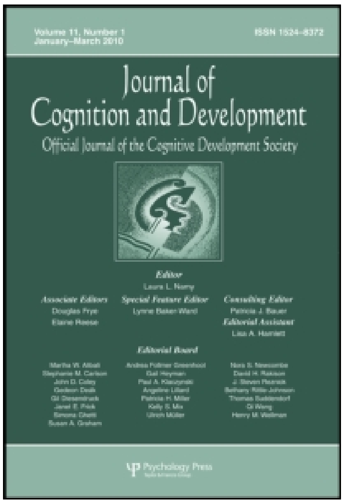

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Filling the Gap on Developmental Change: Tests of a Dynamic Field Theory of Spatial Cognition

Anne R. Schutte[a]; John P. Spencer[b]
[a] University of Nebraska, Lincoln [b] University of Iowa,

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Filling the Gap on Developmental Change: Tests of a Dynamic Field Theory of Spatial Cognition

Anne R. Schutte
University of Nebraska, Lincoln

John P. Spencer
University of Iowa

In early childhood, there is a developmental transition in spatial memory biases. Before the transition, children's memory responses are biased toward the midline of a space, while after the transition responses are biased away from midline. The Dynamic Field Theory (DFT) posits that changes in neural interaction and changes in how children perceive frames of reference underlie the transition. Here, we tested a prediction of the DFT that children younger than the transitional age would show the more advanced developmental pattern when tested with a perceptually salient midline axis. Four age groups (3 years, 6 months; 3 years, 8 months; 4 years; and 5 years) were tested at targets near midline. As predicted, children's responses were biased away from midline.

Despite a long history of studying change, much of the research in cognitive development has characterized behavior at different ages rather than studying *how change occurs* (Brown & DeLoache, 1978; Elman et al., 1996; Siegler, 1996; Thelen, 2000; van Geert, 1998). There has been a push in the last decade toward bridging this gap between characterizing behavior and understanding the mechanisms of development (e.g., Mareschal et al., 2007;

Correspondence should be sent to Anne R. Schutte, Department of Psychology, University of Nebraska-Lincoln, 238 Burnett Hall, Lincoln, NE 68588, USA. E-mail: aschutte2@unl.edu

McClelland & Siegler, 2001; Plumert & Spencer, 2007; Spencer, Thomas, & McClelland, 2009). Rather than looking at performance on either side of a developmental transition, the goal is to understand the processes that move the system through the transition (Granott & Parziale, 2002; Thelen & Smith, 2006). One of the strongest tests of a process-based theory is to use the theory to predict novel ways to advance the rate of developmental change—to create change at an earlier age than is expected based on the literature. This article provides such a test.

Recently, we proposed a process-based account of a developmental transition in spatial memory (Schutte & Spencer, 2009) that builds on earlier work by J. Huttenlocher, Newcombe, and colleagues (J. Huttenlocher, Newcombe, & Sandberg, 1994; Newcombe, Huttenlocher, Drummey, & Wiley, 1998). Remembering the locations of objects is fundamental to successful interaction with the world; however, this is often a difficult challenge when objects are out of view. One strategy for remembering locations is to capitalize on the ways in which space is naturally carved into spatial categories—the coffee table by the couch, the play area on the floor, the bookshelves by the window. In an innovative set of experiments, J. Huttenlocher and colleagues (1994; Newcombe et al.) found that early in development there is a transition in how children remember locations relative to spatial categories. They reported that when 3- to 7-year-olds remember a location in a large, rectangular space, they show biases toward the midline axis of the space. In contrast, 9- to 10-year-olds show biases away from midline. This developmental transition has been replicated in numerous other studies (Hund & Spencer, 2003; Schutte & Spencer, 2002, 2009; Schutte, Spencer, & Schöner, 2003; Spencer & Hund, 2002, 2003).

What is the nature of this developmental transition, particularly around the transition point? What aspects of spatial memory change to create this qualitative developmental shift? Recent results show that this transition is protracted and depends on the target locations children are asked to remember (Schutte & Spencer, 2009). Figure 1 shows a schematic of this protracted course between 3 years, 6 months and 5 years, 4 months. Each panel shows an overview of the task space we used to examine this transition, as well as the target locations probed across conditions. In the task, children had to remember a target location on a large table top (see Figure 4a for a photo of the table). The target locations that were probed were 10°, 20°, 30°, 50°, 60°, and 70° from the midline symmetry axis of the table (see yellow crosses in Figure 1). On each trial, children were shown a single target location. The target disappeared, there was a brief memory delay (5–10 seconds), and then participants pointed to the remembered location. Children in each condition remembered only two targets across trials—a close target and a far target. The target set varied across

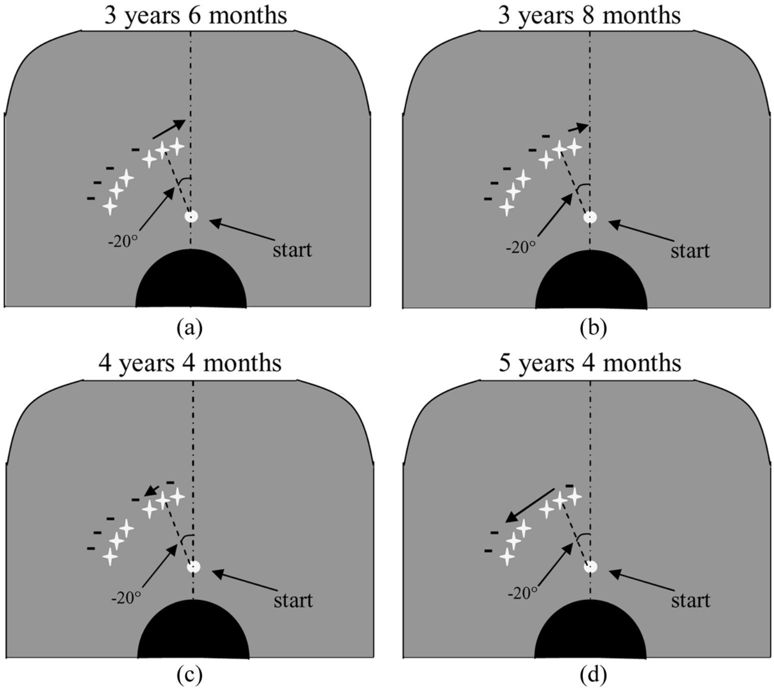

FIGURE 1 Schematic of spatial memory biases for children aged 3 years, 6 months (a); 3 years, 8 months (b); 4 years, 4 months (c); and 5 years, 4 months (d). Target locations are marked by crosses. The −20° target angle is shown for illustration and to provide an anchor point for the different target locations. The target locations from right to left are −10°, −20°, −30°, −50°, −60°, and −70°. The arrows above one or more target locations illustrate the direction of bias for those locations. A "–" above a target means that children do not show a memory bias at that location.

conditions to probe developmental changes in performance relative to the midline axis.

The arrows and dashes in each panel of Figure 1 show the response biases children showed relative to the different target locations. At 3 years, 6 months, children showed attraction toward the midline symmetry axis when the targets were relatively close to midline (Figure 1a) but were unbiased otherwise. Throughout development, this attraction effect narrowed such that by 3 years, 8 months, children were only significantly biased toward midline when the target was 10° from midline (Figure 1b). By 4 years, 4 months, the attraction effect changed qualitatively; now children were biased away from midline but only when the target was 20° away from this axis (Figure 1c). The region of repulsion expanded beyond 4 years, such that at 5 years of age, targets 10° to 50° from midline were biased away from the axis (Figure 1d). By 6 years of age (not shown), responses to all targets were biased away from midline (see Spencer & Hund, 2003). The question is: What processes explain this protracted and complex developmental transition?

