Change-Detection Tasks. After completing both the Rotation Change-Detection Task and the Location Change-Detection Task, infants were presented with one of two change-detection tasks. These two tasks were used as control measures for the Rotation Change-Detection Task in that they allowed us to determine whether infants could discriminate between changing and constant streams in the Rotation Change-Detection Task merely by attending to specific visual features of the stimulus, instead of attending to and representing the stimulus' rotational motion. The two control measures were the Mirror Change-Detection Task (see Figure 12) and the Block Change-Detection Task (see Figure 13). Infants were presented with two trials of the same control task at the end of both testing sessions as long as they remained attentive and calm following the other tasks. Due to attrition over the course of the testing sessions, we only required that infants complete two trials of a control task to be included in the analyses. A total of 21 infants were presented with the Mirror Change-Detection Task, and 25 infants were presented with the Block Change-Detection Task.

Mirror Change-Detection Task. This control task was identical to the Rotation Change-Detection Task with the exception that the two-dimensional, Tetris-like stimulus was presented in the same orientation around the *x*-axis throughout each trial (Figure 12). Consequently, the only change in the changing stream during this task was the mirror reversal of the shape that occurred with every third stimulus presentation. Thus, the task measured infants' ability to discriminate between an object and its mirrored image in the absence of any information regarding the object's rotational trajectory, which allows us to determine whether infants could discriminate between the mirrored and non-mirrored stimulus without necessarily representing its rotational motion (i.e., whether infants could discriminate between the mirrored and non-mirrored streams solely by detecting the mirror reversal in the changing stream, regardless of the stimulus' orientation). The orientation of the stimulus around the *x*-axis was held constant within each testing session for each infant, but varied across the two testing sessions.

As in the previous change-detection measures, we computed a change-detection score that represented infants' relative preference for the image stream containing the mirror image [change-detection score = looking towards the changing stream/(looking towards the changing stream + the constant stream)]. During each session, infants were presented with one trial in which the changing stream was on the left side of the screen and one trial in which the changing stream was in the right side of the screen, with the order of changing-stream side counterbalanced within infants across days and across infants.

Block Change-Detection Task. This task was identical to the Rotation Change-Detection Task with the exception that only one block of the two-dimensional, Tetris-like stimulus was presented during each trial (see Figure 13). This allowed us to determine whether infants were able to discriminate between the changing and non-changing streams in the Rotation Change-Detection Task solely by attending to the location of one salient portion of the Tetris-like stimulus, rather than representing the rotational trajectory of the stimulus itself. At the end of each testing session, infants completed two trials for one of the three disparity conditions. As in the Rotation Change-Detection Task, all infants completed the large disparity condition and either the medium disparity condition or the small disparity condition.

Developmental Milestones Questionnaire

Given previous findings suggesting that motor development relates to implicit mental rotation performance (e.g., Möhring & Frick, 2013; Schwarzer et al., 2013), we asked parents to complete a broad measure of infant development that assesses gross and fine motor skills, namely the Ages and Stages Questionnaire (ASQ):. The ASQ consists of 30 items divided into 5 sections (gross motor, fine motor, communication, problem-solving, and personal/social). Each section is comprised of 6 items that describe actions infants typically begin to perform between 6 and 12 months of age (e.g., child stands independently). Parents indicate whether their infant successfully performs each action by marking "not yet," "sometimes," or "yes."

To quantify infants' motor development, we first coded parents' responses for each item as 1 for "not yet," 2 for "sometimes," and 3 for "yes." We then summed the coded responses for the 6 items within each of the questionnaire's sections to create a single score that measured infants' abilities in the given domain (e.g., fine motor skills). Lastly, we computed a total motor score by summing parents' coded responses to the 6 gross motor and 6 fine motor items.

Results

Before completing any analyses, we computed infants' mean change-detection scores for each task. Change-detection scores were calculated as the proportion of infants' looking to the changing stream relative to their overall looking to either image stream throughout each 60-s trial [i.e., score = changing/(changing + constant)]. Mean change-detection scores were then calculated by averaging children's scores from all trials within a given change-detection task and within a given condition in the case of the Rotation Change-Detection Task. Therefore, mean change-detection scores greater than 0.50 corresponded to greater looking to the changing stream relative to the constant stream, whereas mean change-detection scores less than 0.50 corresponded to greater looking to the constant stream relative to the changing stream. After computing mean change-detection scores, we calculated descriptive statistics that summarized infants' overall performance on each of the change-detection tasks and conducted a series of analyses to examine whether infants' performance on each task varied by task condition, gender, age, and motor skill. Lastly, we conducted correlational analyses to examine the relation between infants' Rotation Change-Detection Task and Location Change-Detection Task performance.

Rotation Change-Detection Task

In preliminary analyses, we examined infants' mean change-detection scores within each of the disparity conditions, as plotted in Figure 14. Mean change-detection scores did not differ from chance in the large disparity (M = 0.50, 95% CI [0.48, 0.53]) or medium disparity (M = 0.52, 95% CI [0.50, 0.55]) conditions: ts < 1.81, ps > .07, ds < 0.31. Binomial tests confirmed that infants did not display a consistent preference for either stream in these conditions (ps > .60). In contrast, mean change-detection scores in the small disparity condition were significantly less than chance (M = 0.44, 95% CI [0.40, 0.48]), indicating that infants looked longer towards the constant stream than the changing stream across small-disparity trials; $t(26) = -2.83$, $p = .009$, $d = -0.54$. This constant-stream preference was confirmed via a binomial test: 21 of 27 infants (78%) displayed a preference for the constant stream in the small disparity condition ($p = .006$).

The descriptive statistics reported above suggest that infants only successfully discriminated between the two image streams in the small disparity condition, a finding consistent with the possibility that infants' performance on the Rotation Change-Detection Task differed by angular disparity. To directly test whether infants' performance varied by disparity condition, we next examined whether differences in infants' change-detection scores across conditions varied for infants in the small-large group relative to infants in the medium-large group. Because all infants completed the large disparity condition, we first ensured that infants' mean change-detection scores in the large disparity condition were similar for the small-large group ($M = 0.50$, $SD = 0.11$) and for the medium-large group ($M = 0.51$, $SD = 0.10$); $t(59) = 0.18$, $p = .855$, $d = 0.05$. Because this was the case, we utilized infants' mean change-detection scores from the large disparity condition as a baseline measure of individual differences on the Rotation Change-Detection Task. Specifically, we calculated a difference score for each infant by subtracting their change-detection score in the large condition from their change-detection score in the other condition they completed. This difference scores represents infants' differential sensitivity to the mirrored orientation of the stimulus as a function of disparity condition.

As would be expected given the findings presented above, mean difference scores for infants in the medium-large group ($M = 0.02$, 95% CI [-0.02, 0.06]) did not differ significantly from 0: $t(33) = 0.90$, $p = .373$, $d = 0.16$. In contrast, mean difference scores in the small-large group were significantly less than 0 ($M = -0.06$, 95% CI [-0.11, -0.02]), indicating that infants' change-detection scores were significantly lower in the small disparity condition than in the large disparity condition: $t(26) = 2.36$, $p = .026$, $d = 0.45$. Although these results suggest that infants' ability to discriminate between the changing and constant streams varied by disparity condition, they do not indicate that the effect of disparity was linear in nature, as would be expected if the Rotation Change-Detection Task elicited analog mental rotation processes.

The results presented above revealed that on infants' performance differed between the large-disparity and small-disparity conditions, but not between the large-disparity and medium-disparity conditions; however, we also observed considerable variability in infants' performance across conditions. Thus, we next considered potential sources of this variability, beginning with gender. Specifically, we conducted a 2 × 2 ANOVA with rotation group (*small-large*, *medium-large*) and gender (*female*, *male*) as between-subjects factors and difference in change-detection scores as the dependent variable. There was neither a main effect of gender [$F(1, 57) = 0.01$, $p = .924$] nor a gender by condition interaction [$F(1, 57) = 0.18$, $p = .678$]. Follow up analyses indicated that girls and boys performed similarly in each of three conditions (see Table 8), and the non-significant effect of gender was consistent across our age range of 6 to 12 months for all three conditions (Fs < 0.47, ps > 0.5). These results do not provide support to the contention that the male advantage in mental rotation performance is first detectable in infancy.

We next considered age as a potential source of variation in infant performance across conditions by conducting an ANCOVA with rotation group (*small-large*, *medium-large*) as a between-subjects factor, age as a covariate, and difference scores as the dependent variable. There was no main effect of age on difference scores [$F(1, 57) = 0.05$, $p = .823$] or an Age × Rotation Group interaction [$F(1, 57) = 0.08$, $p = .772$]. Moreover, age was not related to infants' change-detection scores for any of the three disparity conditions (rs < .06, ps > .68). These results provide evidence of developmental continuity in infants' change-detection task performance between 6 and 12 months of age.

