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Test of a relationship between spatial working memory and perception of symmetry axes in children 3 to 6 years of age

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ABSTRACT

Children's memory responses to a target location in a homogenous space change from being biased toward the midline of the space to being biased away. According to Dynamic Field Theory (DFT), improvement in the perception of the midline symmetry axis contributes to this transition. Simulations of DFT using a 3-year-old parameter setting showed that memory biases at intermediate target locations were related to the perception of midline. Empirical results indicated that better perception of midline was associated with greater memory biases away at the 20° and 40° targets in 3-year-olds, and greater biases away at 60º in 4- to 6-year-olds. Findings support the DFT in that perception of midline is associated with memory biases.

KEYWORDS
Dynamic Field Theory; spatial memory bias; perception of midline; category adjustment model

1. Introduction

Spatial memory is a basic cognitive process that is essential for functioning in our world. Spatial memory is involved when solving a math problem, navigating to work, and searching for an item (e.g., a book). Spatial working memory (SWM) actively maintains location-related information in memory during short-term delays (Lundqvist, Herman & Miller, 2018; Spencer, Simmering & Schutte, 2006). When remembering a location in SWM, people typically remember locations relative to a landmark or a frame of reference, such as the wall of a room or edge of a table. These reference frames are crucial for organizing space so that locations are encoded in an efficient manner. Several studies, however, have found that SWM is systematically distorted relative to such reference frames (e.g., Huttenlocher, Hedges & Duncan, 1991; Schutte & Spencer, 2009; Spencer & Hund, 2002). Interestingly, these biases, called geometric or categorical biases, change over development. This developmental change could be due to changes in memory, perception, or both.

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A developmental transition in geometric biases occurs between 3 and 6 years of age (Huttenlocher et al., 1991; Schutte & Spencer, 2002, 2009; Spencer & Hund, 2003). When 3-year-olds recall the location of a target in a homogenous space (e.g., a table), their memory responses are biased significantly toward the midline symmetry axis of the space (Huttenlocher, Newcombe & Sandberg, 1994; Schutte, Keiser & Beattie, 2017; Schutte & Spencer, 2009), whereas the responses of older children, e.g., 6- and 11-year-olds, and adults are biased significantly away from midline (Huttenlocher et al., 1994; Schutte et al., 2017; Spencer & Hund, 2003). Noteworthily, in addition to changing over development, these biases also depend on the location of the target relative to the midline of the space. Schutte and Spencer (2009) found that the memory responses of children 3 years, 8 months, of age were biased toward midline when the target was close to midline, i.e., 10° from midline, and not biased when the target was farther from midline, e.g., 20° from midline. In contrast, the SWM responses of 5-year-olds were biased away from the midline when the target was 20°, 30°, and 50° from midline, but responses to targets 10°, 60°, and 70° from midline were not biased.

One dominant explanation of the transition in geometric bias – from responses biased toward the midline of a space to biased away from midline, is the category-adjustment model (CA model) (Huttenlocher et al., 1991, 1994). According to the CA model, when recalling the spatial location of a target, people use fine-grained and categorical representations of the location (Huttenlocher et al., 1991). A fine-grained representation is formed using the direction and distance of a target relevant to a reference location, and a categorical representation is formed using boundaries such as edges and the center of a space. When recalling a target location in a homogeneous space, younger children treat the space as one category and use the center of the space as a prototype (Huttenlocher et al., 1994); therefore, younger children respond toward the center of the space, i.e., toward the prototype. In contrast, older children treat the homogenous space as two equally divided spaces – left and right categories, and, therefore, older children respond away from the midline of the space, and toward the prototypes at the centers of the left and right categories. Although the CA model provides a nice description of geometric biases over development, what causes the change in biases is less clear in the model (Plumert & Spencer, 2007; Spencer, Simmering, Schutte & Schöner, 2007).