THE DYNAMIC FIELD THEORY

We explained and quantitatively modeled this developmental transition in spatial memory using the Dynamic Field Theory (DFT) of spatial cognition (Schutte & Spencer, 2009; Simmering, Schutte, & Spencer, 2008; Spencer, Simmering, Schutte, & Schöner, 2007). The DFT is a dynamic systems approach to spatial cognition that has been implemented in a type of neural network architecture called a dynamic neural field. Figure 2a is a simulation of a single spatial recall trial using the model from Schutte and Spencer (2009) with parameters that captured the performance of children aged 3 years, 6 months. The model is made up of three layers (or fields) of neurons (Figure 2a, lower three panels). In each layer, the neurons are arranged according to the location for which they code. In particular, location is along the x axis, activation of the neurons is on the y axis, and time is on the z axis. Note that this three-layered architecture was inspired by the cytoarchitecture of visual cortex (Douglas & Martin, 1998) and has been shown to effectively capture other aspects of visuospatial cognition (Johnson, Spencer, Luck, & Schöner, 2009; Johnson, Spencer, & Schöner, 2009).

The top layer in each panel is an input panel that shows the location and amount of activation that is being input to the model at each time step. In this simulation, there are two inputs: the target input (the peak at −20°) and the input associated with the midline symmetry axis (the small peak at 0°). The second layer in each panel is the perceptual field (PF). This field receives strong input and sends excitation to both of the other layers (see solid arrows). The fourth layer is the spatial working memory (SWM) field. This field receives weak input as well as strong activation from the PF. The SWM field maintains a memory of the target location through self-sustaining neural interactions (see Amari, 1989; Amari & Arbib, 1977; Compte, Brunel, Goldman-Rakic, & Wang, 2000; Trappenberg, Dorris, Munoz, & Klein, 2001). The third layer, Inhib, is a layer of inhibitory interneurons that mediate excitation in the other two fields. The Inhib layer receives input from and projects inhibition broadly back to both the PF and the SWM field.

Perceived and remembered events in the DFT are captured by the gray "peaks" of activation shown in Figure 2a. These peaks reflect a specific type

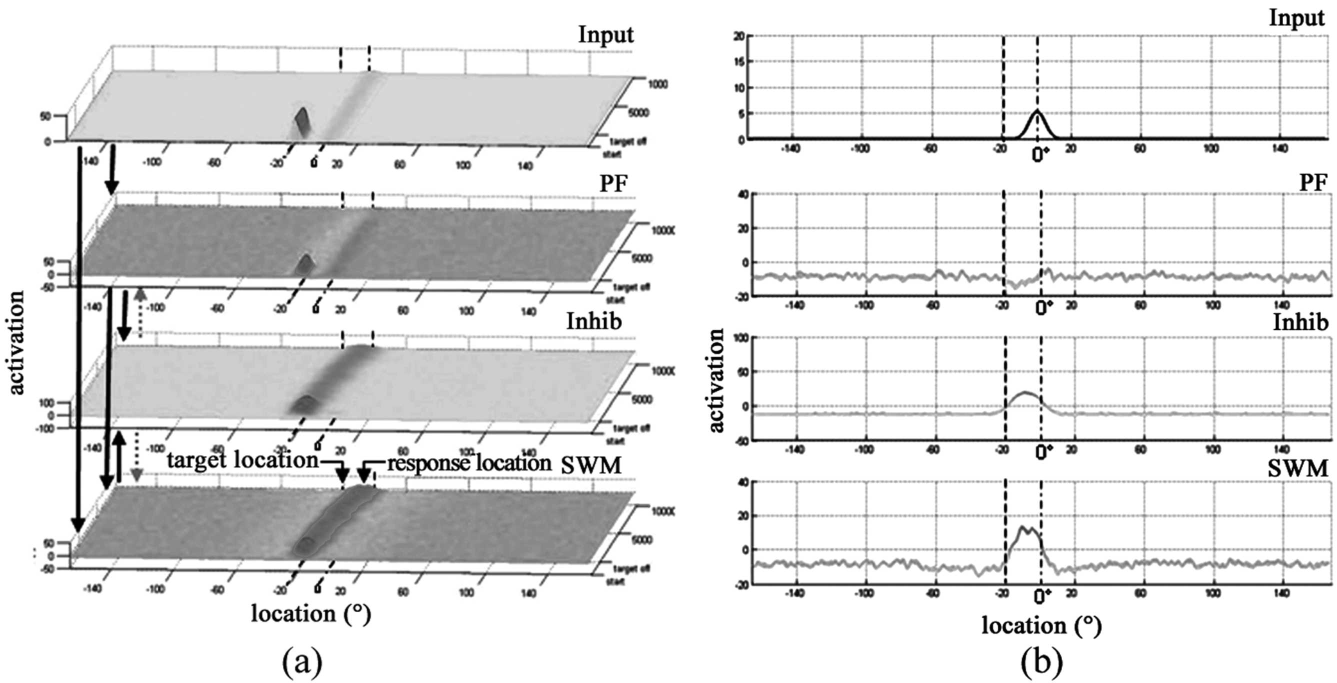

FIGURE 2 The left panel shows a simulation for an exemplar trial of the DFT for children aged 3 years, 6 months (a). Location is along the x axis, activation is along the y axis, and time is along the z axis. Right panel is a cross section of the same simulation at the end of the delay (b). See text for further details.

of neural interaction that underlies the model's performance. Specifically, neurons that are activated in the excitatory layers (PF, SWM) excite neighboring neurons that code for similar locations, that is, neurons that are close along the x axis in Figure 2a. In addition, activated neurons inhibit neighbors that are far away through the inhibitory layer. As these patterns of neural activity evolve over time, they result in an emergent form of local excitation/lateral inhibition which creates localized peaks of activation. For instance, the peak in PF at $-20°$ that appears toward the start of the simulation reflects the local excitatory activation driven by the appearance of the target input (see top layer). This peak is sculpted by the pattern of activation in the inhibitory layer around $-20°$ associated with the same event. A second type of peak is present at $-20°$ in SWM a bit later in the simulation. Note that, once built, this peak is sustained during the entire simulation. This is a key property of SWM: Working memory must sustain neural activation over delays, even when the target location is no longer visible (see Amari, 1989; Amari & Arbib, 1977; Compte et al., 2000, for neural network models that use similar dynamics).

Considered together, the layers in Figure 2a capture the real-time processes that underlie performance on a single spatial recall trial. At the start of the trial, the only activation in the PF occurs around 0°, the location of the midline symmetry axis. The model receives weak input around 0° in both PF and SWM. Note, however, that this weak input is not sufficient to generate a robust peak in either excitatory field. Next, the target appears at the $-20°$ location and creates a strong peak in PF which drives up activation at associated sites in SWM. When the target disappears, the target activation in PF around $-20°$ dies out, but the target-related peak of activation remains stable in SWM. During the memory delay, the peak in SWM near $-20°$ is actively maintained. In addition, there is weak positive input at 0° in both excitatory layers from the continued perception of the midline axis. Although this weak input is not sufficient to create a peak in either field, it is strong enough to cause the peak in the SWM field to drift toward the midline reference axis during the delay.

This drift toward 0° is evident in Figure 2b. This panel shows slices through the layers of the model at the end of the memory delay. As can be seen in the bottom layer, the peak in the SWM field is not centered over the $-20°$ location. Rather, this peak has drifted significantly toward 0°. Consequently, the model would respond that the target was located near $-10°$ after a 10-second delay; that is, the model would show a robust bias toward the midline axis.