Finally, we investigated the potential relation between Rotation Change-Detection Task performance and motor development, as measured by the gross motor and fine motor sections of the ASQ. An ANCOVA with rotation group (*small-large*, *medium-large*) as a between-subjects factor, total motor score as a covariate, and difference scores as the dependent variable revealed no significant main effect of total motor score on difference scores [$F(1, 51) = 0.01$, $p = .934$] or a total motor score by rotation group interaction [$F(1, 51) = 0.08$, $p = .773$]. Consistent with these results, infants' change-detection scores were not correlated with their total motor scores, their gross motor scores, or their fine motor scores for any disparity condition (rs < .09, ps > .52).

Location Change-Detection Task

Infants' mean change-detection scores on the Location Change-Detection Task were significantly greater than chance ($M = 0.55$, $SD = 0.10$), indicating that, on average, infants exhibited longer looking towards the changing stream than the constant stream; $t(61) = 3.72$, $p < .001$, $d = 0.47$. These results suggest that infants were sensitive to the changes in the spatial locations of the items in the changing stream. However, only 59% of infants displayed a preference for the changing stream (i.e., change-detection scores > 0.50; binomial test $p = .10$), revealing substantial individual differences in their performance (see Figure 15 for histogram of change-detection scores). Follow-up analyses revealed that this variability in location change-detection scores could not be attributed to effects of gender ($p = .733$, $d = 0.09$), age ($r = 0.19$, $p = .141$), or any of our three motor skills measures (rs < .10, ps > .53).

Relations between Rotation and Location Change-Detection Task Performance

We next explored whether infants' Rotation Change-Detection Task performance was related to their spatial short-term memory, as measured by the Location Change-Detection Task. Location change-detection scores were not significantly correlated with rotation difference scores [$r(59) = .22$, $p = .082$], although there was a trend such that the higher infants' location change-detection scores, the greater the differences in their performance across the two disparity conditions (see Figure 16). A follow-up ANCOVA indicated that the relation between location change-detection scores and rotation difference scores did not vary between infants in the small-large group and the medium-large group [$F(1, 57) = 0.04$, $p = .837$].

Control Tasks

Mirror Change-Detection Task. Infants' change-detection performance on the Mirror Change-Detection Task did not differ significantly from chance ($M = 0.46$, $SE = 0.04$); $t(21) = -1.01$, $p = .323$, $d = -0.22$. In line with these results, approximately half of infants (48%) displayed a preference for the constant stream, whereas the other half (52%) displayed a preference for the changing stream. Therefore, infants did not discriminate between the Tetris-like stimulus and its mirrored image when it was presented in a single orientation along the *x*-axis. When considered in the context of findings obtained via the Rotation Change-Detection Task (see also Lauer et al., 2015), these results suggest that infants only discriminate between the stimulus and its mirrored image when they are provided with the information necessary to represent the stimulus' expected rotation around the *x*-axis. That is, infants only detect the mirror reversal of the stimulus when they have represented its rotational constraints.

Square Change-Detection Task. Infants' change-detection performance on the Square Change-Detection Task did not differ significantly from chance for any of the three disparity conditions (ts < 1.23, ps > .23, ds < 0.43). Thus, infants did not discriminate between the two image streams. Paired-sample t tests further revealed that mean change-detection scores did not differ by disparity condition (ts < 0.64, ps > .41, ds < -0.20). These results suggest that infants were not able to discriminate between the constant and changing streams in the Rotation Change-Detection Task solely by attending to the location of a single salient feature of the task stimulus.

Discussion

The aim of this study was to characterize the spatial processes that are elicited by implicit mental rotation tasks during the first year of life. To accomplish this, we presented 6- to 12-month-old infants with a Rotation Change-Detection Task that allowed us to index their ability to discriminate between an object and its rotated mirrored image as a function of the angular disparity between the two objects. We also collected measures of infant spatial short-term memory and their motor development. Our findings provide some evidence that infants engaged in spatial processing when presented with the implicit Rotation Change-Detection Task, but our results also countered those of prior studies on this topic by indicating that gender, spatial short-term memory, and motor development did not moderate infants' performance on the implicit mental rotation measure between 6 and 12 months of age. In the following paragraphs, we situate these findings in the context of the broader spatial development literature and suggest promising directions for future research.

The central finding of the present study is that infants' performance on the Rotation Change-Detection Task depended upon the magnitude of the angular disparity between the non-mirrored and mirrored stimuli presented in the two image streams. That is, infants discriminated between the two image streams when the angular disparity between the non-mirrored stimulus and the unexpected rotation of the mirrored stimulus was small in magnitude. However, infants did not appear to discriminate between the two image streams, as measured by their mean change-detection scores, with larger angular disparities. Given the linear relation between angular disparity and mental rotation performance observed in adulthood, we would expect that infant change-detection scores would vary as a function of disparity condition if the implicit Rotation Change-Detection Task recruited analog mental rotation processes. We found a significant effect of disparity condition, consistent with the possibility that task performance could have relied on analog mental representations of spatial rotation. This finding parallels the results of Gerhard and Schwarzer (2018) who recently reported that infants' performance on a habituation task designed to assess mental rotation abilities varied as a function of the angular disparity between the non-mirrored habituation stimulus and the mirrored test stimulus. Moreover, Gerhard and Schwarzer found that infant performance only differed from chance when the angular disparity between the non-mirrored and mirrored stimuli was minimal (0° relative to 54°). This pattern of performance parallels that of the present research: infants in our study performed differently from chance in the small disparity condition, when the angular disparity between the non-mirrored and mirrored stimuli differed by an average of 15°, but infants' change-detection scores did not differ from chance in either of the other disparity conditions, when the angular disparity between the non-mirrored and mirrored stimuli differed by an average of 45° and 75°, respectively. Thus, we did not find clear evidence that the relation between angular disparity and infant performance was linear, a key feature of analog mental rotation in adulthood (e.g., Shepard & Metzler, 1971; Shepard & Cooper, 1986). Future work will therefore be necessary to bring clarity to whether infants' looking times on implicit mental rotation measures scale linearly in relation to angular disparity.

As stated above, we observed that infants' change-detection scores during the Rotation Change-Detection Task significantly differed from chance in the smallest disparity condition, consistent with the results obtained by Lauer and colleagues (2015) when using the same change-detection paradigm. However, infants exhibited significantly greater looking towards the constant stream than towards the changing stream in our study, whereas Lauer et al. found the opposite pattern within the same age range: infants displayed greater looking towards the changing stream relative to the constant stream. The key difference in the task presented in the current study and the procedure implemented by Lauer et al. is that the angular disparity between the expected, non-mirrored stimulus in the constant stream and the unexpected, mirrored stimulus in the changing stream did not differ in the Lauer et al. task. What may account for these surprising differences in infants' visual preferences between the two studies? Generally, infants are expected to display greater looking towards stimuli with greater variability/novelty (Rose et al., 1982). Yet, previous studies using implicit looking-time tasks to assess infant processing, including studies on infant mental rotation, present a more complicated picture of infants' visual preferences. For example, studies employing habituation procedures to assess infant mental rotation have variably reported significant preferences for mirrored and non-mirrored stimuli during the test phase, with the direction of infants' visual preferences depending on their age and motor development (see Table 7 for summary of prior results) and on whether mirrored and non-mirrored stimuli were presented simultaneously or sequentially (see Christodoulou et al., 2016). Together, these findings align with those of Hunter and colleagues (1983), who argued that infants will display greater looking towards a stimulus with greater change only when they have fully processed the stimulus with less change. Therefore, infants are expected to look longer towards stimuli with reduced variability when tasks pose significant processing demands. Considering this, it is possible that infants exhibited a significant preference for the constant stream in our small-disparity condition because it placed greater processing demands on infants (relative to the procedure used by Lauer et al.). Because Lauer and colleagues' work is the only other published study to use the Rotation Change-Detection Task, future research with this paradigm will be necessary to determine the validity of this hypothesis.

In addition to the Rotation Change-Detection Task, infants were presented with the Location Change-Detection Task developed by Oakes and colleagues (2011) to assess infant spatial short-term memory. Overall, infants performed above chance on the Location Change-Detection Task, exhibiting greater looking towards the changing stream across trials regardless of their age. These results suggest that infants were capable of maintaining the spatial location of three items in short-term memory across the ages of 6 to 12 months of age. However, infants' performance on the spatial short-term memory task did not relate to their performance within or across conditions on the Rotation Change-Detection Task. This result counters the possibility that infants' performance on the Rotation Change-Detection task relies on broader spatial memory resources, rather than spatial processes specific to representing object rotation. Nonetheless, the extent to which infants' Rotation Change-Detection Task performance would relate to other types of dynamic spatial processing remains unknown. Thus, our results provide some evidence of specificity in infant spatial processing, but further research examining different aspects of spatial processing will be necessary to fully characterize the extent of this specificity.

