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Keeping Behavior in Context: A Dynamic Systems Account of a Transition in Spatial Recall Biases

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Abstract: In location memory tasks, young children show biases toward reference axes, whereas older children show biases away from axes. As predicted by a dynamic systems model, this transition is gradual and varies across target location (Schutte & Spencer, 2009). Here we tested whether task context would influence the transition by testing children in a sandbox memory task that varied in several ways from Schutte and Spencer’s task, with the key difference being the salience of boundaries. In this task context, the transition was delayed but occurred gradually. These results provide further evidence for the context-dependent nature of behavior over development.

Keywords: memory, dynamic systems, cognitive development, spatial recall, geometric bias

1. INTRODUCTION

Historically, most research in developmental psychology has focused on identifying when children have specific knowledge (e.g., Brown & DeLoache, 1978; Elman et al., 1996; Siegler, 1996; Thelen, 2000; van Geert, 1998). More recently, researchers have shown that children’s demonstrations of their knowledge depend on the details of the task used to elicit the knowledge. For example, early research on infants’ location memory demonstrated that 8- to 10-month-old infants typically make A-not-B errors (searching to a previously correct A location when they just saw the prize hidden at a different, B, location), while 10- to 12-month-old infants perform more accurately. In a different task context, however, even preschoolers will make the A-not-B
error, for example, when they need to complete a multi-step task in order to get the prize (Zelazo, Reznick, & Spinazzola, 1998), or when the task space allows for continuous rather than discrete measures of error (Spencer, Smith, & Thelen, 2001). Numerous other examples of the influence of task context can be found within cognitive development, including conservation of number (e.g., Mehler & Bever, 1967), theory of mind (e.g., Siegal & Beattie, 1991), and visual working memory capacity (e.g., Simmering, 2008).

Seemingly contradictory findings across tasks have led theorists to propose two types of explanations. One argument is that task differences illustrate the dissociation of competence and performance, and that researchers must design tasks that appropriately reveal children’s underlying competence. A drawback of this approach, however, is that results cannot differentiate whether children lack competence or we have not yet discovered the proper task. This limitation has led to an alternative explanation, which we adopt here, that knowledge does not just reside “in the head.” Rather that we must consider behavior in context, that is, how a child’s performance emerges through interactions between the task context and the child (e.g., Thelen & Smith, 1994). This type of explanation is particularly prevalent in dynamic systems and ecological theories, which characterize behavior as the result of the interaction between the brain, body, and environment. For example, Plumert (2008) illustrated how spatial biases in location memory tasks result from the interaction between the task structure (environment) and the cognitive abilities of the person. Specifically, the extent to which spatial memory responses were biased and the direction of the bias depended on the structure of the task space (e.g., the availability of reference axes) and the age of the participant.

The experiments presented here investigated the influence of task context on an established developmental transition in the direction of spatial recall biases (e.g., Schutte & Spencer, 2009). Although several studies have documented this transition, previous studies have yielded conflicting results in terms of when the transition occurs and the rate at which it occurs (Huttenlocher, Newcombe, & Sandberg, 1994; Schutte & Spencer, 2009; Schutte, Spencer, & Schöner, 2003). The current study sought to understand how task structure may lead to these differences in the transition while providing a more complete picture of the transition in the current task, the sandbox task.

Remembering locations is a basic skill necessary for interacting successfully with the world. Even young infants have some ability to remember locations (e.g., Wilcox, Nadel, & Rosser, 1996); however, the ability to remember locations continues to develop throughout childhood and into adolescence (e.g., Hund & Spencer, 2003; Luciana, Conklin, Hooper, & Yarger, 2005). Locations are necessarily remembered relative to a referent. A commonly used referent is the geometric region in which the object is located, for example, on the dining room table or in the living room.

Spatial recall performance that uses the geometry of a space (i.e., edges and symmetry axes) to remember a location results in geometric biases, that is,
biases related to the geometry of the space (e.g., Spencer & Hund, 2002). The transition we examine here is in the direction of geometric biases in spatial memory when remembering locations in homogeneous spaces (Huttenlocher et al., 1994; Schutte & Spencer, 2002). Specifically, young children (e.g., 3-year-olds) are biased toward the midline symmetry axis of a homogeneous space whereas older children and adults are biased away from the symmetry axis.

Huttenlocher and colleagues (1994) were the first to identify this transition, by testing children’s spatial memory using a sandbox task. In this task children had to remember over a short delay the location of a toy buried in a 60 in. long, rectangular sandbox. Huttenlocher and colleagues found that when 4- to 5-year-olds and 6- to 7-year-olds remembered locations distributed along the length of this large, homogeneous space, their responses were biased toward the center of the space. In contrast, 10- to 11-year-olds’ responses were biased away from the center of the space and toward the center of each half (see Figure 1). Note that the change in direction of bias is only apparent at some locations, which are highlighted by the gray dashed box in Figure 1; it is the bias at these locations that will be the main focus of the current paper.

Schutte et al. (2003) tested 2-, 4-, 6-, and 11-year-olds in an A-not-B version of the sandbox task. In this task, children completed six trials at

Figure 1. Diagram of the sandbox with the pattern of geometric biases for younger (a) and older (b) children (e.g., Huttenlocher et al., 1994). The gray dashed boxes highlight the spatial locations for which bias changes directions over development.
one location (the “A” location), followed by three trials at a second nearby location (the “B” location). Across three experiments Schutte et al. tested 4 target locations: 15, 18, 22, and 24 in. from the left edge of the sandbox (i.e., 15, 12, 8, and 6 in. from the center of the sandbox, respectively). Schutte et al. examined the “A” trials for geometric biases and found they generally replicated Huttenlocher et al. (1994): 2- and 4-year-olds’ responses were biased toward midline at all the locations that were tested, and 11-year-olds’ responses were biased away from midline at all locations. Six-year-olds’ responses, however, were not significantly biased toward or away from midline at any location. This differed from Huttenlocher et al. who found that 6- to 7-year-olds’ responses were biased toward midline. Thus, there were slight differences in the details of the transition across these two studies.

Further research showed that the timing and progression of the transition appears to depend on the task context. Research by Spencer and colleagues (Hund & Spencer, 2003; Schutte & Spencer, 2002; Spencer & Hund, 2003) found that in a different spatial recall task, the “spaceship” task, the transition in geometric biases occurred at an earlier age. In this task children remembered the location of a small, spaceship-shaped target on a large (48 × 36 in.) table. By 6 years of age children in this task showed bias away from midline at all of the locations tested (Hund & Spencer, 2003; Spencer & Hund, 2002), which contrasts with results from the sandbox task (Huttenlocher et al., 1994; Schutte et al., 2003).