According to the DFT, the developmental transition in spatial memory is due to a change in the precision and stability of neural processes that underlie SWM and the system that anchors spatial memory to perceived reference frames. Figures 3e–h show exemplary simulations of the DFT across the critical developmental period between 3 years, 6 months and 5 years,

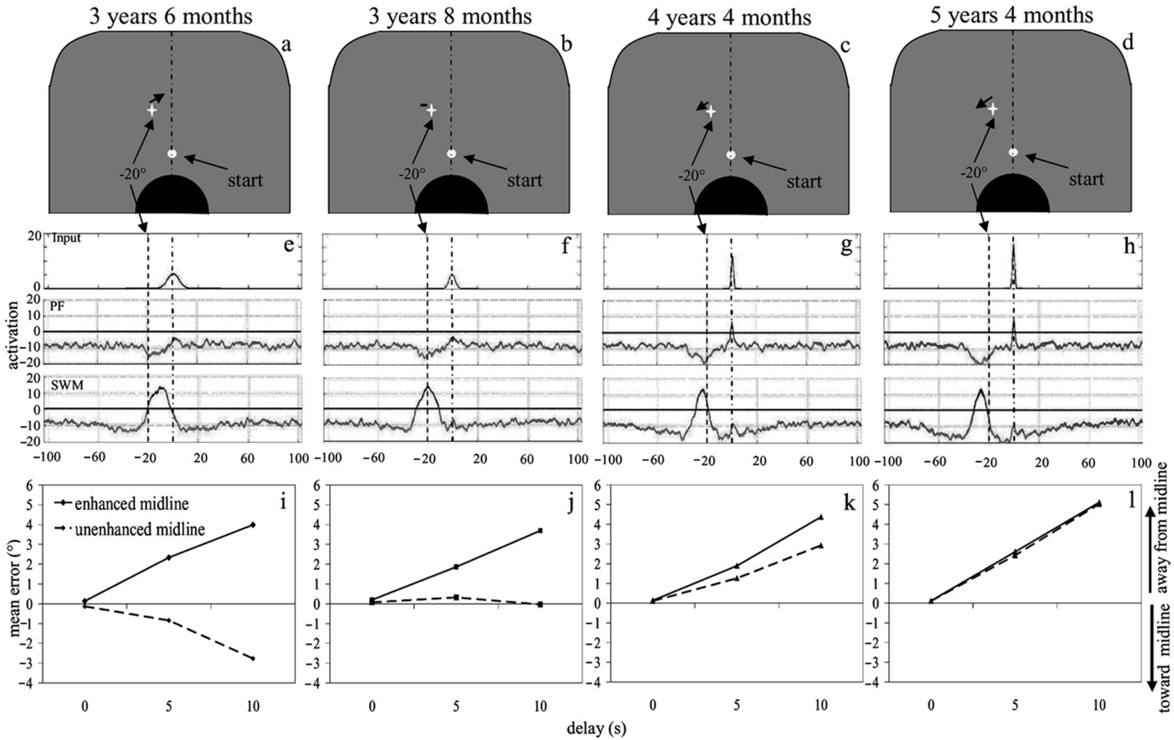

FIGURE 3 Top row shows schematic of spatial memory biases to a −20° target for children aged 3 years, 6 months (a); 3 years, 8 months (b); 4 years, 4 months (c); and 5 years, 4 months (d). Center row (e–h) shows a representative DFT simulation for each age. Bottom row (i–l) shows the mean error across 100 simulations at 0-, 5-, and 10-second delay intervals for the normal midline input strength (unenhanced) and a strong midline input (enhanced). See text for further details.

4 months. As in the simulation in Figure 2b, each simulation in this figure shows the activation of the model at the end of a 10-second memory delay when a target is presented at −20° (see vertical dashed line; for simulation details, see Schutte & Spencer, 2009). The top row in each simulation panel shows the input associated with the midline axis. The middle row shows activation in the PF, and the bottom row shows activation in the SWM field at the end of the delay (the inhibitory layer is not shown for simplicity).

The panels in Figures 3e–h highlight the two primary characteristics of the model that we changed during development. First, to capture children's improved ability to accurately perceive axes of symmetry (Ortmann & Schutte, 2010), we sharpened and strengthened the input associated with the midline axis (see top row of Figures 3e–h). Second, we increased the strength of excitatory and inhibitory neural interactions across the three layers. As a consequence, peaks of activation in SWM became *more precise* across development (see also, Schutte et al., 2003). This is evident in the noticeable sharpening of SWM peaks between 3 years, 6 months (bottom row of Figure 3e) and 4 years, 4 months (bottom row of Figure 3g). In addition, peaks of activation in SWM became *more stable* across development. This causes a reduction in attraction toward midline between 3 years, 6 months and 3 years, 8 months (compare the reduced bias toward 0° in the bottom rows of Figures 3e and 3f). The increase in stability also enables a new form of interaction between the perceptual and SWM fields: With stronger neural interactions at 4 years, 4 months, the model can simultaneously maintain a peak of activation at midline in the PF (see middle row of Figure 3g) and a peak of activation near the target location in SWM (see bottom row of Figure 3g). This results in a new response pattern: The SWM peak is repelled from midline after a 10-second delay due to overlapping inhibition in the shared inhibitory layer (see bias away from −20° in the bottom row of Figure 3g). Effectively, the midline peak in the PF which is anchored by cues in the task space "pushes" the peak in SWM away from 0°.

MODEL PREDICTIONS

The goal of the present study was to test this process-based account of the transition in spatial memory. This is important because the DFT provides the only account of the complex, protracted transition in spatial memory in early development (see Schutte & Spencer, 2009). Although this is the case, aspects of the model had to be "fit" to empirical results post-hoc. Thus, the present study tested a novel, a priori prediction of the DFT—that we should be able to get 3-year-olds to respond like 4-year-olds in a particular variant of our task. Tests of this prediction highlight the utility of formal modeling within developmental science and the critical back-and-forth between theory and experiment that can shed light on underlying developmental processes.

According to the DFT, the transition in spatial memory results from changes in the strength of neural interactions that underlie perceptual and working memory processes. Of course, it is not possible to manipulate the strength of neural interactions directly. Nevertheless, a key feature of the DFT is that behavior results from the soft assembly of a host of factors that come together in context (for discussion, see Thelen, Schöner, Scheier, & Smith, 2001). One central factor is the precision with which the system perceives reference cues in the task space (see top row of Figures 3e–h). Simmering and Spencer (2007) recently showed that manipulating perceptual cues in the task space can create and destroy biases away from a perceived reference frame on a trial-to-trial basis with adults. In the current study, we asked whether manipulation of perceptual cues would have an equally dramatic effect in development: Can we create the pattern of bias shown by older children in our spatial memory task with 3-year-olds simply by manipulating the perceptual structure of the midline axis?

To probe this possibility in the DFT, we ran two sets of simulations using model parameters from Schutte and Spencer (2009) for the four age groups depicted in Figure 3: one set with the midline input strength set to the value used in Schutte and Spencer (unenhanced midline) and one set with a stronger input (enhanced midline). The results at 1-, 5-, and 10-second delays, averaged across 100 simulations for each parameter set, are shown in the bottom panels in Figure 3. Note that, as with the exemplary simulations, the target was always presented at $-20°$.

With the unenhanced midline, the model showed a systematic shift in bias across this age range from strong attraction toward midline at 3 years, 6 months to bias away from midline at 4 and 5 years (see dashed lines in Figures 3i–l). When we used an enhanced midline input, however, all age groups showed strong bias away from midline (see solid lines in Figures 3i–l). Note, however, that the stronger midline input had the strongest effect on the younger ages. The 5-year-old model was already strongly biased away from midline without the enhanced midline input, and the strength of this bias did not change (see Figure 3l). We empirically tested these predictions in the following experiment.