Our findings also did not suggest that infants' performance on the Rotation Change-Detection Task varied by gender. These results contrast those of some previous studies on infant implicit mental rotation performance in which boys outperformed girls (e.g., Moore & Johnson, 2008; Quinn & Liben, 2008), including the only other study to use the change-detection paradigm administered in the present work (i.e., Lauer et al., 2015). However, as detailed in Table 2, most studies on this topic have not found evidence of a gender difference in infants' mental rotation performance on implicit tasks. Our findings add to a growing body of evidence that girls and boys perform similarly on implicit mental rotation tasks during infancy. Nevertheless, it is important to note that post-hoc power analyses indicated that our sample size only afforded adequate power (>.80) to detect large gender differences ($d > .75$) in infant performance. Given evidence that gender differences in mental rotation are relatively small in magnitude across childhood (Lauer et al., 2019), future research with larger samples of infants will be necessary to conclude whether a small male advantage is indeed present in infancy.

In addition to the lack of gender differences, our results countered earlier findings suggesting that infants' performance on implicit mental rotation measures varies as a function of their motor experience. Results from studies that have used habituation and violation-of-expectation measures to assess infants' mental rotation abilities have reported a positive association between mental rotation performance and motor skills, particularly when motor skills are assessed using measures of self-locomotion (e.g., Frick & Möhring, 2013; Gerhard & Schwarzer, 2018; Schwarzer et al., 2013a, 2013b). However, one recent longitudinal study with a large sample size ($N > 150$) did not find evidence of this association between 5 and 9 months of age, a critical period of infant motor development (Erdmann et al., 2018). Our findings also did not provide support for a relation between motor development and infants' mental rotation performance across an even wider span of development (i.e., 6 to 12 months of age). Conflicting results across studies may be attributable to paradigmatic differences, as studies that have documented an association between mental rotation performance and infant motor development have relied on habituation and violation-of-expectation procedures composed of 3-dimensional stimuli. Future research that examines the relations between infant motor experience and their performance across multiple spatial tasks would be useful in addressing this possibility. Such studies will be most informative if they rely on larger samples of infants, given that few studies to date, including the present research, have had adequate power (>.80) to detect small or medium relations between infants' performance on mental rotation tasks and their motor skills.

There are a number of limitations that should be considered when interpreting our findings. Although our sample size was large relative to most other studies in the relevant literature (see Table 7), a larger sample size would provide us with greater power to detect differences in disparity conditions and to quantify the magnitude of correlations between infant mental rotation performance and other measures of interest (e.g., spatial short-term memory, motor skills, age), as previously noted. In addition, the current study presented infants with only three disparity conditions, limiting inferences about the extent to which infants' looking behavior was consistent with analog mental rotation processes. More specifically, because infants displayed chance performance on two of the three disparity conditions, our conclusions regarding the extent to which infant performance varied as a function of disparity condition were limited. In future work, increasing the number of disparity conditions would allow for greater insight into the role of angular disparity in infants' change-detection scores. As the linear relation between angular disparity and mental rotation performance is considered the behavioral signature of mental rotation in adulthood, this represents a promising direction for future research aimed at characterizing the development of analog mental rotation processes during early childhood.

In conclusion, our findings provide some evidence that infants' performance on the Rotation Change-Detection Task varied as a function of the angular disparity between mirror and non-mirrored stimuli. These results are consistent with the possibility that infants form analog spatial representations of object rotation when presented with implicit mental rotation tasks. However, caution is necessary when interpreting our findings given infants' chance performance on multiple task conditions, calling for future research that further considers the extent to which implicit spatial measures elicit analog mental rotation processes in infancy.

General Discussion

The present research consists of three studies designed to examine the development of analog mental rotation processes between infancy and adulthood. In these studies, we administered novel implicit measures of spatial processing to infants, 4-year-olds, and adults in order to characterize continuity and discontinuity in analog mental representations of spatial rotation across development. Results from implicit measures of spatial processing suggested that such tasks may have elicited analog mental rotation processes at all three developmental time points. Furthermore, implicit mental rotation task performance was associated with explicit mental rotation task performance both at 4 years of age and in adulthood. Gender differences in implicit performance were also present at age 4 and in adulthood, but we found no evidence of gender differences in spatial processing during infancy. Gender differences in explicit performance also varied across development: a substantial male advantage in explicit mental rotation task performance was observed in adulthood, but girls and boys performed similarly on the explicit mental rotation measure administered at 4 years of age. In the following paragraphs, we interpret these results in light of previous findings on the development of mental rotation skills and discuss the theoretical and practical implications of our results.

Our findings contribute novel insight into the spatial processes that underlie performance on mental rotation tasks and their continuity across development. Prior research on young children's mental rotation abilities has reported seemingly inconsistent results: whereas infants appear to engage in spatial processing on implicit mental rotation measures (e.g., Lauer et al., 2015; Möhring & Frick, 2013; Moore & Johnson, 2008), preschool-aged children often display chance-level performance on explicit mental rotation tasks prior to 5 or 6 years of age (e.g., Frick, Hansen, & Newcombe, 2013; Hawes et al., 2015; Kosslyn, Margolis, Barrett, Goldknopf, &

Daly, 1990). These paradoxical results have raised questions about whether implicit and explicit mental rotation tasks elicit similar mental processes and how to conceptualize developmental change in mental rotation performance in light of differing paradigmatic approaches (cf., Frick et al., 2014). To our knowledge, the present research is the first to examine the relation between these two types of mental rotation tasks administered contemporaneously during development and to directly compare implicit mental rotation performance across multiple age groups. Specifically, we administered a novel Spatial Oddball Task to adults and 4-year-olds that measured participants' sensitivity to unexpected changes in the orientation of a rotating stimulus, as indexed by pupil dilation. We examined pupillary responses to the unexpected orientations of the stimulus in relation to the angular disparity between its expected and unexpected orientations, allowing us to analyze the linearity of the relation between angular disparity and response outcomes (i.e., the "signature" of analog mental rotation processes; Shepard & Metzler, 1971). In both age groups, participants' pupillary responses during the Spatial Oddball Task were consistent with analog mental rotation processes, particularly in males. Moreover, participants who exhibited greater pupil dilation in response to greater angular disparities (i.e., a pattern consistent with analog mental rotation processes) relative to their peers also performed comparatively better on an explicit mental rotation measure. These results indicate that similar processes may underlie implicit and explicit mental rotation task performance at two disparate time points in development: preschool age and adulthood. Furthermore, our findings suggest developmental continuity in implicit mental rotation processes across these two age groups.

In addition to shedding light on the validity of our implicit spatial processing measure, our results also contribute insight into preschool-aged children's mental rotation skills. As mentioned above, prior research has demonstrated that children often fail to perform above chance on explicit mental rotation tasks before 5 years of age (see Frick et al., 2014). However, our results suggest that children may engage in analog mental rotation processes, as measured by implicit tasks, prior to the age at which their explicit mental rotation performance reveals their underlying competence. Stated in another way, preschool-aged children's seemingly adult-like performance on our implicit mental rotation measure is incongruent with their otherwise impoverished mental rotation abilities as measured via explicit measures that require children to discriminate between rotated mirrored objects (similar to mental rotation tasks administered to adults; Shepard & Metzler, 1971).

What may lead to these apparent inconsistencies in performance across implicit and explicit tasks? One possibility is that young children fail on explicit measures due to difficulties with task comprehension, particularly when tasks require that they make same/difference judgments about mirrored images (e.g., Kosslyn, Margolis, Barrett, Goldknopf, & Daly, 1990; Marmor, 1975). Another possibility is that implicit measures provide young children with additional scaffolding necessary to form analog spatial representations of rotating objects. More specifically, unlike most explicit measures of mental rotation skill, our implicit Spatial Oddball Task presented the stimulus in numerous rotated views across a series of trials, potentially increasing children's ability to interpolate the rotational motion of the stimulus across stimulus presentations and facilitating their ability to represent and predict its rotational motion. Additionally, participants' responses during the Spatial Oddball Task presumably rely on mental simulations of the stimulus' future rotational motion given the former orientations of the object. In contrast, explicit mental rotation tasks require participants to actively initiate the mental rotation of the stimulus. Therefore, it remains possible that the additional demand of initiating the rotation of the stimulus posed by explicit mental rotation tasks results in preschool-aged children's relatively poor performance on explicit mental rotation measures.