Spencer and colleagues proposed the Dynamic Field Theory (DFT), a dynamic systems model of spatial cognition, to explain the transition in geometric biases (e.g., Schutte & Spencer, 2009; Simmering, Schutte, & Spencer, 2008; Spencer, Simmering, Schutte, & Schöner, 2007). The DFT presents a mechanistic explanation for the developmental changes in spatial memory, and predicts that the transition in geometric biases depends on target location and the structure of the task space (Schutte & Spencer, 2009, 2010).

The DFT is a dynamic systems model instantiated in a network of neural fields (see Figure 2). The model is made up of three interconnected fields: an excitatory perceptual field (first layer, Figure 2a) which codes for the perceptual structure in the task space, including the target location; an excitatory working memory field (third layer, Figure 2a) which receives excitatory input from the perceptual field (see solid arrows) and maintains the memory of the target location; and an inhibitory field (second layer, Figure 2a), which receives input from both the perceptual and working memory fields (see solid arrows) and sends inhibition back to both fields (see dashed arrows). For each layer in Figure 2a, location is represented along the x-axis, activation along the y-axis, and time along the z-axis.

Figure 2 illustrates how the model works through examples of memory trials to two locations in the sandbox task. At the start of a trial, the only activation is that representing the edges of the sandbox and the midline symmetry axis. When the toy is buried at the hiding location (e.g., 10 inches
Figure 2. Two simulations of the DFT with targets 10 in. (a) and 14 in. (b) from midline. The midline of the sandbox is at 0 and the right edge of the sandbox is at 30. See text for further details (color figure available online).
in Figure 2a) this creates a localized “peak” of activation in the perceptual field which sends activation to the working memory and inhibitory fields. Once the toy is completely buried, the activation in the perceptual field dies out, but the activation in the working memory field self-sustains due to neural interactions within and between the fields. In the DFT, bias in spatial memory emerges through interactions between fields (described further below): if excitation dominates, then the midline peak attracts the peak held in working memory, leading to a bias toward midline; if inhibition dominates, the midline peak repels the peak in working memory, leading to a bias away from midline.

According to the DFT, developmental changes in spatial memory are the result of quantitative changes in two factors: the precision of neural interactions and the perceptual salience of the midline symmetry axis (Schutte & Spencer, 2009; Simmering, Schutte, & Spencer, 2008; Spencer et al., 2007). Schutte and Spencer (2009) used the DFT to model the transition in geometric biases in the spaceship task, and found that quantitative changes in the strength of neural interactions and in the precision and salience of the perception of midline (i.e., strengthening and narrowing the input associated with midline) resulted in a gradual reduction in bias toward midline, followed by the emergence of repulsion from midline later in development. Importantly, the DFT predicts that children will not transition all at once from showing bias toward midline at all locations to showing bias away from midline; rather, in the DFT, the magnitude and direction of drift change differentially for different locations over development. This predicted difference across target locations is due to changing overlap between the (target) memory peak and the excitation or inhibition associated with the midline symmetry axis (described further later).

Schutte and Spencer (2009) tested this prediction by testing four groups of children between 3 and 5 years of age in the spaceship task. Results supported the DFT: over development the direction of memory errors changed from being biased toward midline, to not being biased, to being biased away from midline. Moreover, the transition did not occur for all target locations at once; rather, when the transition occurred depended on the target location. Specifically, targets furthest from midline were the first to transition from being biased toward midline to not being biased. The target closest to midline was the last to transition from biased toward midline to not being biased. In the model, this occurred as the spread of excitation associated with midline reduced due to increasing precision in the perception of the midline symmetry axis and strengthening inhibitory connections. Bias away from midline first emerged at an intermediate target location and gradually extended such that targets closer to midline and further from midline became biased away from midline. As with the decrease in bias toward midline, this nonlinear change in bias away also results from both increasing precision in the perception of midline and the increase of inhibition as neural interactions strengthen over development (see Schutte & Spencer for further detail).
As described before, research using the sandbox task found that the transition in geometric biases occurred later in development and biases were more consistent across locations within a given age group than in the spaceship task. What is the source of the differences across these studies? We explore three possibilities in this paper. First, previous studies using the sandbox task did not examine the timing of the transition in detail, that is, they used relatively coarse developmental sampling (i.e., 4- to 5-year-olds, 6- to 7-year-olds, and 10- to 11-year-olds in Huttenlocher et al., 1994; 2-, 4-, and 6-year-olds in Schutte et al., 2003). By contrast, Schutte and Spencer (2009) included separations of less than one year between age groups in the spaceship task. Examining the transition over a finer sampling of development can provide important tests of the DFT account of this developmental transition. Specifically, a finer sampling will allow tests of whether the transition in bias will occur at different points in development depending on the distance of the target location from midline.

The second possible source of differences across studies is the difference in task spaces: the sandbox was slightly larger and more rectangular (60 \times 16 in.) than the table used in the spaceship task (48 \times 36 in.). Huttenlocher and colleagues (1994) found that the transition in biases occurred earlier in development (compared to the sandbox task) in a paper and pencil task that used a small rectangle (20 \times 5 cm) as the task space. In a larger space, the midline symmetry axis might be more difficult to perceive due to the distance between the edges. According to the DFT, a less salient symmetry axis should result in more bias toward the axis (Schutte & Spencer, 2010). Therefore, the transition in the sandbox task may have occurred later than in the spaceship task because the sandbox is slightly larger, resulting in a perceptually-weaker midline. In addition, the salience of the edges differed across task spaces. The edges of the sandbox were painted bright primary colors, providing strong contrast with the sand in which the toys were buried. By contrast, the spaceship table presented a homogeneous gray surface that blended into the black edges; moreover, the spaceship task was conducted in a dimly-lit room (to improve visibility of the computer-projected targets on the table), making the edges even less salient to children performing the task.

The third important difference across studies was the layout of target locations within the task space. In the spaceship task, all of the targets were closer to midline than to the outer edges of the table, and each child only responded to two target locations (one on each side of midline). By contrast, in the sandbox task used by Huttenlocher et al. (1994), each child responded to targets distributed evenly throughout the entire task space. Whether the targets were closer to midline or the edges of the task space should influence performance; responses to the targets closer to the edge should be biased toward the center of the space for all ages (see Figure 1). Depending on the type of analyses conducted (i.e., curve fits across the task space, as in Huttenlocher et al., versus \( t \)-tests comparing error to zero, as in Schutte &
having targets distributed across the sandbox could mask slight biases away from midline at target locations that are closer to the center of the task space. Moreover, the difference in the proximity of targets to one another could influence performance, as Schutte et al. (2003; see also Schutte & Spencer, 2002; Spencer & Hund, 2003) found that children’s memory for location was biased toward their memory of previously remembered target locations. Critically, interactions between targets depended on their proximity to one another. Thus, memory of the targets should have interacted very little in the spaceship task used by Schutte and Spencer, because there were only two targets that were farther from each other and on opposite sides of the table, compared to the Huttenlocher and colleagues’ sandbox task, which used several target locations spread across the width of the sandbox.