EXPERIMENT 1

In Experiment 1, we tested the quantitative predictions shown in Figure 3 with four groups of children: a pretransition group (3 years, 6 months), a

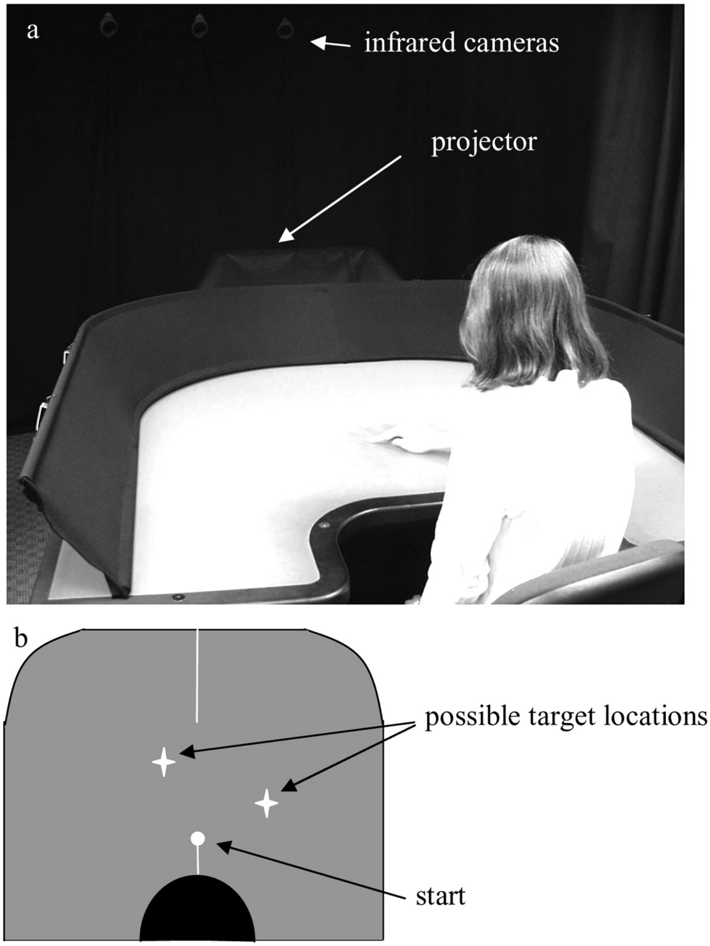

FIGURE 4 Apparatus used for spaceship task (a). Targets are projected onto the table from beneath and responses are recorded using a motion tracking system. Note that the lights in the room were turned on for the photograph but were dimmed during the experiment so the table appeared black. Schematic shows the table top with the enhanced midline axis display and sample target locations relative to the starting point (b).

group early in the transition (3 years, 8 months), a group just post-transition (4 years, 4 months), and a group well past the transition (5 years, 4 months). To keep the task the same as in Schutte and Spencer (2009), two target locations were used: $-20°$ and $60°$. The primary target of interest for testing the predictions of the theory was the $-20°$ target.

A crucial empirical question is how to make the midline axis more salient. One possibility would be to draw a line down the middle of the table, effectively subdividing the space for children. Although this might have the predicted effect, this deviates substantially from our previous work which examined children's ability to use a perceived axis of symmetry. A second alternative is suggested by the adult perceptual literature: Studies with adults have shown that symmetry axes can be made more salient by adding cues that highlight symmetry (e.g., Li & Westheimer, 1997). Inspired by this work, we added structure to the midline axis by adding lines above and below the region that contained the targets (see Figure 4b). This highlights the symmetry axis but still requires children to use a "virtual" axis to divide space into regions.

Methods

Participants. Thirteen children aged 3 years, 6 months ($M = 3;6.5$, $SD = 0.48$ months); 12 children aged 3 years, 8 months ($M = 3;8.7$, $SD = 0.50$ months); 10 four-year-olds ($M = 4;4.4$, $SD = 0.42$ months); and 11 five-year-olds ($M = 5;5.4$, $SD = 0.62$ months) participated. Seven additional children participated (five aged 3 years, 6 months; two aged 3 years, 8 months) but were not included in analyses for the following reasons: Three only participated in one session due to scheduling conflicts, and four stopped playing early. Children participated in two sessions generally scheduled a week apart.

Apparatus. Participants sat at a large table, the surface of which was a rear projection screen (see Figure 4a) with a display size of 0.91 m $\times$ 1.22 m and a resolution of 1,024 $\times$ 768 pixels. Dimmed room lights and black curtains prevented the use of external cues. A yellow dot projected along the midline axis of the table 15 cm from the front edge was the starting point. Perceptual structure was added to the midline reference axis by adding two lines to the axis: one that started 30 cm above the start dot and extended to the top of the table and one below the start location (see Figure 4b). A computer led participants through the game. Participants' movements of a rocket (5.5 cm high, 2 cm diameter) were recorded at 150 Hz using an optical-electronic motion analysis system (Optotrak, Northern Digital Inc.).

Procedure. The child played a warm-up game on the floor to help "Buzz Lightyear" find lost spaceships. The experimenter gave the child the rocket and showed the child two flashcards, one with a spaceship and one with a star. The experimenter placed both cards face down on the floor. When the experimenter said, "go," the child was encouraged to place the rocket on the spaceship card. The warm-up game was played until the child successfully found at least two spaceships.

Next, the child moved to the "spaceship table" (Figure 4a). The session began with demo trials that were identical to the test trials except that the experimenter performed the task. Generally, children required only one demo. Each trial began when the computer said, "Let's look for a spaceship." At this point, the start dot and lines were illuminated on the table. Following a random pretrial delay, a spaceship-shaped target appeared on the table for 2 seconds. This was followed by a 0-, 5-, or 10-second delay. The child's task was to move the rocket from the starting location to where the spaceship was hiding when the computer said "go, go, go." After each trial, the target was reilluminated for 1.5 seconds. The child received verbal and visual feedback from the computer based on whether he/she found the spaceship, was close to the spaceship, or was not so close (see Schutte & Spencer, 2009).

Design. Children recalled the locations of two targets separated by 80° as in Schutte and Spencer (2009). The target counter-clockwise from midline was always near midline (inner target), and the target clockwise from midline was always far from midline (outer target). The target locations were −20° and 60° from midline. These locations were chosen to allow for direct comparisons to data from Schutte and Spencer (2009). Note that Schutte and Spencer (2009) did not counterbalance which side of midline the inner and outer targets were located on, because children sometimes show differences in the magnitude of errors to the left and right of midline (see, e.g., Schutte & Spencer, 2002; Spencer & Hund, 2003). By keeping the target layout consistent across children, this eliminated one source of variance. Note, however, that studies have consistently reported uniformity in the general pattern of biases relative to the midline axis (Hund & Spencer, 2003; J. Huttenlocher et al., 1994; Schutte & Spencer, 2002; Spencer & Hund, 2003).

Delays of 0, 5, and 10 seconds were used. For the 4- and 5-year-olds, there were 48 test trials divided evenly between two experimental sessions—8 trials to each target at each delay. Children completed 6 practice trials at the start of each session. For the 3-year-olds, there were 36 test trials divided evenly between the two experimental sessions—6 trials to each target at each delay. Three-year-olds completed 2 practice trials at the start of each session. We reduced the number of trials for 3-year-olds to reduce fatigue effects. The target presentation and order of the delays were randomized.

Methods of analysis. Optotrak data were used to identify a starting and ending location for each trial (for details, see Schutte & Spencer, 2009).

We calculated directional error as the angle between the line connecting the start location and the target location and a line connecting the start location and the ending location. *Negative directional errors* indicate errors *toward midline* relative to the target location.