The Dynamic Field Theory (DFT) of SWM (Schutte & Spencer, 2009; Simmering, Schutte & Spencer, 2008) has also been used to explain how the transition in geometric biases occurs. DFT is a dynamic systems model that explains developmental change as the result of the interaction of changes in perception and higher cognitive processes. The model uses a type of neural network, dynamic neural fields (DNF), which models behavior as sustained peak of activation in a field of interconnected neurons. In the SWM model, the sustained peak is the memory of the target location. According to the spatial precision hypothesis, two changes in the model contribute to the transition in SWM bias: neural interactions become stronger and the perception of the symmetry axis becomes more accurate (Schutte & Spencer, 2009; Schutte, Spencer & Schöner, 2003; Simmering et al., 2008).

In this study, we aim to examine how perception of the symmetry axis of a homogenous space is associated with SWM. According to the DFT, the target peak being maintained in SWM moves toward the symmetry axis if it overlaps with the excitation from the axis, and away from the axis if it overlaps with inhibition from the axis (see below for details). One of the changes that influences this overlap is the perceptual precision of the symmetry axis. How precisely a child can localize a symmetry axis changes gradually over development (Ortmann & Schutte, 2010; Schutte, Simmering & Ortmann, 2011; Schutte & Spencer, 2009). Although, 3-year-olds are relatively accurate at localizing the symmetry of axis of a homogenous space, their perception of a symmetry axis is less accurate than 4- to 6-year-olds, and 4- to 6-years-olds are less accurate than adults (Ortmann & Schutte, 2010). Children who have a more precise perception of the symmetry axis should display more SWM biases away from the midline, and this association should vary depending on how close the target is to the axis. Specifically, over development the relationship should initially be significant at intermediate locations, e.g., 20°, where inhibition from the perception midline peak first overlaps with the working memory peak (Schutte & Spencer, 2009). In slightly older children, the relationship between perception of midline and spatial memory should be significant for targets closer to midline and/or farther away from midline, because these children have a more precise perception of midline. In the model, this increase in precision is captured by a narrower and stronger midline peak. This narrower and stronger peak will result in greater inhibition closer to midline as well as greater inhibition across a larger span. Thus, as precision increases, the relationship between midline and SWM bias becomes significant at both targets closer to midline and farther away from midline (Schutte & Spencer, 2009).

The goal of the current study was to test how perception of the symmetry axis and spatial memory bias were related in both the model proposed by Schutte and Spencer (2002, 2009) and in children. First, simulations of the model were conducted to generate specific predictions about the relationship between the perception of midline and SWM biases at various target locations using the parameter set for the transition point in geometric biases. In Experiment 1, the specific predictions generated in the simulations were tested empirically in a group of 3-year-olds. In Experiment 2, the relationship between spatial memory biases and perception of midline was tested in 4- to 6-year-olds.

2. Simulations of Dynamic Field Theory

DFT has been used to model many behaviors, including language (Spencer, Lipinski & Samuelson, 2010), decision making (Wilimzig, Schneider & Schöner, 2006), cognitive switching (Buss & Spencer, 2014), and SWM (Schutte & Spencer, 2010; Schutte et al., 2003), among others. The DFT model of SWM represents particular locations through populations of spatially-tuned neurons arranged in three neural fields (see Figure 1): a perceptual field (Figure 1a), an inhibitory field (Figure 1b), and a SWM field (Figure 1c). Each "neuron" codes for a specific location, and the activation level of each neuron evolves over time. For each field in the two left panels in Figure 1, location is on the x-axis, activation is on the y-axis, and time is on the z-axis. The figure shows the activation in each field over the time course of one SWM trial. The right panels show the state of each field at the end of the memory delay, i.e., the final time-step. In these panels, location is on the x-axis and activation is on the y-axis.