Another difference in target layout between the sandbox task used here and the spaceship task used by Schutte and Spencer (2009) is that we included the same locations on both sides of the sandbox. Doing this allows us also to examine whether there are differences in bias across sides. Other studies using the sandbox task have not analyzed effects of side of the task space; however, Schutte and Spencer (2002) report side differences using the spaceship task. Schutte and Spencer (2002) found that in the spaceship task, 3-year-olds were more strongly biased toward midline when the targets were on the left side than when the targets were on the right side of midline. It is possible that targets on the right side of midline transition earlier than targets on the left side of midline. Schutte and Spencer (2009) were not able to examine this due to presenting each target on only one side of the space. The larger scale of the sandbox allows us to examine differences across side while still keeping locations far enough apart to minimize long-term memory effects.

The DFT predicts that the same general pattern—biases changing from toward midline, to unbiased, to away from midline over development—should occur during the transition in the sandbox task as in the spaceship task, as the mechanisms underlying developmental changes in spatial memory should not depend on the task. However, the specific timing of when the transition occurs for each of the locations should differ by the task context. In dynamic systems terms, the child’s memory system and the task space are part of a system that organizes in the moment.

In a sense, in comparison to Schutte and Spencer (2009) in the current study we are holding the memory part of the system constant (i.e., there is no reason to expect substantial differences in memory abilities between the children in Schutte and Spencer (2009) and the children in the current study), and varying the environment. Although the environment is an important part of the system and manipulating it can result in major changes, there are still some things we would expect not to change. Specifically, if the transition in biases predicted by the DFT results from changes in the strength of neural interactions underlying memory, this pattern should occur in any task context. However, if the direction of bias at a specific location depends on where that
target is relative to other targets and the midline and edges of the task space, as well as the perception of the midline and edges, then changes in these factors across tasks should affect the development timing of the pattern of biases. Thus, differences in the stimulus details between the spaceship and sandbox tasks (i.e., how close the targets are to each other, the more salient outer edges of the sandbox) may result in differences in the timing of the transition and differences in the pattern across targets during the transition.

Two critical differences between tasks that we expect will influence performance are the layout of the targets and the salience of the edges of the task space. The slightly larger size of the task space may influence the timing of the transition, but it should not influence the pattern of response bias during the transition. To examine how the layout of the targets and salience of the edges influence performance in the DFT, we ran exemplar simulations incorporating these differences. The simulations used parameter settings from Schutte and Spencer (2009).

To model the sandbox task, the locations were changed to those previously used in this sandbox task and an outer reference axis was added as an input. In the DFT the strength of the input of a reference axis is based on the perceptual salience of the axis (Schutte & Spencer, 2010). Although even young children are good at perceiving vertical symmetry axes (e.g., Ortmann & Schutte, 2010), the outer edge of the sandbox should still be more perceptually salient due to it being visible and a different color from the sand, and, therefore, the outer edge is a stronger input than the midline symmetry axis.

Simulations of the model using Schutte and Spencer’s (2009) 5-year-old parameter settings are shown in Figure 2. Note that, for simplicity, we modeled only the side of the sandbox that contained the target. Figure 2a shows a simulation with the target 10 in. from midline (i.e., 20 in. from the outer edge), and Figure 2b shows a simulation with the target 14 in. from midline (i.e., 16 in. from the outer edge). There are three inputs into the perceptual field (top layers): two reference axis inputs (midline and the right edge of the sandbox) and the target input. The target input is a strong input that is only presented while the target is visible. Because the reference axes are always perceptually available, the reference axis inputs remain active throughout the trial. Critically, in order to capture the greater salience of the outer edge, the input for the edge of the sandbox is stronger than the midline input. Specifically, the input for the edge of the sandbox was 1.6 time stronger than the input for the midline. This level of input allowed for a strong input that was not so strong it destroyed the peak associated with the target input.

Activation from the perceptual field is fed into the inhibitory and working memory fields. The target input builds a localized peak of activation centered at the target location in the working memory field. The peak self-sustains due to excitatory interactions among the neurons within the working memory field and inhibition that is projected back broadly from the inhibitory field.
(see dashed arrows in Figure 2). During the delay the target peak drifts away from midline due to inhibition associated with the activation at midline (see Schutte & Spencer, 2009, for further details).

Figure 2b shows a simulation with the target at 14 in. At this location, the target peak in working memory drifts away from the reference axis input at the outer edge of the sandbox, that is, toward the midline of the sandbox, even though the target is closer to midline than the outer edge. This drift is the result of inhibition associated with the activation at the edge of the sandbox “pushing” the peak away from the outer axis. The inhibition associated with the edge of the sandbox is stronger than the inhibition from the midline of the sandbox because activation is stronger at the more salient edge of the sandbox. Over development, as neural interaction becomes more precise and the perception of midline becomes stronger, the bias away from the outer edge at 14 in. should decrease, although it may not disappear completely. Overall, the pattern of bias found in these exemplar simulations is different from that found by Schutte and Spencer. Specifically, none of the parameter settings (i.e., “ages”) used by Schutte and Spencer led the model to show bias away from midline at one location and toward midline at another location.

Based on the previous findings by Schutte and Spencer (2009) and the exemplar simulations run here, we generated two predictions of the DFT, which we tested in two experiments. First, we predicted that for targets in the central region of the sandbox (see gray boxes, Figure 1) there should be a gradual developmental transition in bias that depends on target location: rather than a complete transition from all locations showing bias toward midline to all locations showing bias away from midline, bias should reduce differentially based on the distance from midline. Specifically, biases at the intermediate (14 in.) location should decrease, but not reduce completely due to bias away from the outer edge; responses to locations closest to midline should be the last to reduce in bias due to the stronger excitatory contributions from midline. We tested this prediction by using a smaller sampling rate over development than has been used in prior studies of this task and testing memory only for locations within the range that shows developmental change. The sampling rate we used was one year. Although having groups one year apart is still a rather coarse sample, given the prolonged nature of the transition in the sandbox (Huttenlocher et al., 1994; Schutte et al., 2003) this sampling rate should provide a comprehensive picture of the transition.