Trials that were not within two standard deviations of the median error for each target at each delay and trials for which our automated analysis software could not find valid start or end locations were rechecked manually. Following this, all trials that did not have a valid start or end location were eliminated. Overall, 3.4% of trials were eliminated (3;6 = 50 trials [11.6%]; 3;8 = 21 trials [4.9%]; 4;4 = 3 trials [0.7%]; 5;4 = 5 trials [0.9%]). We also eliminated trials on which children made a perseverative error; that is, they responded to a just-previous target rather than to the target on the current trial. Inclusion of these trials could result in a false bias toward midline, because the other target was always on the opposite side of midline. To prevent this, we removed trials with an error greater than $\pm 50°$ (see Schutte & Spencer, 2009). This resulted in the elimination of 4.1% of the trials.

Following removal of trials, children aged 3 years, 6 months completed an average of 28.3 trials ($SD = 5.26$); those aged 3 years, 8 months completed an average of 34.3 trials ($SD = 1.75$); 4-year-olds completed an average of 45 trials ($SD = 3.06$); and 5-year-olds completed an average of 47.7 trials ($SD = .47$). One child (aged 3 years, 6 months) had cells without any valid trials. This child was not included in the final analyses.

Results

Inner target analyses. The focus of the present study is on the critical $-20°$ target. Mean directional errors for this target can be seen in Figures 5a–d (solid lines). For comparison, data from Schutte and Spencer (2009) are also shown (dashed lines). As predicted by the DFT, all age groups were biased away from midline with the enhanced midline input. This contrasts with results from Schutte and Spencer (2009) for the two 3-year-old groups.

Mean directional error was analyzed in a two-way analysis of variance (ANOVA) with age (3;6, 3;8, 4, 5) as between-subjects factors and delay (0 seconds, 5 seconds, 10 seconds) as within-subjects factors. There was a main effect of delay, Wilks' $\Lambda = .82$, $F(2,40) = 4.28$, $p < .05$. As delay increased, the bias away from midline increased (0 seconds, $M = 2.30$; 5 seconds, $M = 4.64$; 10 seconds, $M = 6.24$). *T*-tests comparing error across delays revealed that the 0-second delay was significantly different from the 5-second, $t(44) = -2.70$, $p = .01$, two-tailed, and the 10-second delays, $t(44) = -2.72$, $p < .01$, two-tailed. The 5-second and 10-second delays were not significantly different from each other, $t(44) = -1.54$, *ns*, two-tailed. There were no other significant effects in the ANOVA.

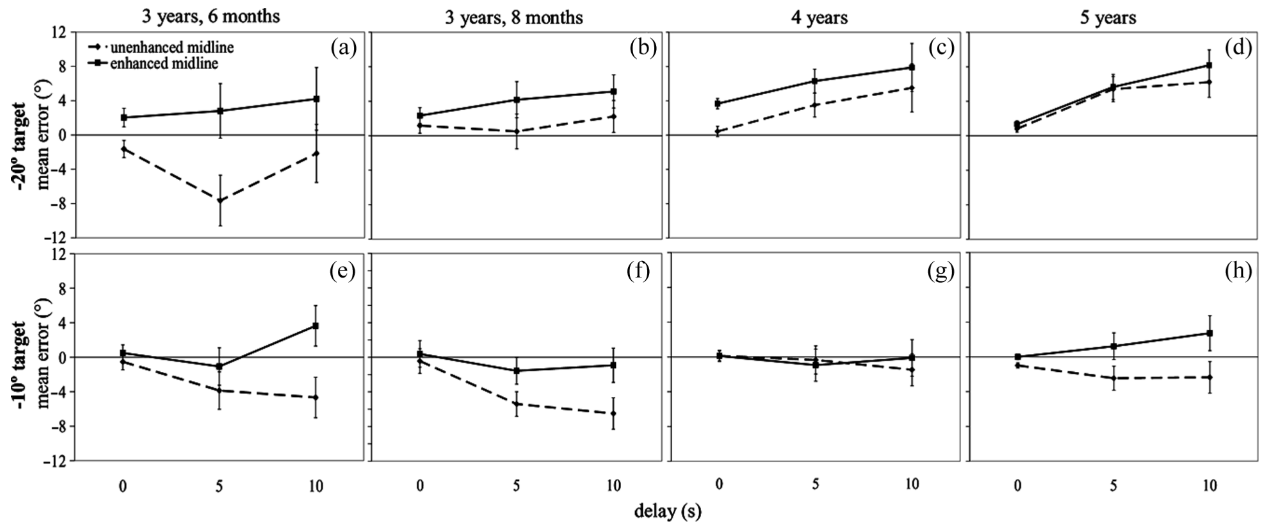

FIGURE 5 Mean directional error across age groups to the −20° target in Experiment 1 (a–d, top row) and mean directional error across age groups to the −10° target in Experiment 2 (e–h, bottom row). Positive errors are away from the midline reference axis, and negative errors are toward the midline reference axis. Data from Schutte & Spencer (in press) are shown for comparison (dashed lines).

As in Schutte and Spencer (2009), planned comparisons were conducted for each age group comparing mean directional error collapsed across 5- and 10-second delays to zero error. Given that children's errors at 5 and 10 seconds were not significantly different from each other, collapsing the data allowed for the most accurate measure of children's performance, because it included the most trials in each individual mean. Note that all of the *t*-tests comparing mean directional error to zero error were one-tailed due to the predicted direction of effect. The younger 3-year-olds' responses were biased away from midline at −20°, $M = 5.17$, $t(11) = 1.83$, $p < .05$. The older 3-year-olds' responses were biased significantly away from midline, $M = 3.54$, $t(11) = 3.18$, $p < .01$, as were the 4-year-olds' responses, $M = 7.66$, $t(9) = 3.54$, $p < .01$, and the 5-year-olds' responses, $M = 6.60$, $t(10) = 3.50$, $p < .01$.

Although results were in the predicted direction, a central question is whether these data differ significantly from data reported by Schutte and Spencer (2009). Thus, we conducted *t*-tests for each age group across experiments using the data collapsed across 5- and 10-second delays. Given that we predicted the direction of change, all *t*-tests were one-tailed. There was a significant difference between biases of those aged 3 years, 6 months with the enhanced midline and without the enhanced midline (Schutte & Spencer, 2009), $t(24) = -2.69$, $p < .01$. There was also a marginal difference at 3 years 8 months of age, $t(23) = -1.62$, $p = .06$. There was not a significant difference across experiments at 4 or 5 years of age (4 years, $t(18) = -1.15$, *ns*; 5 years, $t(21) = -0.42$, *ns*).