In contrast to our findings on adults and preschool-aged children, our infant study provided a more equivocal picture regarding the presence of analog mental rotation processes during the first year of life. Using a novel Rotation Change-detection Task, we found that infants' ability to discriminate between an object and its mirrored image varied as a function of the angular disparity of the images, as measured by infants' looking behavior. These results provide a conceptual replication of the findings of Gerhard and Schwarzer (2018), who recently reported that infants appeared to more easily discriminate between a rotated object and its mirrored image, as measured via a habituation task, when there was no angular disparity between the habituation and test objects relative to when there was a moderate disparity (i.e., 54°) between the two objects. However, in neither study was there evidence that infants' looking times scaled across multiple angular disparity conditions. Our ability to detect such a pattern was limited given infants' chance-level performance on two of the three disparity conditions in the current research. Thus, although infants' looking patterns were consistent with the possibility that the Rotation Change-Detection Task elicited analog mental rotation processes, future research that examines this question with greater granularity will be necessary to determine whether infants' looking behavior is truly suggestive of analog mental rotation processes.

In addition to informing our understanding of the developmental continuity of the spatial processes recruited during mental rotation tasks, the present studies further our knowledge of the developmental emergence of gender differences in explicit mental rotation performance. Meta-analyses have demonstrated a robust male advantage in explicit mental rotation performance in adulthood (Voyer et al., 1995). Furthermore, Lauer and colleagues (2019) found that this gender difference did not emerge until the elementary-school years and gradually increased in size across childhood and into early adulthood. However, some studies using looking-time tasks to examine mental rotation processes in infancy have reported large gender differences in infants' performance consistent with those observed later in development (e.g., Moore & Johnson, 2008; Quinn & Liben, 2008), though infants did not display gender differences in their implicit task performance in the present work (see also Christodoulou et al., 2016; Erdmann et al., 2018; Slone et al., 2018). Nevertheless, prior findings of a male advantage in infants' implicit mental rotation performance proffer the possibility that this gender difference emerges earlier in life when assessed via implicit measures. The results of our first two studies are in line with this conjecture. In Study 1, adults exhibited a male advantage in mental rotation performance when measured by both the explicit task (d = 1.17) and the implicit Spatial Oddball Task (d = 0.66), suggesting that gender differences in the implicit processes tapped by the Spatial Oddball Task related to those found in adults' explicit performance. Interestingly, in Study 2, 4-year-olds' explicit mental rotation performance did not differ by gender, yet children exhibited the same gender difference as adults on the Spatial Oddball Task (d = 0.85). These results support the contention that implicit mental rotation measures may be better suited to detecting gender differences in mental rotation during the preschool years, relative to explicit measures. Consequently, future research examining the developmental trajectory of gender differences on implicit, rather than explicit, mental rotation tasks across childhood has the potential to advance our understanding of the developmental emergence of gender differences in mental rotation skills.

Beyond the theoretical relevance of our findings, the early emerging individual and gender differences in spatial processing documented in the present research are of practical interest as well. Substantial empirical evidence suggests that mental rotation skills are critical to success in male-dominated science, technology, engineering, and mathematics (STEM) fields across development (e.g., Gilligan, Hodgkiss, Thomas, & Farran, 2017; Hodgkiss, Gilligan, Tolmie, Thomas, & Farran, 2018; Kozhevnikov, Motes, & Hegarty, 2007; Jones & Burnett, 2008; Wu & Shah, 2004), and that the gender difference in mental rotation contributes to gender disparities in STEM attainment by adolescence (Casey et al., 1995; Ganley et al., 2014). There has been less research into these relations during early childhood, but recent longitudinal studies suggest that a longitudinal relation between superior mental rotation skills and math achievement emerges by the first years of elementary school (e.g., Casey et al., 2015; Geer, Quinn, & Ganley, 2018; Gunderson et al., 2012; Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2017) and perhaps within the first years of life (Lauer & Lourenco, 2016). In Study 2, Spatial Oddball Task performance was associated with concurrent performance on a math achievement measure at 4 years of age, suggesting that the early spatial processes tapped by our implicit mental rotation measure may also have relevance for individual differences in STEM achievement by preschool age. Moreover, our finding of gender differences in 4-year-olds' Spatial Oddball Task performance suggest that these early-emerging spatial processes may contribute to the later male advantage in explicit mental rotation performance that we observed in adulthood. Fortunately, prior training studies have demonstrated a moderate degree of malleability in spatial abilities across development for both genders (for meta-analyses, see Baenninger & Newcombe, 1989; Uttal et al., 2013). In the context of these findings, our results indicate that interventions aimed at fostering the development of spatial cognitive processes during the preschool years, especially in girls, could be formative in reducing barriers to academic achievement in STEM fields.

When interpreting the results of the current studies, it is important to note that inferences about developmental continuity between infancy and preschool age were limited by paradigmatic differences across these two age groups. To assess infant mental rotation processes, we relied on a modified version of the spatial change-detection task developed by Lauer and colleagues (2015), an implicit task that measures visual preferences. However, we developed the Spatial Oddball Task to measure mental rotation processes via pupillometry in 4-year-olds and adults. Although the two tasks were composed of similar stimuli and had similar design parameters, differences in outcome measures (i.e., looking time vs. pupillary response) and procedures may have resulted in apparent inconsistencies in our findings across studies. In the Spatial Oddball Task in Paper 1, participants were instructed to direct their attention towards the screen at the beginning of the task, meaning that participants' looking times throughout the task did not reflect their spontaneous looking behavior (as in infancy). Conversely, in the change-detection task administered in Paper 2, stimuli were presented in their unexpected orientations for only 500 ms at a time, an interval too brief to evoke reliable pupillary responses consistent with novelty detection. These paradigmatic differences prevented us from directly comparing participants' responses to aberrations in the orientation of the rotating stimulus across studies and age groups. Future research that administers our Spatial Oddball Task to infants would allow for direct comparison of mental rotation processes in infants, 4-year-olds, and adults. In addition to elucidating the extent of developmental continuity in spatial processing between infancy and adulthood, such research would have the potential to contribute greater insight into the developmental trajectory of gender differences in implicit mental rotation processes across early childhood. Thus, this research represents a promise direction for future work on this topic.

To conclude, the present research sheds light on the development of analog mental rotation processes between infancy and adulthood, suggesting that such processes manifest within the first years of life, prior to the age at which children first perform reliably above chance on explicit measures of mental rotation (Frick et al., 2014). Moreover, our findings indicate that gender differences in spatial processing, as measured by our implicit Spatial Oddball Task, emerge by 4 years of age. Prior research has demonstrated that mental rotation performance positively relates to math achievement throughout childhood (e.g., Geer et al., 2018; Gunderson et al., 2012; Lauer & Lourenco, 2016), and gender differences in mental rotation contribute to the gender gap in STEM success later in development (e.g., Casey et al., 1995; Ganley et al., 2014). When combined with these findings, our results suggest that educational interventions aimed at developing the early spatial processes recruited during mental rotation tasks may be beneficial to promoting children's academic achievement in STEM domains.

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Table 1. *Results of Analysis of Variance Examining Adults' Performance on the Implicit Mental Rotation Task as a Function of Disparity Condition and Gender*

	F	***p***	$\boldsymbol{\eta^2_p}$
Disparity condition	1.47	.236	0.03
Gender	0.41	.526	0.01
Disparity condition × Gender	3.46	.035*	0.07

Note. $^*p < .05$

Table 2. *Tasks Administered in Study 2 by Domain and Cognitive Construct*

Domain	Construct	Task
Spatial	Implicit mental rotation	Spatial Oddball Task
	Explicit mental rotation	CMTT
	Spatial working memory	Location Working Memory Task
Math	Symbolic math	WJ-Applied Problems
General	Verbal working memory	WJ-Numbers Reversed
	Vocabulary	WJ-Picture Vocabulary

Note. CMTT: Children's Mental Transformation Task (Levine et al., 1999); WJ: Woodcock-Johnson Tests of Achievement & Cognitive Abilities-III (Woodcock et al., 2001)

Table 3. *Results of Analysis of Variance Examining 4-Year-Olds' Performance on the Implicit Mental Rotation Task as a Function of Disparity Condition and Gender*

	F	p	η^2_p
Disparity condition	0.04	.996	0.00
Gender	0.66	.422	0.01
Disparity condition × Gender	4.72	**.011***	0.09

Note. *$p < .05$

Table 4. *Gender Differences in 4-Year-Olds' Performance by Task.*

Task	Outcome variable	Girls		Boys		
		M	***SD***	***M***	***SD***	***d***
Spatial Oddball Task	Slope	0.01	0.03	-0.01	0.03	0.85**
CMTT	Proportion correct	0.47	0.19	0.45	0.19	0.08
Location Memory Task	Proportion correct	0.71	0.24	0.61	0.32	0.34
WJ-Applied Problems	Total correct	15.65	3.70	15.14	3.93	0.13
WJ-Numbers Reversed	Total correct	3.48	3.15	3.81	2.98	-0.11
WJ-Picture Vocabulary	Total correct	16.00	2.86	15.24	3.48	0.24

Note. **Two-sample *t*-test indicated $p < .01$.