We also expected that the full transition to bias away from midline across locations would occur later in the sandbox task than the spaceship task due to the size of the space; the larger space should reduce the perceptual salience of the midline symmetry axis, and Schutte and Spencer (2010) demonstrated that increasing the salience of the symmetry axis accelerates the developmental transition. However, because the developmental changes in neural interaction should not be influenced by the task, a reduction in bias should occur at the same point in development across tasks, i.e., between 3 and 4 years of
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age. Specifically, our second prediction was that an overall reduction in bias should occur at some locations between 3 and 4 years of age due to changes in neural interaction. The exact pattern of change, however, may not be the same across tasks due to task differences; even after the bias toward midline has reduced at locations close to midline, bias toward midline should remain at further locations due to inhibition (i.e., repulsion) from the outer edge. To test this prediction we included locations out to 14 in. from midline (16 in. from the outer edge), where we expected bias away from the edges should be evident even though the locations were still closer to the midline symmetry axis than they were to midline.

In addition to including targets out to 14 in., we also included locations on both sides of the sandbox. Doing this allowed us to examine whether there were differences in bias across sides. Other studies using the sandbox task have not analyzed effects of side of the task space even though they included targets on both sides of midline; however, Schutte and Spencer (2002) report differences across sides when children were tested in the spaceship task. They found that 3-year-olds were more strongly biased toward midline when the targets were on the left side than when the targets were on the right side of midline. It is possible that targets on the right side of midline transition earlier than targets on the left side of midline.

2. EXPERIMENT 1

2.1. Method

2.1.1. Participants. Fifteen 3-year-olds ($M = 3$ years $7.5$ months, $SD = 3.5$ months, 5 females, 10 males), 16 4-year-olds ($M = 4$ years 4.8 months, $SD = 4.2$ months, 11 females, 5 males), 16 5-year-olds ($M = 5$ years 5.4 months, $SD = 3.5$ months, 7 females, 9 males), 17 6-year-olds ($M = 6$ years 6.7 months, $SD = 2.8$ months, 8 females, 9 males), and 15 7-year-olds ($M = 7$ years 6.4 months, $SD = 0.8$ months, 7 females, 8 males) participated in the study. Data from four additional 3-year-olds were collected but were not including in the analyses due to experimenter error (two 3-year-olds), the child not completing the task (one 3-year-old), or equipment failure (one 3-year-old). Children were primarily middle class, and all parents provided written consent.

2.1.2. Materials. A circular sandbox (17 in. diameter, 5 in. deep) was used for the training trials. The sandbox used for the test trials was 60 in. long, 16 in. wide, and 20 in. high with a false bottom 6 in. from the top of the sandbox. The sandbox was painted dark blue, and was filled with approximately 4 in. of play sand. White markings painted every 6 in. on the outside wall of the experimenter’s side of the sandbox helped the experimenter identify the hiding locations. The markings were not visible from the participant’s view.
A wooden bar with holes drilled through the bar at one-inch intervals ran along the length of the sandbox approximately 2 in. beneath the top of the sand. Wooden pegs were positioned in the holes at the hiding locations and were not visible above the sand. Small toys (approximately 1 in. tall by 1 in. wide by 1 in. deep) were hidden by placing them over the top of the pegs and covering them with sand.

A digital video camera was mounted on the ceiling above the sandbox. Following each session, participants’ responses were scored from the videos using a grid placed over a computer monitor. Curtains that reached from the ceiling to the floor were hung around the sandbox to block the view of external landmarks. Participants sat on a child-sized chair at the center of one side of the sandbox with the experimenter seated in a chair opposite the child.

2.1.3. Procedure. Sessions began with six training trials that were conducted using the small, round sandbox. On the first trial, the experimenter half-buried a toy in the center of the circular sandbox, counted to 5, and then encouraged the child to reach for the toy. On the second trial the experimenter buried the toy in the same location with only the top showing. On the remaining four training trials, the toy was buried completely in locations at 12, 3, 6 or 9 o’clock relative to the child, with the order randomized across participants. Following the training trials, the experimenter and child moved to the large sandbox.

Each test trial began with the experimenter placing a toy on the peg at the target location, drawing the child’s attention to the hiding location, and then covering the toy completely with sand. After the toy was buried such that its location was not marked in any way, the experimenter asked the child to look up from the sandbox. The experimenter and child counted to 5, and then the child was asked to search for the toy.

2.1.4. Experimental Design. Toys were hidden at one of eight possible hiding locations: 16, 20, 24, 28, 32, 36, 40, or 44 in. from the left edge of the sandbox (i.e., ±2, ±6, ±10, and ±14 in. from midline). We chose to not include locations closer to edges of the sandbox because memory biases at these locations do not change direction over development (e.g., Huttenlocher et al., 1994; see Figure 1). Children completed two trials to each location for a total of 16 trials; for each participant, the order of hiding locations was randomized with the constraint that the same location could not be used on consecutive trials.

2.1.5. Behavioral Scoring. All sessions were taped and scored at a later time using a grid affixed to a computer monitor. Scorers coded the sessions following the procedures used by Schutte et al. (2003). Responses were coded to the nearest half inch. A second scorer coded 18% of the sessions. The mean deviation (absolute value) between the two scorers was 0.23 in. (SD = 0.39
in.). If the difference between scorers was greater than 1 in., two independent scorers viewed the video tape and agreed on the score (8 trials, 3.33% of double-coded trials). For all disagreements of 1 in. or less the initial scorers’ values were used (remaining 96.7%).

2.1.6. Method of Analysis. Each child completed two trials to each location. Mean error to each location was computed for each participant by subtracting the correct location from the location of the child’s response. Errors toward midline were coded as negative and errors away from midline were coded as positive (i.e., errors on the left side of the sandbox were multiplied by −1). Coding error in this manner allowed us to examine differences across the sides of the sandbox. To test in detail for gradual age- and target-dependent changes in errors we conducted a series of ANOVAs with Distance (2, 6, 10, 14 in. from midline) and Side of Sandbox (left, right) as within-subjects variables and Age (3, 4, 5, 6, 7 years) and Gender (male, female) as between-subjects variables. In addition to the follow-ups of the interactions in the ANOVA, in order to determine if children’s responses were significantly biased toward or away from midline, we conducted planned t-tests, collapsed across side to determine if mean error to each distance for each age group was significantly different from zero.

Schutte and Spencer (2009) found that there was high variability in geometric bias across participants during the transition. To examine the variability of performance across participants and locations, we classified each child’s performance at each location as being biased toward midline, biased away from midline, or unbiased using the classification scheme developed by Schutte and Spencer. Specifically, we used absolute (i.e., unsigned) error to compute the standard error across all locations for each age group. The standard error was then used to compute the critical mean error necessary, based on the t-distribution, for a child in each age group to be classified as showing significant bias toward or away from midline at that location. The value of each child’s mean error at each location was compared to this critical value, and children’s errors were classified as biased if their mean error was greater than the critical error (note that, in this sample, no mean errors equaled the critical value). In these cases, the direction of their error was used to classify their performance as biased toward (i.e., negative errors) or away from (i.e., positive errors) midline at that location. If their mean error for the location was less than the critical value, it was classified as unbiased (i.e., not significantly different from zero).