The DFT predicts that directional errors should be shifted systematically away from midline with added perceptual structure. Analyses of mean directional error support this view. It is possible, however, that only some children were affected by this manipulation. Thus, we examined individual differences within each age group using a classification scheme used by Schutte and Spencer (2009). The classification scheme was based on each child's directional error, collapsed across the 5- and 10-second delays. For each age group, we computed the standard error to the −20° target. This standard error was then used to compute the critical mean error necessary, based on the *t*-distribution, for each target to be significantly biased toward or away from midline for each age group. If a child's error was greater than the critical value and the error was positive, the child was classified as being *biased away from* midline. If a child's error was greater than the critical value and the error was negative, the child was classified as being *biased toward* midline. Otherwise, the child was classified as *unbiased.*

The proportion of children in each classification group for the −20° target can be seen in Figure 6a. The majority of children in all but the 4-year-old age group were biased away from midline at −20°. At 4 years of age, the majority of children were unbiased, but many also showed a robust bias away from

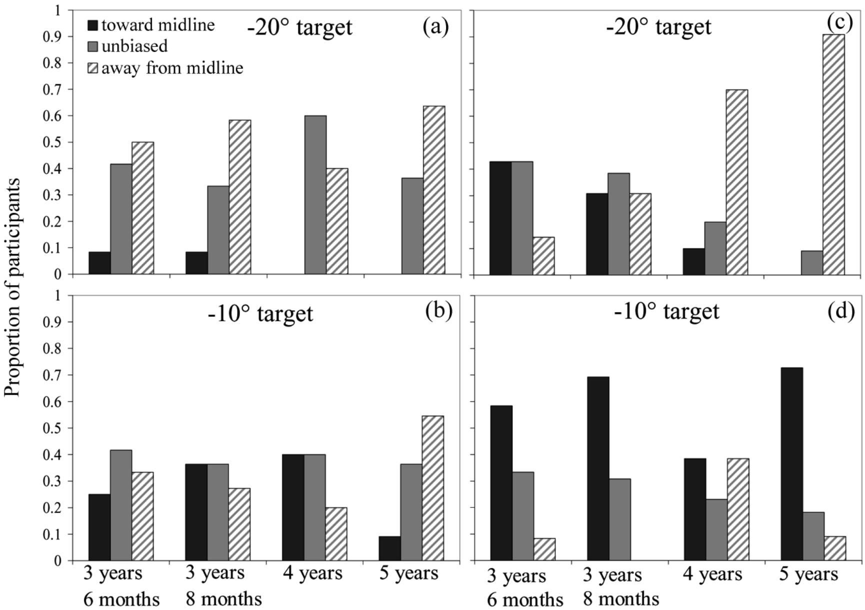

FIGURE 6 Proportion of children biased toward midline (black bars), away from midline (gray bars), or unbiased (striped bars) for each age at −20° (Experiment 1; a) and −10° (Experiment 2; b) targets. Data from Schutte and Spencer (2009) are shown in the right panels (−20° [c] and −10° [d]).

midline. Critically, there were very few children across all age groups who were biased toward midline. These results contrast with individual difference analyses from Schutte and Spencer (2009; see Figure 6c). In that study, more children were biased toward midline than away from midline at 3 years, 6 months of age. At 3 years, 8 months of age, all three categories—toward midline, unbiased, and away from midline—were approximately equal.[1]

We statistically compared the proportion of children in each categorization group from the present experiment to data from Schutte and Spencer (2009) by computing the Pearson chi-square across experiments for each age group separately. The two 3-year-old groups were marginally different across the two studies while the 4- and 5-year-olds were not significantly different (3;6: $\chi^2(2,\ N=26)=5.54$, $p=.06$; 3;8: $\chi^2(2,\ N=25)=4.79$,

[1]Note that the critical mean error used by Schutte and Spencer (2009) was lower than the critical mean error used here. Nevertheless, when we use the critical mean error from Schutte and Spencer (2009) with the present data, more children end up biased away from midline, and the lower criterion has little effect on the number of children biased toward midline.

$p = .09$; 4;0: $\chi^2(2, N = 20) = 2.62$, *ns*; 5;0: $\chi^2(2, N = 23) = 1.35$, *ns*). These results are consistent with analyses of the group data showing a systematic shift in children's response biases with the enhanced perceptual cues added to midline.

Outer target analyses. Mean directional error to the outer targets was analyzed in an ANOVA with age (3;6, 3;8, 4, 5) as a between-subjects factor and delay (0 seconds, 5 seconds, 10 seconds) as a within-subjects factor. There was a significant delay main effect, Wilks' $\Lambda = .73$, $F(2,40) = 7.28$, $p < .05$, and a significant delay $\times$ age interaction, Wilks' $\Lambda = .71$, $F(6,80) = 2.52$, $p < .05$. Follow-ups revealed a significant delay effect at 4 years of age, $F(2,18) = 11.98$, $p < .001$, but not at 3 years, 6 months, $F(2,22) = 2.22$, *ns*; 3 years, 8 months, $F(2,22) = 2.13$, *ns*; or 5 years of age, $F(2,20) = 2.53$, *ns*. The 4-year-olds were biased slightly away from midline at the 0-second delay and toward midline at the 10-second delay (0-second delay, $M = 3.16$; 5-second delay, $M = 1.82$; 10-second delay, $M = -6.03$).

As with the inner target, we conducted *t*-tests comparing mean error for the outer target to 0 collapsed across the 5- and 10-second delays. There were no significant biases for the youngest three age groups. Five-year-olds, however, were biased significantly away from midline, $M = 3.50$, $t(10) = 3.15$, $p = .01$, two-tailed. This differs from the 5-year-olds in Schutte and Spencer (2009) who were unbiased at 60°. Therefore, for the 5-year-olds, the enhanced perceptual cues had an effect as far out as 60° from midline.

Discussion

This experiment tested a novel, a priori prediction of the DFT that modifying the perceptual structure of a virtual midline axis would affect children's response biases during a developmental transition in spatial memory. When we changed a single parameter in the model—the strength of the midline input—we produced a qualitative change in the direction of bias at −20°. Likewise, a small change to the task space—adding perceptual structure to the midline axis—resulted in the predicted shift in children's biases at this same location. Importantly, the bias away from midline was robust in analyses of both group data and individual differences. In addition, 5-year-olds were biased away from midline at 60°—a location that in previous studies was unbiased until 6 years of age (Schutte & Spencer, 2009; Spencer & Hund, 2003).

These data provide strong support for the DFT. This theory predicted an entire pattern of results across four groups of children separated in age by 2 years. Indeed, the quantitative match between the theory and the empirical data was quite good, despite the fact that we only scaled a single parameter (the strength of the midline input). This demonstrates that our theory can generate robust predictions. Before evaluating the DFT in greater detail, however, we turn to a second test of the theory's predictions.

EXPERIMENT 2

Results from Experiment 1 suggest that our manipulation of perceptual structure helped children perform in a more developmentally advanced manner consistent with the DFT. It is also possible, however, that the addition of cues caused a *global* change in how children approached the task; that is, children showed a different response pattern because they remembered locations in a fundamentally different way. The present experiment examined these alternatives.

Schutte and Spencer (2009) found that the developmental transition in spatial memory depended on the target location probed at each age. Some targets, such as $-20°$, transitioned to the repulsion pattern relatively early (at 4 years of age; see Figure 1). Other targets, such as $-10°$, showed robust attraction at the youngest ages (see Figure 1) and did not show a systematic bias away from midline until much later (at 6 years of age; Schutte & Spencer, 2009; Spencer & Hund, 2003). If our manipulation helped children perform in a more developmentally advanced manner, then we would expect that the shift toward the repulsion pattern with enhanced perceptual input should occur later for targets that transition later. Thus, in the present experiment, we examined children's performance to a $-10°$ target with the enhanced midline display. We expected that children would not show attraction toward midline at the youngest ages in contrast to results from Schutte and Spencer (2009). Moreover, we expected that there would not be a significant bias away from midline until 4 years of age or older—that is, after the youngest age (3 years 8 months) at which we found significant bias away from midline in Experiment 1.

It is possible, however, that an enhanced midline input has a more global impact on children's ability to remember locations. For instance, children might show biases away from midline for *all* target locations with an enhanced midline input because they can more easily divide the space into left and right regions. This predicts that children should show the same pattern found in Experiment 1: All children aged 3 years, 8 months and older should show robust bias away from midline at $-10°$. Such a result would violate a central claim of the DFT—that spatial memory biases during the developmental transition depend on the child's developmental level and the target location probed.