Table 5. *Correlation Matrix of Relations between Slope on the Spatial Oddball Task and 4-Year-Olds' Performance on Explicit Measures of Cognitive Functioning*

		1	2	3	4	5	6
1. Implicit mental rotation task	*r*	–					
(Spatial Oddball Task slope)	*p*	–					
2. Explicit mental rotation task	*r*	**.33**	–				
	p	.021	–				
3. Spatial working memory	*r*	.11	.17	–			
	p	.477	.263	–			
4. Symbolic math ability	*r*	**.35**	**.36**	**.38**	–		
	p	.019	.018	.011	–		
5. Verbal working memory	*r*	.26	**.39**	**.34**	**.55**	–	
	p	.091	.008	.026	<.001	–	
6. Vocabulary	*r*	.18	.11	.17	**.42**	**.34**	–
	p	.232	.479	.278	.005	.023	–

Note. Significant correlations ($p < .05$) are bolded.

Table 6. *Regression Results Predicting Spatial Oddball Task Slope*

	β	*t*	*p*
Gender	.35	2.41	.021
Explicit mental rotation	.28	1.80	.079
Spatial working memory	-.06	-0.42	.680
Verbal working memory	.17	1.00	.325
Vocabulary	.06	0.43	.673

Note. Gender coded as +1 (female) and -1 (male).

Table 7. *Summary of Prior Results Obtained Using Different Looking-Time Paradigms to Assess Infants' Mental Rotation Abilities in the First Year of Life*

Paradigm	**Article**	***N***	***M* Age**	**Gender Difference**	**Direction of Visual Preference**
Change-detection	Lauer et al. (2015)	56	10 mo	Yes	Mirror
Familiarization	Quinn & Liben (2008)	24	3 mo	Yes	Mirror
	Quinn & Liben (2014)	24	3 mo	No	Mirror
	Quinn & Liben (2014)	48	7 mo	Yes	Mirror
Habituation	Christodoulou et al. (2016)	48	5 mo	No	Non-mirror
	Constantinescu et al. (2018)	61	5 mo	Yes	Mirror
	Gerhard & Schwarzer (2018)	76	9 mo	No	Mirror
	Gerhard & Schwarzer (2018)	76	9 mo	No	Non-mirror
	Erdmann et al. (2018)	208	5 mo	No	Non-mirror
	Erdmann et al. (2018)	168	9 mo	No	No preference
	Moore & Johnson (2008)	40	5 mo	Yes	Mirror
	Moore & Johnson (2011)	40	3 mo	Yes	Non-mirror
	Schwarzer et al. (2013)	24	9 mo	No	Mirror
	Schwarzer et al. (2013)	24	9 mo	No	No preference
	Schwarzer, Freitag, & Schum (2013)	58	9 mo	No	Mirror
	Slone, Moore, & Johnson (2018)	104	4 mo	No	No preference
Violation of Expectation	Frick & Mohring (2013)	38	9 mo	No	Mirror
	Mohring & Frick (2013)	40	6 mo	No	Mirror

Notes. Gender Difference: Yes indicates a significant gender difference, whereas No indicates that the reported gender difference was not significant. Direction of Visual Preference corresponds to whether infants exhibited significantly greater looking to the mirror test stimulus (Mirror), to the non-mirror (Non-Mirror) stimulus, or to neither test stimulus (No preference).

Table 8. *Mean Change-Detection Scores by Rotation Change-Detection Task Condition and Gender and Statistics Evaluating Gender Difference in Performance*

	Girls		Boys			
Rotation condition	*N*	*M* (*SD*)	*N*	*M* (*SD*)	*d*	*p*
Small disparity	14	0.44 (0.13)	13	0.44 (0.08)	-0.03	.947
Medium disparity	16	0.51 (0.07)	18	0.53 (0.08)	0.23	.503
Large disparity	30	0.50 (0.11)	31	0.51 (0.10)	0.04	.878

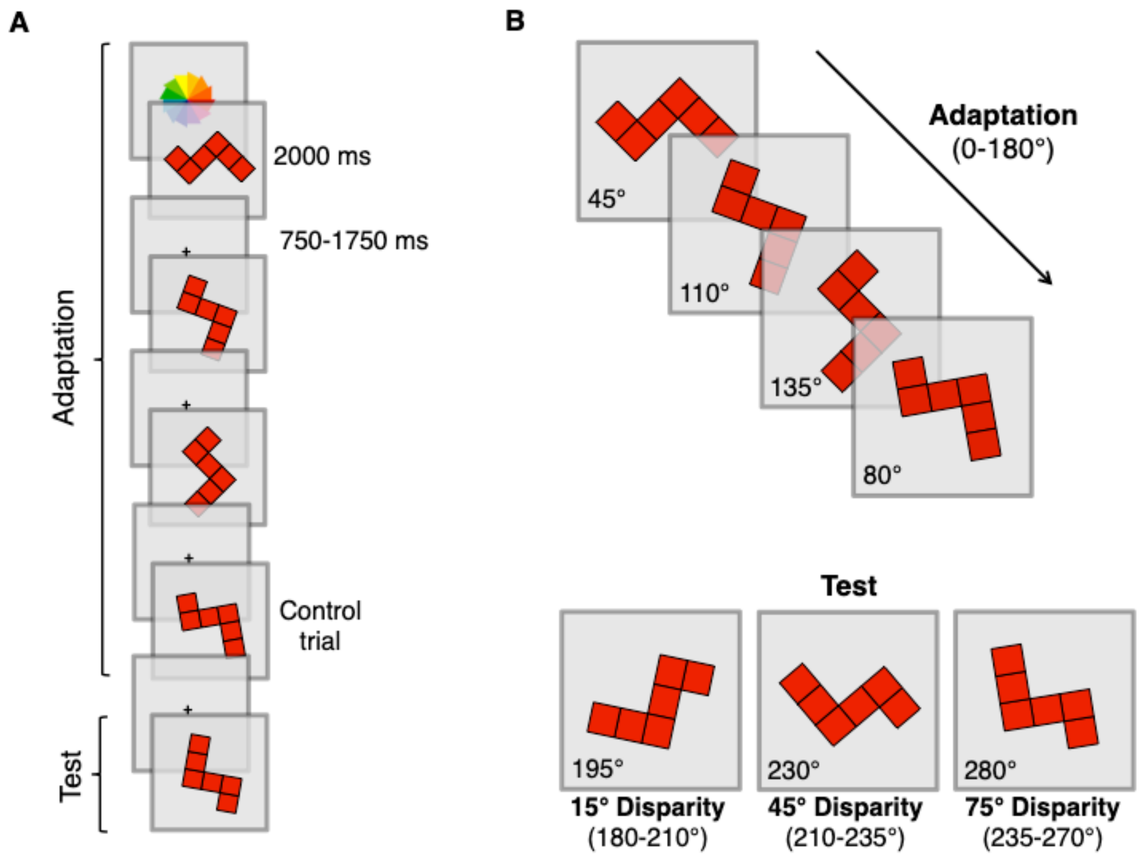

Figure 1. Spatial oddball paradigm designed to assess participants' pupillary responses to differing degrees of rotational change. (**A**) Participants were first presented with three to five adaptation trials during which the stimulus appeared in different orientations along the picture plane within a range of 180°. The final stimulus presented during the adaptation sequence was used as a "control" trial to provide a baseline measure of participants' pupillary responses to the stimulus when it was presented at a novel, but orientation within the 180° adaptation arc. Following each adaptation sequence, participants were presented with a single test trial in which the stimulus deviated from the expected by range by 15°, 45°, or 75°, depending on the disparity condition. (**B**) Example adaptation trials (top) and test trials for the three disparity conditions (bottom). In this example, adaptation trials presented the stimulus within an expected arc of 0 to 180°.

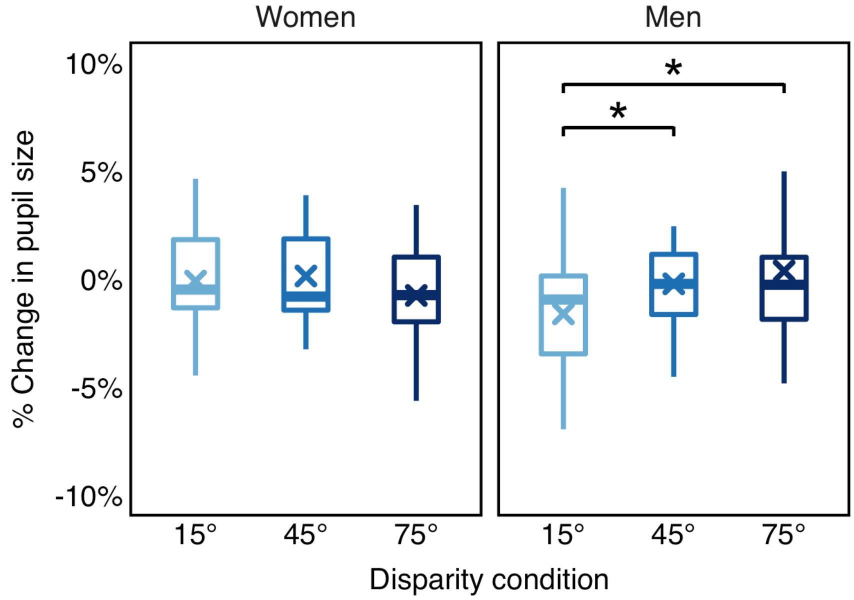

Figure 2. Side-by-side boxplot depicting the percent change in adults' pupil size between control and test trials as a function of disparity condition and gender. A percent change in pupil size greater than 0 indicates that pupil size was greater during test trials relative to control trials. There was a significant interaction between gender and disparity condition (p =.035, η^2_p = .07).