2.2. Results and Discussion

To assess differences in performance across locations and development, we analyzed mean error using a repeated-measures ANOVA with Distance and Side as within-subjects variables and Age and as a between-subjects variable.
In these analyses errors away from midline were coded as positive and errors toward midline were coded as negative. Mean errors for each distance at each age can be seen in Figure 3a, and mean errors collapsed across midline can be seen in Figure 3b. As the figure shows, errors were small for locations near midline, with increasing error for the farther distances. In addition, errors were largest for 3-year-olds, and reduced over development. The ANOVA revealed significant main effects of Age, $F(4, 74) = 4.62, p = .002, \eta^2 = .20$, and Distance, $\Lambda = .80, F(3, 67) = 6.04, p = .001, \eta^2 = .20$, which were subsumed by a significant Side $\times$ Distance $\times$ Age interaction, $\Lambda = .74, F(12, 190) = 1.90, p = .037, \eta^2 = .09$. We followed-up the three-way interaction by conducting a Side $\times$ Age ANOVA at each Distance. If the transition is gradual as predicted, there should be a gradual change in bias over age at each target location.

At 14 in. the only significant effects were a main effect of Side, $F(1, 4) = 4.60, p < .05, \eta^2 = .06$, due to responses on the right of midline ($M = -1.10 \text{ in.}, SD = 2.40 \text{ in.}$) being biased more strongly toward midline than responses on the left of midline ($M = -0.52 \text{ in.}, SD = 2.00 \text{ in.}$), and a significant main effect of Age at 14 in., $F(4, 74) = 5.68, p < .001, \eta^2 = .24$. As predicted, there was a decrease in bias across ages, from a strong bias toward midline at 3 years to near zero error at 7 years, with the largest reduction in bias between 3 and 4 years (see Figure 3). Bonferroni post hoc tests comparing mean error between age groups revealed that only 3-year-olds’ errors differed significantly from all other age groups; there were no other age differences. Two-tailed $t$-tests comparing mean error to zero error showed that 3- and 5-year-olds’ responses were biased significantly toward midline (3-year-olds: $t(14) = -3.47, p < .05$; 5-year-olds: $t(15) = -2.21, p < .05$) while the responses of the other age groups were not significantly biased at this distance (all $p$s $>.10$).

At 10 in. there was a significant Side $\times$ Age interaction, $F(4, 74) = 3.05, p < .025, \eta^2 = .14$, and a significant main effect of Age, $F(4, 74) = 2.73, p < .05, \eta^2 = .13$. Follow-up analyses examining Side at each Age at this distance revealed a significant effect for only 4-year-olds, $F(1, 15) = 11.20, p < .01, \eta^2 = .43$, due to biases in opposite directions on either side of midline (left: $M = 0.96 \text{ in.}, SD = 0.98 \text{ in.}$; right: $M = -1.07 \text{ in.}, SD = 1.97 \text{ in.}$). Thus, 4-year-olds’ mean errors showed an overall leftward bias, rather than consistent bias toward or away from midline. Although errors were generally smaller at 10 in. than at 14 in., the Age main effect showed the same pattern for both distances: across age groups there was a decrease in bias, from a bias toward midline at 3 years to near zero error at 7 years (see Figure 3). Bonferroni post hoc tests revealed that 3-year-olds’ errors were significantly different from 6-year-olds’; no other age groups differed significantly. Two-tailed $t$-tests comparing mean errors to zero showed that 3-year-olds’ responses at 10 in. were biased significantly toward midline while the responses of the other age groups were not significantly biased (3-year-olds: $t(14) = -2.12, p = .05$; all other $p$s $>.10$).
Figure 3. Mean error in Experiment 1 for each distance from midline at each age (a). Mean error for each distance from midline collapsed across side (b). Positive errors are toward midline and negative errors are away from midline. In (b) asterisks indicate mean errors significantly different from zero error ($p < .05$), and plusses indicate marginally different from zero error ($p < .10$).
Analyses at both 6 in. and 2 in. revealed no significant effects. Errors at these two distances were near zero for all age groups (see Figure 3).

In summary, geometric bias varied as predicted, with different patterns of developmental change depending on the location’s distance from midline: 3-year-olds’ responses were biased significantly toward midline at both 10 in. and 14 in. whereas 6- and 7-year-olds’ responses were not significantly biased at any distance. Performance at 4 and 5 years was mixed, with 4-year-olds’ responses not significantly biased at any location and 5-year-olds’ responses significantly biased toward midline at 14 in. (see Figure 3). In addition, the side of the sandbox had some influence on performance, with larger errors on the left at 14 in. (that did not depend on age), and different directions of bias for 4-year-olds at 10 in.

Using the classification scheme developed by Schutte and Spencer (2009), we classified each child’s mean response as being biased toward midline, away from midline, or not significantly biased. The percentage of children in each classification for each location at each age is shown in Figure 4. Over development there is a clear change in the pattern of bias across locations with the largest differences at 6 and 10 inches. Specifically, the majority of 3-year-olds are classified as biased toward midline at 14 inches, and the percentage decreases as the distance from midline decreases. Likewise, the percentage biased away from midline increases as locations approach midline. At 4 years of age, the percentage biased toward midline, away from midline, and unbiased is relatively evenly split except at 6 in. where the majority are biased away from midline. By 5 years of age, the majority of children are also biased away from midline at 6 in., and at 6 years of age the majority of children are biased away from midline at both 6 and 10 in. The majority of the 7-year-olds are biased away at 6 inches as well, although at 10 in. there are as many biased toward midline as are biased away from midline. At 14 in. the majority of children are classified as biased toward midline at all ages except 6 years of age where more children are classified as unbiased.

Interestingly, although mean errors were not significantly biased in the t-tests described above, many 4-, 5-, 6-, and 7-year-olds’ errors were classified as biased away from midline at 6 and 10 in. using this alternative method. This contrast in results is due to the magnitude and direction of errors affecting the significance of the t-tests (i.e., a few large errors toward midline and many small errors away from midline would average to near zero), but not the classifications. It is also important to note that there were many responses classified as unbiased, which supports the proposal that the transition from being biased toward to being biased away from midline is gradual with variability in timing across children and locations.