Method

Participants. Thirteen children aged 3 years, 6 months ($M = 3;6.7$, $SD = 0.35$ months); 12 children aged 3 years, 8 months ($M = 3;9.2$, $SD = 0.65$ months); 10 four-year-olds ($M = 4;5.1$, $SD = 0.61$ months); and 11 five-year-olds ($M = 5;5.2$, $SD = 0.55$ months) participated. Seven additional children participated (two aged 3 years, 6 months; two aged 3 years, 8 months; two 4-year-olds; one 5-year-old) but were not included in analyses for the following reasons: One was excluded for experimenter error, two only participated in one session due to scheduling conflicts, three stopped playing early, and one did not understand the game. Children participated in two sessions generally scheduled a week apart.

Apparatus, procedure, and design. The apparatus and procedure were the same as in Experiment 1. The design was the same as in Experiment 1 except the target locations were $-10°$ and 70° from midline.

Methods of analysis. The methods of analysis were the same as in Experiment 1. As in Experiment 1, trials that did not have a valid start or end location were eliminated. Overall, 3.4% of trials were eliminated (younger 3-year olds = 32 trials [6.8%]; older 3-year-olds = 14 trials [3.3%]; 4-year-olds = 2 trials [0.4%]; 5-year-olds = 3 trials [0.6%]). We also eliminated all trials with an error greater than ±50° (see Schutte & Spencer, 2009). This resulted in the elimination of 5.6% of the trials.

Following removal of trials, children aged 3 years, 6 months completed an average of 32.4 trials ($SD = 3.68$); those aged 3 years, 8 months completed an average of 32.9 trials ($SD = 2.0$); 4-year-olds completed an average of 46 trials ($SD = 3.5$); and 5-year-olds completed an average of 47.1 trials ($SD = 1.6$). Two children (one aged 3 years, 6 months; one aged 3 years, 8 months) had cells without any valid trials. These children were not included in the final analyses.

Results

Inner target analyses. We began by analyzing the data from the critical $-10°$ target. Mean directional errors can be seen in Figures 5e–h (solid lines). For comparison, data from Schutte and Spencer (2009) are also shown (dashed lines). As can be seen in the figure, the enhanced midline input influenced responses at $-10°$. The three youngest age groups were not generally biased, while the 5-year-olds were biased slightly away from midline over delay. This contrasts with results from Schutte and Spencer (2009) where both 3-year-old groups were biased toward midline at $-10°$

with no systematic biases for 4- and 5-year-olds. Performance at -10° also contrasts with performance at the -20° target in Experiment 1 which showed biases away from midline across all age groups.

Mean directional error was analyzed in a two-way ANOVA with age (3;6, 3;8, 4, 5) as a between-subjects factor and delay (0 seconds, 5 seconds, 10 seconds) as a within-subjects factor. There were no significant effects. As in Experiment 1, planned comparisons were conducted comparing mean directional error collapsed across 5- and 10-second delays to zero error (see also, Schutte & Spencer, 2009). There were no significant biases toward or away from midline for the three youngest age groups (3;6: $M = 2.17$; 3;8: $M = -1.66$; 4;0: $M = -0.16$). The 5-year-olds' responses, however, were significantly biased away from midline, $M = 2.62$, $t(10) = 1.98$, $p < .05$, one-tailed. These results generally support our predictions: The enhanced midline reduced the bias toward midline for the youngest age group and increased the bias away from midline in the oldest age group.

As in Experiment 1, data from the inner target were directly compared to data from Schutte and Spencer (2009) by conducting *t*-tests for each age on the data collapsed across 5- and 10-second delays. There was a significant difference between biases of those aged 3 years, 6 months with the enhanced midline and without the enhanced midline (Schutte & Spencer, 2009), $t(22) = -2.56$, $p < .01$, one-tailed. There was also a significant difference at 3 years, 8 months of age, $t(22) = -1.84$, $p < .05$, one-tailed. There was not a significant difference between the enhanced and unenhanced midline at 4 years of age, $t(21) = -0.27$, *ns*, one-tailed. There was a significant difference at 5 years of age, $t(21) = -2.54$, $p < .01$. Thus, the shift in bias caused by the enhanced midline was significant for the two 3-year-old groups and the 5-year-old group (see Figures 5e, f, and h).

Using the same procedure as in Experiment 1, we examined individual differences by classifying children in each age group as being biased toward midline, unbiased, or biased away from midline. The proportion of children in each classification group for the -10° target can be seen in Figure 6b. In contrast to results from the -20° target, the proportion of participants in each classification group at -10° was more distributed, with the exception of the 5-year-olds where more children were in the unbiased or biased away from midline classifications. These results contrast with those of Schutte and Spencer (2009) who found that the majority of children were biased toward midline, even at 5 years of age.

As in Experiment 1, we statistically compared the proportion of children in each group from Experiment 2 to data from Schutte and Spencer (2009) by computing the Pearson chi-square for each age group separately. The two 3-year-old and the 4-year-old groups were not significantly different across the two studies, but the 5-year-olds showed a statistically robust shift in the distribution across categories between the two studies (3;6: $\chi^2(2, N = 24) = 3.51$, *ns*; 3;8: $\chi^2(2, N = 24) = 4.15$, *ns*; 4;0: $\chi^2(2, N = 23) = 1.17$, *ns*; 5;0: $\chi^2(2, N = 23) = 10.59$, $p = .005$). In particular, with the enhanced midline there were significantly fewer 5-year-old children biased toward midline and more 5-year-olds biased away from midline at −10° (see Figure 6).

Outer target analyses. Mean directional error to the outer targets was analyzed in an ANOVA with age (3;6, 3;8, 4, 5) as a between-subjects factor and delay (0 seconds, 5 seconds, 10 seconds) as a within-subjects factor. There was a significant delay main effect, Wilks' $\Lambda = .82$, $F(2,39) = 4.23$, $p < .05$, and a significant delay × age interaction, Wilks' $\Lambda = .65$, $F(6,78) = 3.16$, $p < .05$. Follow-ups revealed a significant delay effect at 3 years, 6 months of age, $F(2,22) = 4.28$, $p < .05$. These children showed a bias toward midline over delays (0-second delay, $M = 1.80$; 5-second delay, $M = -4.07$; 10-second delay, $M = -6.48$). No other effects reached significance.

Next, we conducted *t*-tests comparing mean error to the outer target to 0 collapsed across the 5- and 10-second delays. The two 3-year-old groups were significantly biased toward midline at 70° (3;6: $M = -4.51$, $t(11) = -2.19$, $p = .05$; 3;8: $M = -4.14$, $t(10) = -2.29$, $p < .05$, all tests two-tailed). No other effects reached significance. It is not clear why 3-year-olds showed a small but significant bias toward midline at 70°. It is possible that the enhanced midline input influenced children's perception of a horizontal axis parallel to the front of the table. The 70° target would be relatively close to such an axis. Interestingly, this only occurred for the 3-year-olds. It is possible that for the older ages, the bias away from midline—although non-significant for the 4-year-olds—was strong enough to counteract a bias away from the horizontal axis; thus, the two effects essentially cancelled each other out. It is also possible that the memories of the older children were more stable than the 3-year-olds, and as a result, the influence of the horizontal axis was not detected.

Discussion

At −10°, the three youngest age groups were not biased, while the 5-year-olds were biased away from midline over delay. This contrasts with results from Schutte and Spencer (2009). Thus, enhancing the midline input systematically shifted the pattern of results toward a more developmentally advanced pattern where 3-year-olds were unbiased rather than attracted toward midline, and 5-year-olds were biased away from midline—the same pattern 6-year-olds show with the unenhanced midline

(Spencer & Hund, 2003). These patterns were evident in analyses of both mean directional error and individual difference classifications. Critically, our results demonstrate that the effect of the enhanced midline did not globally alter how children remembered locations in the spaceship task; rather, the effect depended on the target location probed, consistent with the DFT.