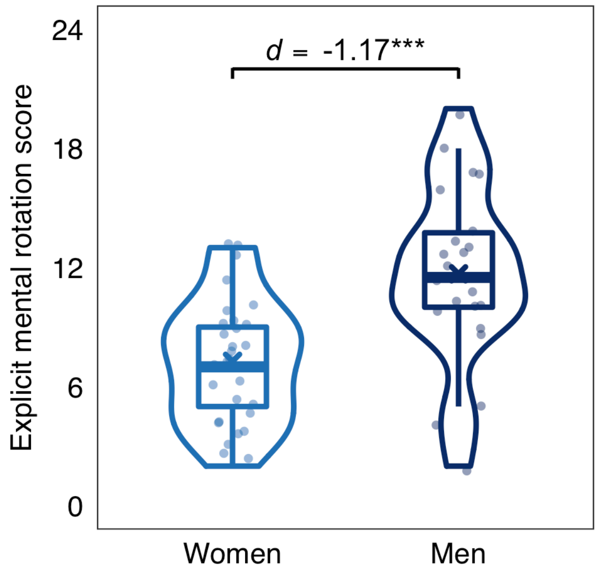

Figure 3. Side-by-side boxplot displaying the significant gender difference in adults' performance on the explicit mental rotation task. *Note.* ***p < .001.

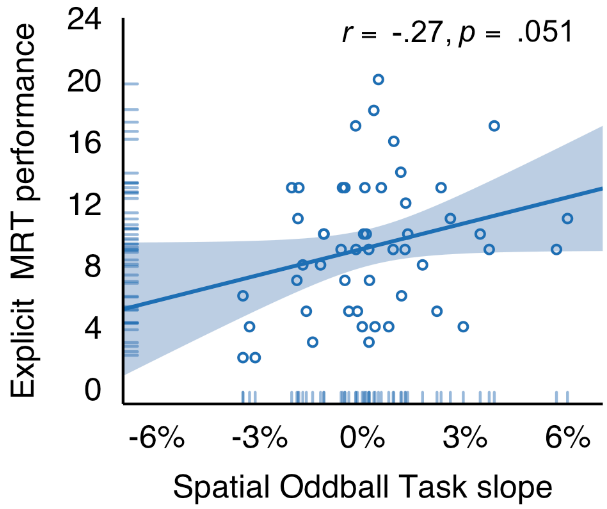

Figure 4. Scatter plot with marginal rug plots illustrating the relation between Spatial Oddball Task slope and explicit mental rotation test (MRT) performance.

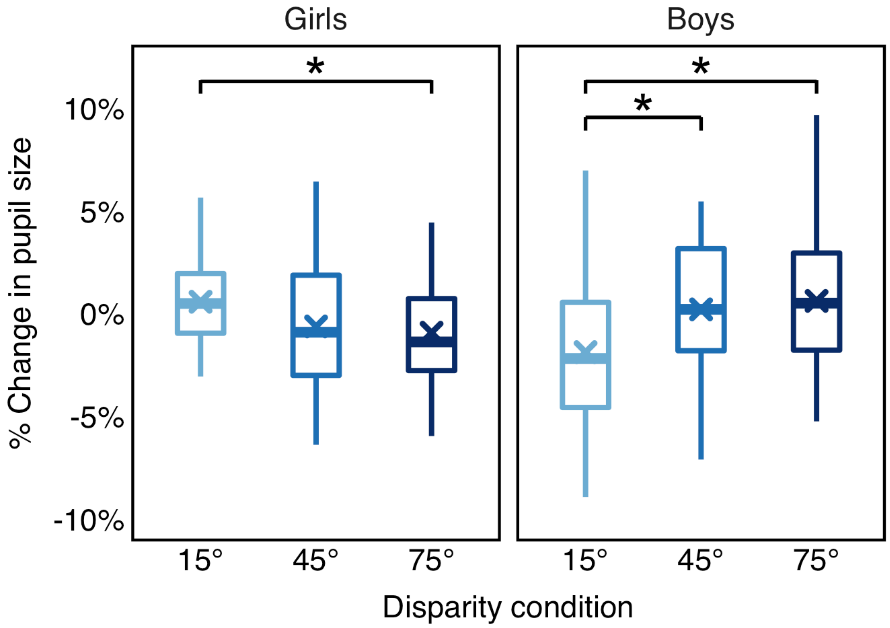

Figure 5. Side-by-side boxplot depicting the percent change in 4-year-olds' pupil size between test and control trials as a function of disparity condition and gender. The interaction between gender and disparity condition was significant. *Note*. *Paired t tests indicated that $p < .05$.

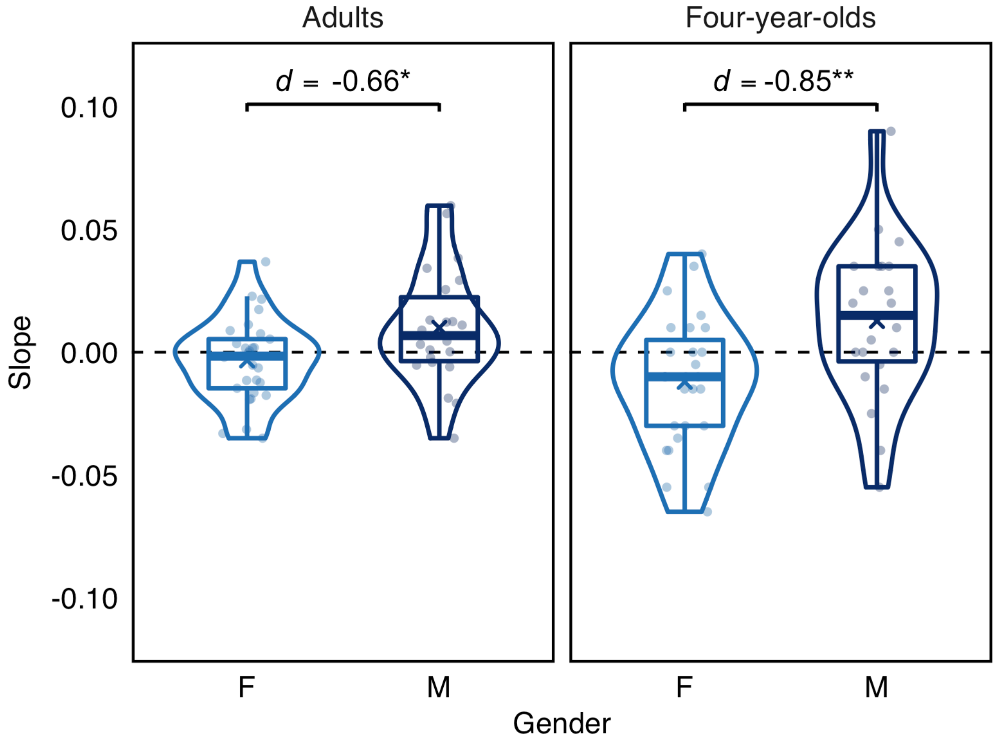

Figure 6. Side-by-side boxplot of gender differences in Spatial Oddball Task slope by age.

Results from Study 1 are shown on the left, and results from Study 2 are shown on the right.

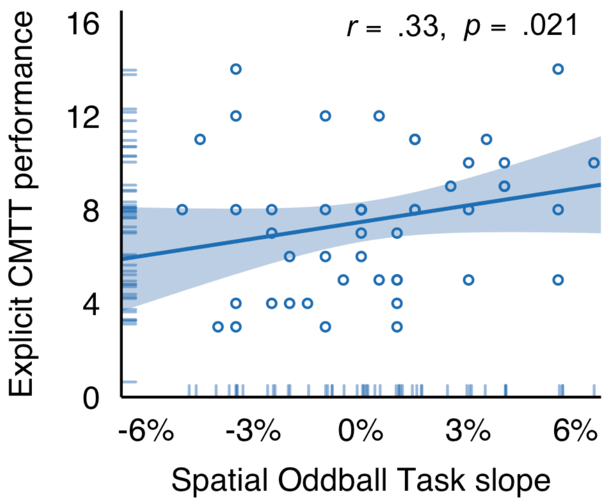

Figure 7. Scatter plot with marginal rug plots illustrating relation between Spatial Oddball Task slope and explicit mental rotation performance, as measured by the Children's Mental Transformation Task (CMTT; Levine et al., 1999).