These results are consistent with our predictions of a gradual transition in biases over development, which raises the question of why the ANOVA and t-test analyses revealed so few significant effects. As described before, many of the mean errors were not significantly different from zero, potentially due to differences in magnitude and direction of errors across participants.
Figure 4. Percentage of children biased toward midline, unbiased, and biased away from midline for each age at each location in Experiment 1 (color figure available online).
Comparing the magnitude of mean errors reported here to previous sandbox studies, it appears that errors in our study were generally smaller than those found by Huttenlocher et al. (1994). There were a number of small differences in the methodology between Huttenlocher et al.’s study and ours (described further in the General Discussion) which may contribute to the differences in performance between studies. For our next experiment, we wanted to try to increase the size of the errors children made, as it is possible that mean errors would show more significant modulation across age groups and locations if individuals’ errors were larger. Previous research has shown that longer delays result in larger biases in spatial recall tasks (e.g., Hund & Plumert, 2002; Schutte & Spencer, 2002; Spencer & Hund, 2003). The length of delay was not precisely controlled in the Huttenlocher et al. study, but description of their procedure suggests their delay may have been longer than the 5 s delay used in Experiment 1. Therefore, we chose to increase the length of the delay in an attempt to increase errors and magnify children’s biases, hopefully revealing in more detail how biases change over development.

3. EXPERIMENT 2

In Experiment 2 we increased the length of the delay by having the experimenter count to 15 instead of 5. Increasing the delay should increase the magnitude of errors and amplify any developmental differences. In addition to examining the gradual transition in more detail, increasing the delay will provide a stronger test of whether or not children show bias away from midline in this age range.

3.1. Method

3.1.1. Participants. Fifteen 3-year-olds ($M = 3$ years 6.7 months, $SD = 3.7$ months, 8 females, 7 males), 15 4-year-olds ($M = 4$ years 6.5 months, $SD = 3.6$ months, 3 females, 12 males), 18 5-year-olds ($M = 5$ years 5.4 months, $SD = 3.8$ months, 9 females, 9 males), 15 6-year-olds ($M = 6$ years 6.8 months, $SD = 4.1$ months, 7 females, 8 males), and 14 7-year-olds ($M = 7$ years 4.8 months, $SD = 1.0$ months, 8 females, 6 males) participated in Experiment 2. Data from two additional 3-year-olds, one 4-year-old, and one 5-year-old were collected but not included in the analyses due to experimenter error. Children were primarily middle class, and all parents provided written consent.

3.1.2. Materials, Procedure, and Experimental Design. All details of the materials, procedures, and experimental design were the same as Experiment 1, except the experimenter and child counted to 15 instead of 5.
3.1.3. Behavioral Scoring. All sessions were coded using the same procedure as Experiment 1. Responses were coded to the nearest half inch. A second scorer scored 26% of the sessions for the 4- to 7-year-olds. Due to high variability in the 3-year-olds, a second scorer scored all of the 3-year-old sessions. The mean deviation (absolute value) between the two scorers was 0.55 in. ($SD = 1.69$ in.). If the difference between scorers was greater than 1 in., two independent scorers viewed the video tape and agreed on the score (36 trials, 6.8% of double-coded trials). For all disagreements of 1 in. or less the initial scorers’ values were used (remaining 93.2%).

3.1.4. Method of Analysis. The method of analysis was identical to that used in Experiment 1.

3.2. Results and Discussion

Figure 5a shows mean error across age and distance from midline, and Figure 5b shows mean error collapsed across side of the sandbox. As the figure shows, errors were again smallest for locations near midline, with increasing error for the farther distances, and largest for 3-year-olds, with a reduction over development. Overall, the magnitude of errors was larger than in Experiment 1 (cf. Figure 3), suggesting that increasing the length of delay increased response bias. As in Experiment 1, to examine whether the biases were significantly different from zero, we analyzed mean error collapsed across midline using a repeated-measures ANOVA with Distance and Side as within-subjects variables and Age as a between-subjects variable. There was a significant main effect of Side, $\Lambda = .94$, $F(1, 72) = 5.04$, $p = .028$, $\eta^2 = .07$. Overall errors were larger on the left ($M = -1.0$ in.) than on the right side ($M = 0.4$ in.). The ANOVA also revealed significant main effects of Distance, $\Lambda = .74$, $F(3, 70) = 8.33$, $p < .001$, $\eta^2 = .26$, and Age, $F(4, 72) = 7.60$, $p < .001$, $\eta^2 = .30$, as well as a significant Distance $\times$ Age interaction, $\Lambda = .65$, $F(12, 185) = 2.75$, $p = .002$, $\eta^2 = .13$.

To follow-up the Distance $\times$ Age interaction we examined Age effects at each Distance. There were marginal or significant Age effects at each Distance except 2 inches (2 in.: $F(4, 72) = 1.36$, n.s., $\eta^2 = .07$; 6 in.: $F(4, 72) = 8.00$, $p < .001$, $\eta^2 = .31$; 10 in.: $F(4, 72) = 9.33$, $p < .001$, $\eta^2 = .34$; 14 in.: $F(4, 72) = 2.29$, $p = .068$, $\eta^2 = .11$). Bonferroni post hoc

\(^1\)The number of trials on which there was disagreement between coders of more than 1 in. was higher than in Experiment 1 due to a number of trials on which the two coders disagreed as to which of the child’s hands contacted the sand first. The majority of these cases were due to 3-year-olds reaching with both hands. In these cases, the differences in error values were quite large (i.e., greater than 5 in.) because the child’s hands were far apart in the task space; this also leads to a higher mean deviation than in Experiment 1.
Figure 5. Mean error in Experiment 2 for each distance from midline at each age (a). Mean error for each distance from midline collapsed across side (b). Positive errors are toward midline and negative errors are away from midline. In (b) asterisks indicate mean errors significantly different from zero error ($p < .05$), and plusses indicate marginally different from zero error ($p < .10$).
Dynamic Systems Account of a Transition in Spatial Recall

Tests comparing mean error between age groups revealed that at 6 in. 3-year-olds’ errors differed significantly from all other age groups (all \( p < .01 \)). At 10 in. 3-year-olds’ errors differed significantly from 5-, 6-, and 7-year-olds’ errors (all \( p < .01 \)), and marginally from the 4-year-olds (\( p = .065 \)). At 14 in. 3-year-olds’ errors differed marginally from the 6-year-olds’ errors (\( p = .055 \)). There were no other significant age differences for any target locations.