GENERAL DISCUSSION

Results from the present study provide robust support for the prediction of the DFT that enhancing the midline axis would cause young children to show a more developmentally advanced response pattern in the spaceship task. Critically, the change in bias depended on the age of the child and the target location probed. These results support the claim of our theory that subtle changes in the perception of the midline axis influence the development of spatial memory biases.

Our findings are clearly consistent with the DFT, but are they also consistent with other accounts of the development of spatial memory? In particular, are these data consistent with the Category Adjustment (CA) model proposed by Huttenlocher and colleagues (J. Huttenlocher, Hedges, & Duncan, 1991; J. Huttenlocher et al., 1994)? According to this model, the transition in spatial memory over development reflects children's emerging ability to subdivide space into two categories. Young children treat large, homogeneous spaces as one category with a prototype at the center, and as a result, their recall responses are biased toward the prototype at the center of the space. Older children and adults, however, subdivide large spaces into two categories with spatial prototypes at the center of the left and right categories. Thus, their responses are biased away from the midline of the task space and toward prototypes to the left and right.

Data from Experiment 1 appear to be consistent with the CA model. Experiment 2 presents more of a challenge, however, because children did not show robust bias away from midline until 5 years of age. If children are subdividing space into left and right categories relatively early in development at $-20°$, one would expect the new form of spatial subdivision to have a global influence on recall responses; that is, children should be biased away from the category boundary at $-10°$. This was not the case. More generally, it is important to note that the CA model does not capture the entire pattern of results reported by Schutte and Spencer (2009; see Figure 1). For instance, in Figure 5, one can see that children aged 3 years, 8 months in Schutte and Spencer (2009) showed attraction toward midline at $-10°$ but were unbiased at $-20°$. According to the CA model, the attraction toward midline can be explained as attraction toward a prototype at midline. If this is the case, there should be robust attraction at –20°, but there was not. Thus, although the CA model can explain aspects of the pattern shown in Figure 5, the entire pattern of results from this study and our previous study are not consistent with this model of spatial memory development.

A primary difference between the CA model and the DFT is that the CA model posits a qualitative shift in the nature of the midline symmetry axis over development. In particular, midline is treated as a prototypical location early in development and as a category boundary later in development. By contrast, the DFT captures the qualitative shift in children's performance relative to midline without a shift in the nature of the midline axis—this axis remains a perceived axis of symmetry between 3 and 6 years and beyond (see, e.g., Spencer & Hund, 2002). This is evident in Figure 3: The midline axis is an input to the model throughout the developmental period we have studied; what changes over time is the quantitative strength and precision of the input. As noted earlier, these quantitative changes contribute to the emergence of a qualitatively new ability in the model—the ability to simultaneously hold onto a perceptual representation of the midline axis while actively sustaining a working memory for the target location.

What are the developmental consequences of this achievement? One consequence is an overall enhancement in the precision of spatial cognition. For instance, once the system can form a stable perceptual peak, it is able to track online changes in that input when, for instance, the child moves or the landmark moves (for details, see Spencer, Perone, & Johnson, 2009; Spencer et al., 2007). This helps keep working memory anchored to the current perceptual scene. Moreover, if the system can accurately maintain multiple perceptual peaks, working memory becomes more reliable because the directions in which working memory peaks can drift are reduced. Essentially, the perceptual peaks help "lock" working memory into particular spatial regions. This is similar to the type of adaptive advantage J. Huttenlocher and colleagues (1994) discussed as a consequence of more detailed spatial subdivision. The DFT, however, explains how changes in "subdivision" can emerge from quantitative changes in the precision of neural interactions within a PF.

Interestingly, this example highlights a second difference between the CA model and the DFT: These models differ in the level at which they explain behavior (for discussion, see Schutte & Spencer, 2009). The CA model explains behavior at the level of computational theory and does not specify the processes that underlie developmental change. By contrast, the DFT explains behavior at the level of process and is grounded in neural principles. In particular, the DFT represents locations in space using a population of spatially tuned neurons consistent with cortical neurophysiology (e.g., in motor cortex: Georgopoulos, Kettner, & Schwartz, 1988; Georgopoulos, Taira, & Lukashin, 1993; in premotor cortex: di Pellegrino & Wise, 1993; in prefrontal cortex [PFC]: di Pellegrino & Wise; Wilson, Scalaidhe, & Goldman-Rakic, 1993), and the multilayered architecture of the DFT is consistent with the multilayered structure of visual cortex (see Douglas & Martin, 1998; for related network models, see Compte et al., 2000; Tanaka, 2000). In addition, several studies have demonstrated that dynamic fields can be directly estimated through single-cell recording studies (e.g., Bastian, Riehle, Erlhagen, & Schöner, 1998; Erlhagen, Bastian, Jancke, Riehle, & Schöner, 1999).

Given that the DFT captures process in a neurally grounded way, how does this model explain developmental change? As discussed in the Introduction, the model captures development through two changes: a sharpening and strengthening of the input associated with the midline axis and an increase in the strength of excitatory and inhibitory neural interactions. In Schutte and Spencer (2009), these changes were made by changing particular parameters "by hand." How might these changes occur in the developing child? The first type of change in the model—change in the precision of the midline input—likely reflects a type of perceptual learning as children's ability to perceive symmetry axes improves (Ortmann & Schutte, 2010). Although we are currently investigating the processes that underlie this form of perceptual learning, the present study provided support for this aspect of the DFT by manipulating the perceptual cues in the task space. By changing the exactness with which children at or near the transition point perceived the virtual midline axis, we were able to "push" them toward a more developmentally advanced response pattern.

The second type of developmental change in the model—changes in neural interaction—may occur as the result of biological and/or experience-dependent neurophysiological changes. For example, the PFC—an area implicated in working memory for both spatial and nonspatial information—is still developing during this period of development (Gogtay et al., 2004; Rakic, 1995; Sowell, Thompson, Tessner & Toga, 2001), and the pruning of synapses and myelination are also still occurring in many areas of the brain (P. R. Huttenlocher, 1990; Sampaio & Truwit, 2001). All of these processes should lead to more precise and stronger forms of neural interaction within cortical fields (Edin, Macoveanu, Olesen, Tegner, & Klingberg, 2007). Similarly, Hebbian processes (which have been directly implemented within the DFT; see Spencer, Dineva, & Schöner, 2009) could cause changes in the strength and precision of neural interaction as a function of experience remembering spatial locations in different contexts.

We conclude by highlighting three central contributions the present study makes to the developmental literature. First, it provides a strong test of a new theory of spatial cognitive development (see Simmering et al., 2008; Spencer et al., 2007). Second, it provides support for the dynamical systems view that children's behavior is softly assembled from multiple processes that come together in a moment in a task (see Spencer, Simmering, & Schutte, 2006; Thelen & Smith, 1994). Smith, Thelen, and colleagues provided a canonical demonstration of this in infancy in the context of the Piagetian A-not-B error, showing that they could create and eliminate this error through manipulation of often-subtle task factors (Diedrich, Highlands, Spahr, Thelen, & Smith, 2001; Diedrich, Thelen, Smith, & Corbetta, 2000; Smith, Thelen, Titzer, & McLin, 1999). Here, we have demonstrated that we can also create and eliminate response patterns associated with developmental changes in spatial memory via the manipulation of task-specific factors.

Third, this report offers a novel example of the utility of formal process modeling in developmental science. Although one might have predicted that changing perceptual cues in a spatial memory task in early development would have *some* effect on children's responses, the DFT did something much more precise: It quantitatively predicted how responses in the transitional age groups would be affected. This highlights the generative nature of process modeling and the useful dialogue between theory and experiment that can ensue when accounts of development are pushed to this level of analysis.

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