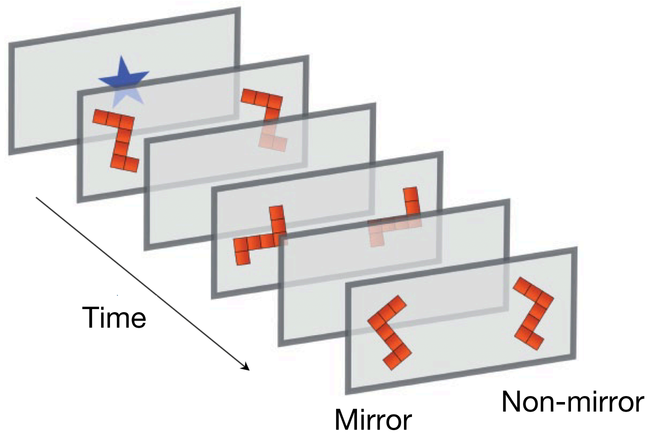

Figure 8. Change-detection paradigm designed by Lauer and colleagues (2015) to assess mental transformation processes in infancy. Infants were simultaneously presented with two peripheral image streams that contained a single 2-dimensional Tetris-like shape. In both image streams, the shape appears in a novel orientation (i.e., rotated to a new position along the picture plane) each time the stimulus is presented. The two image streams are identical except that, on every third presentation of the stimuli, the shape in one image stream (i.e., the mirror stream) is the mirrored image of the shape in the other stream (i.e., the non-mirror stream). If infants detect the mirror reversal of the shape in the mirror stream, they are expected to display greater looking towards the mirror stream relative to the non-mirror stream, as found by Lauer et al.

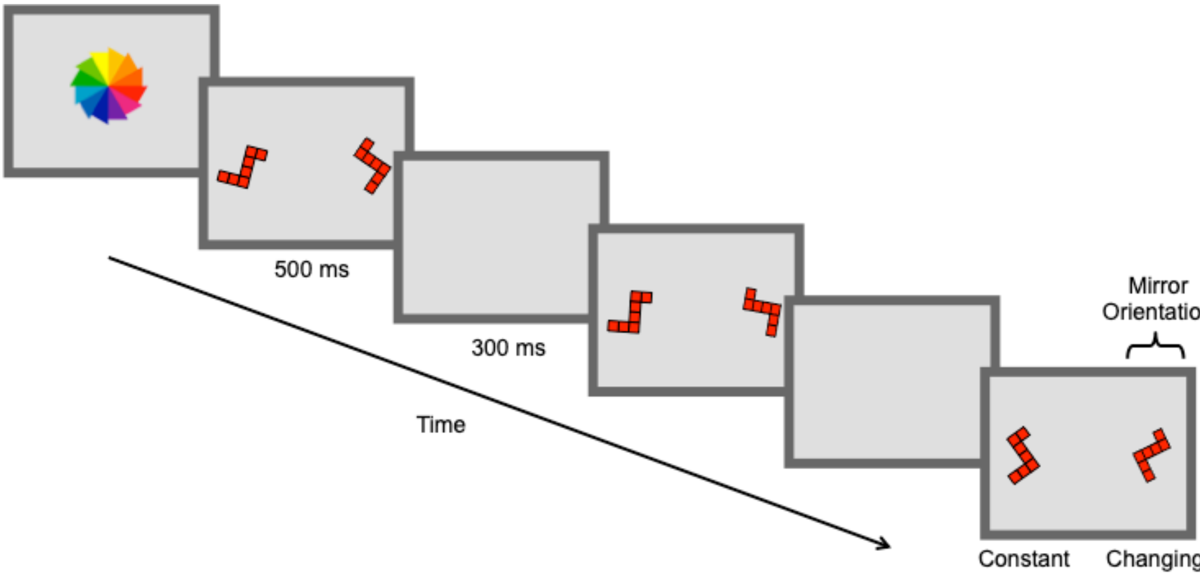

Figure 9. Rotational Change-Detection Task Paradigm. Infants are presented with two image streams that contain a single Tetris-like shape presented at different orientations along the picture plane. The shape is presented in both streams simultaneously for 500 ms and is followed by an interstimulus interval of 300 ms. The orientation of the shape varies within a range of 180° in both image streams with the exception that on every third stimulus presentation, the shape in the changing stream appears in an orientation that is outside of the expected 180° range and reflected along the horizontal axis (i.e., mirrored).

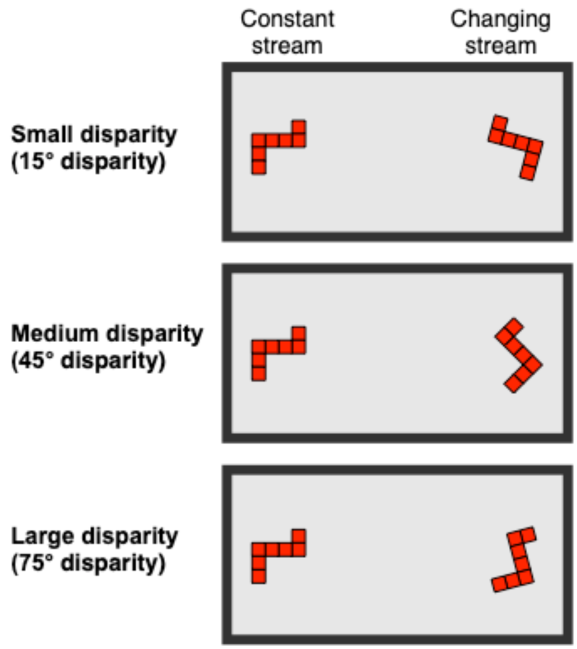

Figure 10. Example stimulus presentations for each of the three Rotation Change-Detection Task conditions. The stimulus in the constant stream is presented in a novel rotation that is within the expected 180° arc. The stimulus in the changing stream has been rotated outside of the expected 180° arc and horizontally reflected into its mirrored image.

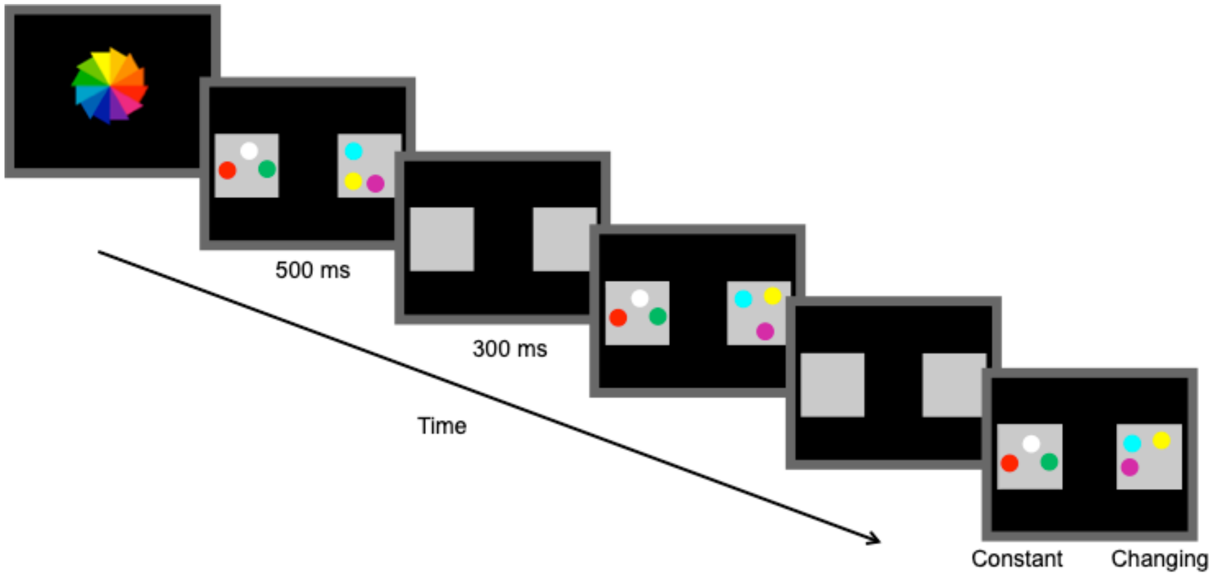

Figure 11. The Location Change-Detection Task (Oakes, Hurley, Ross-Sheehy, & Luck, 2011) designed to assess infants' spatial short-term memory capacities.