To determine if responses were significantly biased toward or away from midline at each distance that showed an Age effect, we conducted two-tailed \( t \)-tests for each age comparing mean error (collapsed across side) to zero. At 14 in., 3- and 4-year-olds showed significant bias toward midline, 5-year-olds’ responses showed marginal bias toward midline, 6-year-olds’ responses showed no bias, and 7-year-olds’ responses showed bias toward midline (3-year-olds: \( t(14) = -2.84, p = .013 \); 4-year-olds: \( t(14) = -2.43, p = .03 \); 5-year-olds: \( t(17) = -2.04, p = .058 \); 6-year-olds: \( t(14) = -1.05, n.s. \); 7-year-olds: \( t(13) = -2.80, p = .015 \); see Figure 5b). At 10 in. the 3-year-olds’ responses were biased significantly toward midline, \( t(14) = -3.70, p = .002 \), 4-year-olds’ responses were biased marginally toward midline, \( t(14) = -1.80, p = .09 \), 5-year-olds’ responses were biased significantly away from midline, \( t(17) = 2.59, p = .019 \), and 6- and 7-year-olds’ responses were not biased, \( p > .10 \). At 6 in. from midline 3-year-olds’ responses were biased significantly toward midline, \( t(14) = -4.41, p < .001 \); the responses of the other age groups were not significantly biased at this distance (\( p > .10 \)).

In summary, results generally showed a gradual reduction in bias toward midline that depended on target location. With the longer delay used in this experiment, bias toward midline occurred for no age groups at 2 in., for only 3-year-olds at 6 in., for 3- and 4-year-olds at 10 in., and for all but 6-year-olds at 14 in. To understand this change in bias in more detail, we again examined the variability of performance across participants by examining each child’s bias, using the method described in Experiment 1.

The percentage of children in each classification for each location at each age is shown in Figure 6. Over development there is a clear change in the pattern of error across locations with the largest differences at 6 and 10 inches. Specifically, the majority of 3-year-olds are classified as biased toward midline at all but the 2 in. location (where most were unbiased). At 4 years of age, the majority of children are still classified as biased toward midline, but the proportion is less than the 3-year-olds, and many 4-year-olds are biased away from midline at 6 in. By 5 years of age, the majority of children are biased away from midline at 10 in., and at 6 years of age the majority of children are biased away from midline at both 6 and 10 in. The majority of the 7-year-olds are biased away at 6 inches as well, although at 10 in. the split is about half biased toward and half biased away from midline. At 14 in. the majority of children are classified as biased toward midline at all ages.
Figure 6. Percentage of children biased toward midline, unbiased, and biased away from midline for each age at each location in Experiment 2 (color figure available online).
As in Experiment 1, the responses of several of the older children were biased away from midline, even though as a group children’s mean responses were not significantly biased away from midline. Specifically, the t-tests only revealed a significant bias away from midline for 5-year-olds at 10 in., while in the classifications many 5-, 6-, and 7-year-olds’ responses were classified as biased away from midline at 6 and 10 in. It is also important to note that even though average errors were larger in Experiment 2 than in Experiment 1, there were still many children classified as unbiased.

As in Experiment 1, responses varied some across sides of the sandbox. Specifically, responses were biased more strongly toward midline on the left side than on the right. In contrast, most effects of side in Experiment 1 were in the opposite direction. Specifically, in Experiment 1 at 14 in. responses on the right side of the sandbox were biased more strongly toward midline than responses on the left side of the sandbox, and at 10 in. 4-year-olds were biased more strongly toward midline on the right side. The cause of the differences across the sides of the sandbox is not clear. Children have been found to show hemispheric differences in spatial awareness (e.g., Dobler et al., 2005), and it is possible that left-right differences in spatial awareness may cause differences in performance across the sides of the sandbox. For example, children completing a line bisection task have been found to bisect lines slightly to the left of center (Manly, Cornish, Grant, Dobler, & Hollis, 2005). If children are bisecting the sandbox slightly to the left of the symmetry axis, this could lead to slight differences in geometric biases across sides.

Why this would cause the inconsistent side differences found across experiments is not clear. Other studies using the sandbox task have not analyzed effects of side of the task space; however, Schutte and Spencer (2002) report side differences using the spaceship task. Consistent with the results of Experiment 2, Schutte and Spencer (2002) found that in the spaceship task, 3-year-olds were more strongly biased toward midline when the targets were on the left side than when the targets were on the right side of midline. It is difficult to make any conclusions as to the causes of the side differences based on the results of two studies, especially given the inconsistent results in the current study. These results underscore, however, the need to analyze differences across sides of a task space in spatial memory studies.

4. GENERAL DISCUSSION

These experiments tested two predictions of the DFT. The first prediction was that the reduction in geometric biases in the sandbox task should be gradual and depend on target location, with the changes in biases beginning between 3 and 4 four years of age. This prediction was supported. At several target locations, there was a significant reduction in bias toward midline between 3 and 4 years in both experiments (see Figures 4 and 6). Additionally, although
there was a significant reduction in bias toward midline by 4 years, it was not until 6 or 7 years that the bias toward midline reduced completely.

This study was the first to examine developmental changes in the sandbox task using a small enough sampling interval to find these gradual, but significant, changes in geometric biases between 4 and 7 years. The gradual reduction in bias found here replicated the gradual reduction found by Schutte and Spencer (2009) using a different spatial memory task. Note, however, that we did not find a clear bias away from midline, even in our oldest age group; we discuss possible reasons for this next.

The second prediction we tested was that bias toward midline would reduce first for targets close to midline and last for targets furthest from midline due to inhibition from the edges of the sandbox. This prediction was also supported. Responses to the target 14 in. from midline (the closest to the edges) were still biased toward midline at 5 years, and even at 7 years in Experiment 2, while responses to the other target locations were not significantly biased toward midline. This pattern of reduction in bias varied from that found by Schutte and Spencer (2009), who found that bias reduced first for the targets furthest from midline. Thus, as predicted by the DFT, differences in contexts, specifically the salience of the outer edges, influenced the pattern of error over development.

Although the current results confirmed our predictions, one may ask whether they provide strong support for the DFT in contrast to other theories. A prominent alternative theory to the DFT is the Category Adjustment Model (CAM; Huttenlocher, Hedges, & Duncan, 1991); although these theories generate similar predictions in many cases, they differ in a small number of critical ways (see Schutte & Spencer, 2009, for a detailed discussion). According to the CAM, people use two types of information to remember a location: fine-grained and categorical information. The fine-grained information is the direction and distance of the target from a landmark or reference axis. Categorical information consists of the boundaries and the prototypical location, that is, the center of the category or region in which the target is located. When the location is recalled these two types of information are then combined with variable relative weightings. As people become uncertain about the fine-grained information due to interference or a long delay, they weight the categorical information more heavily due to greater certainty about the category. This weighting results in a bias toward the prototype at the center of the category. Furthermore, the developmental transition in geometric biases is attributed to older children and adults dividing a space into two or more categories by using symmetry axes as boundaries, whereas young children treat a space as one category (see Figure 1).