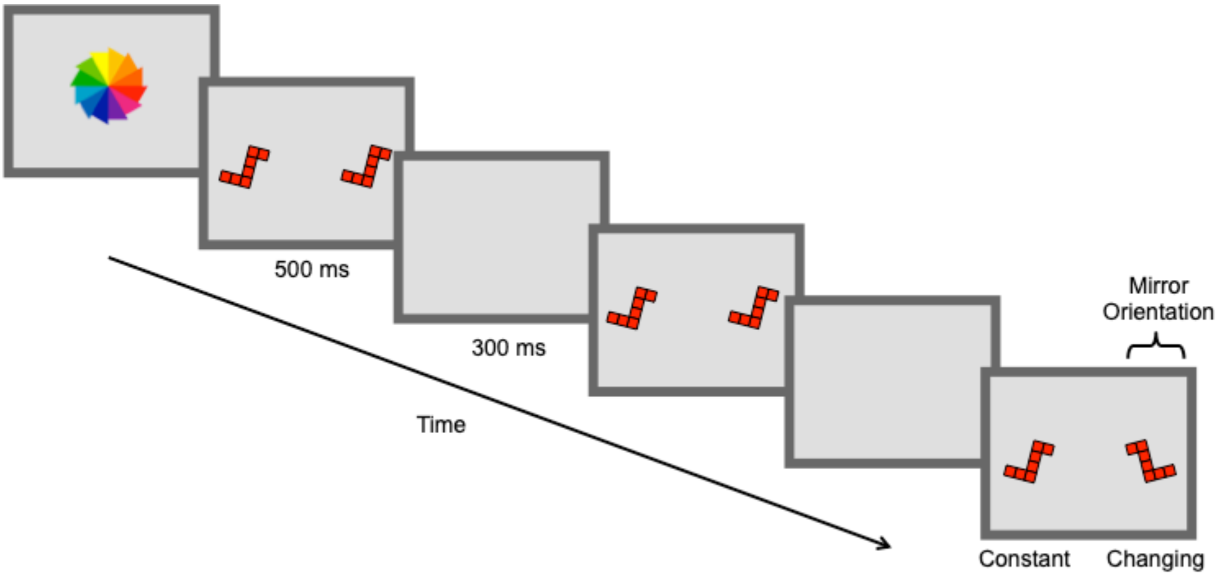

Figure 12. The Mirror Change-Detection Task designed to assess infants' ability to discriminate between an object and its rotated mirrored image in the absence of rotational change.

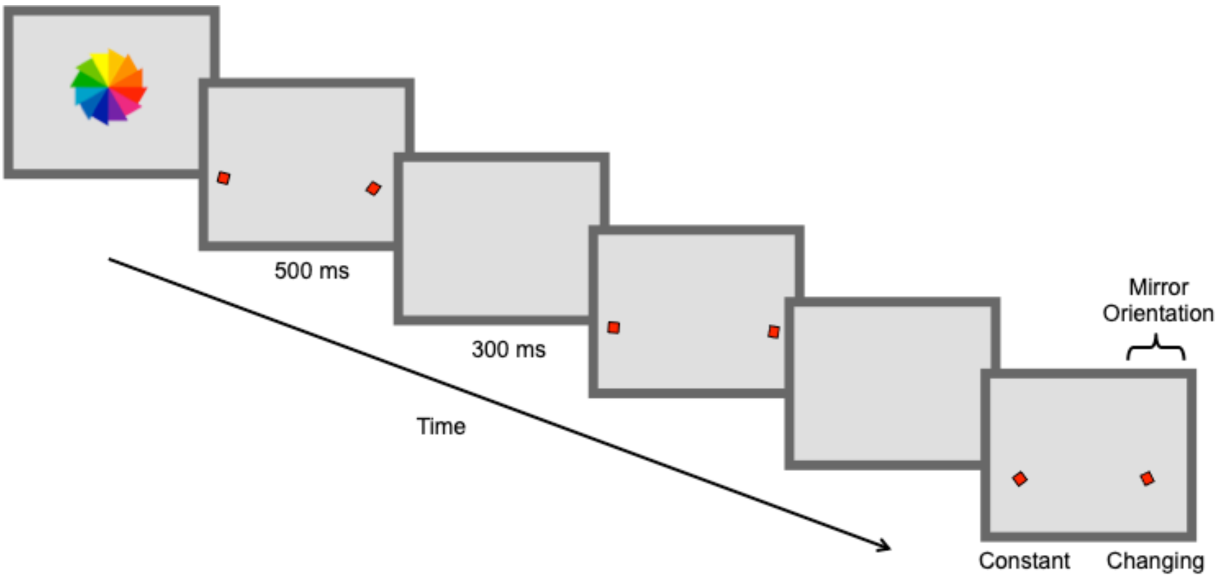

Figure 13. The Block Change-Detection Task Paradigm.

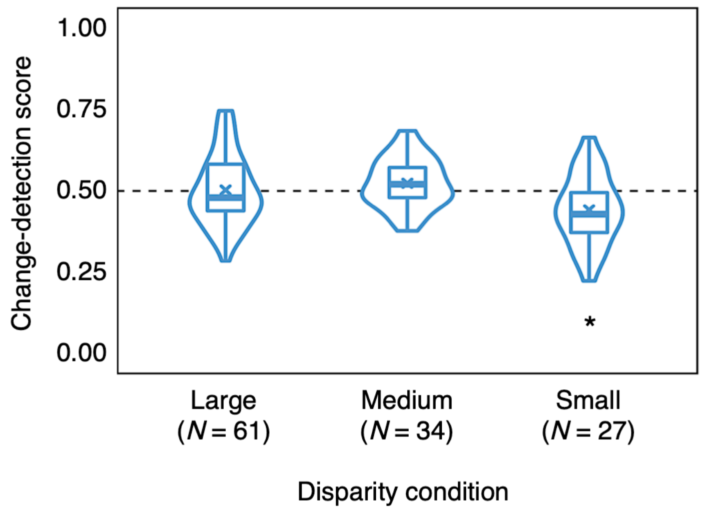

Figure 14. Side-by-side boxplot of infants' mean change-detection scores in the three different Rotation Change-Detection Task disparity conditions. Crosses denote condition means.

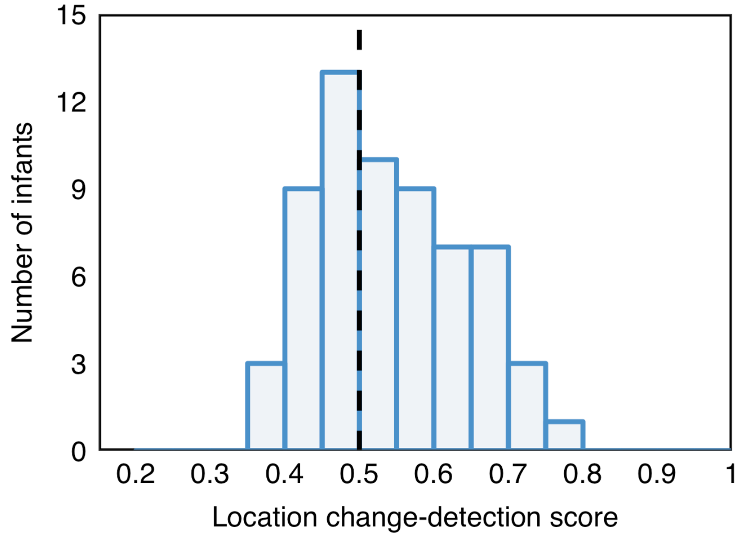

Figure 15. Histogram of mean Location Change-Detection Task scores. Change-detection scores greater than 0.5 indicate greater looking towards the changing stream; change-detection scores less than 0.5 indicate greater looking to the constant stream.

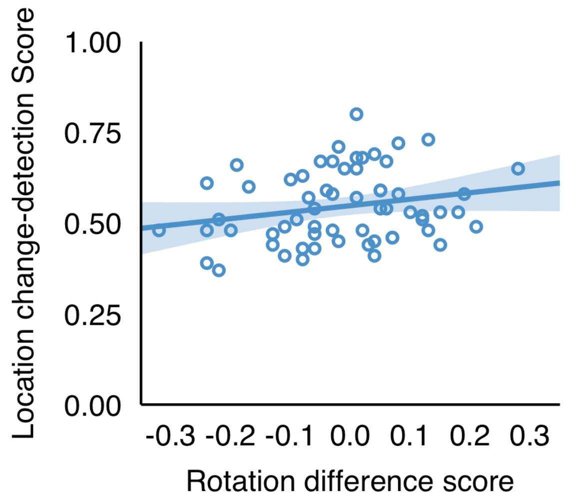

Figure 16. Scatterplot of the relation between the infants' difference scores obtained from the Rotation Change-Detection Task and their location change-detection scores.