It is difficult to evaluate whether the CAM would predict these results because the model does not specify the mechanism by which participants assign categories to the task space on a trial-by-trial basis. In a chapter discussing the CAM approach to development, Huttenlocher and Lourenco (2007) state that “the use of imposed boundaries to subdivide a space emerges
only gradually,” and “would seem to reflect an increasing ability to impose complex category structure on a space” (p. 20). Although these statements are suggestive of the kind of gradual transition we predicted here, we are aware of no studies that have proposed this prediction, much less tested it directly. Without further explanation of how children form categories in the tasks we describe here, one cannot predict how the task context would influence performance in that model (although see Fitting, Wedell, & Allen, 2005, 2008, for an adaptation of the CAM that addresses how categories are formed in adults).

One additional contrast between the sandbox and spaceship task merits further consideration: in the current study, we found no significant bias away from midline in the mean error analyses, even at 7 years of age. This finding replicates the results of Schutte and colleagues (2003) who found no significant bias away from midline at 6 years in the sandbox task. However, Schutte and Spencer (2009) found that repulsion from midline in the spaceship task began to emerge at some locations by 4 years, and by 6 years all locations tested showed bias away from midline (see also Hund & Spencer, 2003; Spencer & Hund, 2003). The lack of a significant bias away from midline in the current experiments and in Schutte et al. may be due to the relative imprecision of measurement in the sandbox task. Unlike the spaceship task used by Schutte and Spencer, which measures errors to the nearest degree, the sandbox task only measures errors to the nearest half inch. Additionally, responses in the spaceship task were coded using a motion tracking system while the sandbox task relied on coding from videos. The imprecision in coding may mask small biases.

In general, due to improvements in memory with age, biases away from midline are smaller than biases toward midline, simply because as children develop their memories become more stable, and, therefore, the size of biases decreases even though they are still significant (Hund & Spencer, 2003). The sandbox task may be too imprecise to pick up on these smaller biases, (e.g., an error of a quarter of an inch away from midline may be coded as zero error which would result in no significant bias). It is also possible that biases away from midline are smaller in the sandbox task than the spaceship task due to there being more perceptual structure available for coding location (i.e., more salient edges resulting in more salient vertical and horizontal reference frames).

It is important to note, however, that our interpretation of bias depends in part on the statistical analysis used. In particular, the $t$-tests assessing error at each location in Experiment 2 showed no significant bias away from midline at any age, except for 5-year-olds at 10 in. In contrast, the individual difference analyses suggest that bias away may emerge at an even younger age in a majority of children: in Experiment 1, the majority of 4-year-olds’ responses were biased away from midline at 6 in., and in Experiment 2 by 5 years a majority of children’s responses showed bias away from midline at 10 in. and at 6 years the majority showed bias away at both 6 and 10 in.
Interestingly, Huttenlocher et al. (1994) found that 6- to 7-year-olds were biased toward midline, contrasting with results from other studies using the sandbox task (Schutte et al., 2003, as well as the present study). One potential source of the difference between sandbox studies is that Huttenlocher and colleagues used a different analysis technique to examine the pattern of bias. Specifically, they computed curve fits to test for a pattern. It is unclear whether Huttenlocher et al.'s conclusions would have differed had they used a different analytical approach; perhaps direct tests comparing error to zero may have revealed results similar to the results we found here. In addition to the method of analysis, there are several other differences in Huttenlocher et al.'s study that could have led to different results.

These differences include sampling larger age groups (e.g., 6- to 7-year-olds in Huttenlocher et al.), having children remember locations that were distributed across the full width of the sandbox, differences in procedures during the delay (see below), and having children complete just one trial to each target location. In our studies, completing two trials to each location may have reduced bias by stabilizing memory through repetition (e.g., Schutte & Spencer, 2002); however, we reanalyzed the data including only the first trial to each target location and found the same pattern of error. Therefore, the number of trials alone does not explain the difference.

We consider the most likely explanation of the differences between our results and previous sandbox studies to be related to the procedure during the delay on each trial. Huttenlocher et al. (1994) had children rotate so their back was to the sandbox during the delay. Although the children looked up from the sandbox in the current study, it is possible that it is more difficult for children to maintain a location in memory when their entire body moves.

Newcombe, Huttenlocher, Drummey, and Wiley (1998) found that children 1 1/2 to 3 years of age were less accurate when they had to move around the sandbox than when they just turned around. They did not include a condition where children did not move at all, but it is possible that, even for older children, the amount of movement during the delay influenced children’s ability to stably maintain a location in memory. According to DFT, when a person is turned away from the task space there is no longer a perceptual input related to the reference axes. A long-term memory of the axes would still have an effect on location memory, but the long-term memory input would be broader, i.e., less precise, and weaker than the perceptual input. This would have an effect on the size and direction of errors. In age groups far from the transition point, this procedure would result in more variability in errors without changing the direction of the errors; however, it would cause children at or just past the transition point to regress and make errors that are biased toward midline instead of away from midline. Further studies will be needed to test this possibility in detail.

In summary, our results indicate that the conflicting results from previous studies—showing children transitioning at different ages and perhaps
at different rates—arose from differences in the task structure across studies (Huttenlocher et al., 1994; Schutte & Spencer, 2009; Schutte et al., 2003). Importantly, although we did not predict the precise pattern of performance across all target locations and ages, we were able to qualitatively predict the ways in which children’s performance should be influenced by differences between the sandbox and spaceship tasks. Moreover, we demonstrated that some aspects of the developmental transition should be constant across tasks; specifically, the transition began between 3 and 4 years of age, biases first reduced before switching directions, and targets closer to midline transitioned sooner. These characteristics of the transition are predicted by the mechanism of development in the DFT.

Perhaps the most controversial of these claims is that due to changes in neural interaction, the transition should begin at the same point in development in different tasks, although the length of the transition and exact pattern of bias during the transition varied by task. What would influence the timing of the start of the transition? The timing of the start of the transition should be influenced by prior developmental experiences. Thus, there was some individual variability in when the transition began for children (see Figures 4 and 6); however, given that the samples in Schutte and Spencer (2009) and the current experiments were probably similar to each other in many ways (e.g., primarily middle class), the majority began the transition at the same point in development. However, given that brain development is influenced by experience (see, e.g., Johnson, 1999, for a review), we would expect that children growing up in different circumstances may transition at a different point in development.

In conclusion, the results reported here present a challenge to theories of any phenomena, to develop a mechanistic account of how and why task context should influence performance. Within the domain of spatial cognition, our results provide strong evidence for the gradual nature of developmental change, as well as the importance of considering how small changes in the task can shift the timing of some characteristics of the transition in geometric biases. The DFT provides an account of how details of the task influence performance while still proposing some aspects of developmental change that remain stable across tasks. A promising direction for future research in the area would be to use longitudinal studies focusing on individual differences as a way to determine the causal factors influencing the development of spatial memory in early childhood.

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