Inputs to the perceptual field (top layer, Figure 1a) create peaks of activation that encode the locations of perceptual cues in the task space, e.g., frames of reference and the target location. In the simulations in

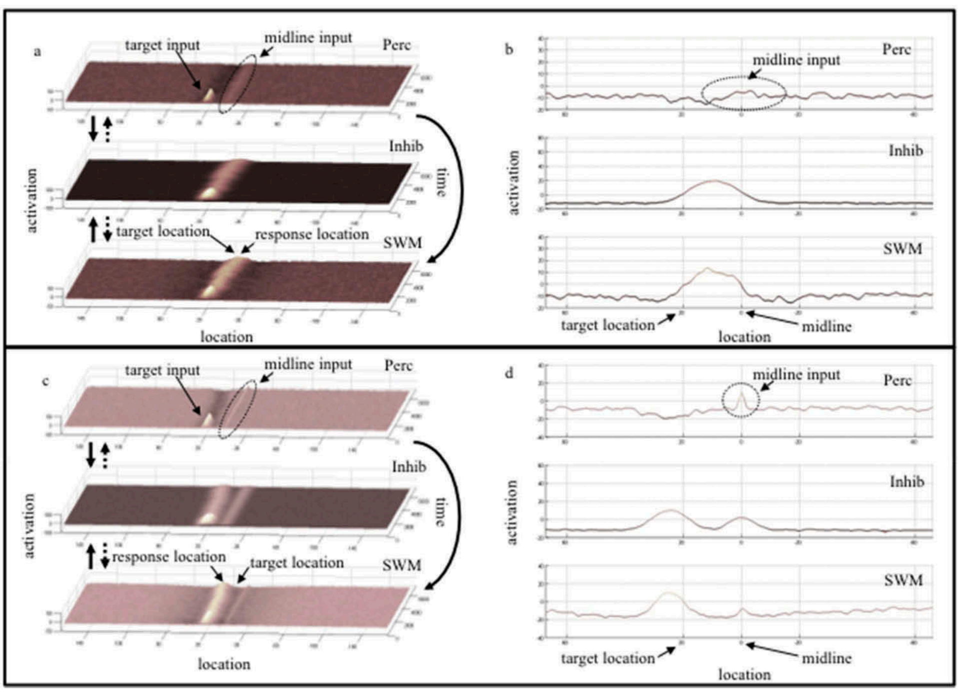

Figure 1. Simulation of one trial of Dynamic Field Theory (DFT). The complete fields are on the left and a time slice from the end of the trial is on the right. The top panels (a, b) are simulation using the 3 years 6 months parameter set from Schutte and Spencer (2009), and the lower two panels (c, d) are a simulation from the 5 years 4 months parameter set from Schutte and Spencer. See text for further details.

Figure 1, there are two inputs to the perceptual field, a strong target input at 20° and a weaker midline input at 0°, which marks the symmetry axis of the task space. The width and strength of the midline input represents the model's "perception" of the location of midline: broad, weaker input represents poorer localization of the symmetry axis and narrower, stronger input represents improved localization of the axis. The perceptual field sends positive activation to the inhibitory and SWM fields (see solid arrows). The SWM field (bottom layer, Figure 1a) 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 inhibitory field (middle layer, Figure 1a) is a layer of inhibitory interneurons that mediate excitation in the other two fields. The inhibitory layer receives input from, and projects inhibition broadly back, to both the perceptual field and the SWM field (see dashed arrows).

The peaks of activation in the SWM field are maintained through a local excitation/lateral inhibition function (Amari, 1977). Neurons that are sufficiently activated send excitation to nearby neurons (i.e., those that are close by along the x-axis). Through the inhibitory layer, activated neurons also inhibit neurons that are farther away. These recurrent connections lead to self-sustaining peaks of activation that are maintained during the delay. The self-sustaining peaks are the model's "memory" of a location. A key aspect of these fields is that during the memory delay, the self-sustaining peak can drift. For example, during the delay in the simulation shown in Figure 1a, the peak drifted toward 0°, or toward the midline reference axis. This drift is due to weak positive input at 0° from the continued perception of the midline axis. Although this weak input is not sufficient to create a self-sustaining peak in either the perceptual or SWM field, it is strong enough and broad enough to cause the peak in the SWM field to drift toward 0° during the delay. Specifically, although the midline input is too weak to be visible in Figure 1a,b, the width of the input spans from approximately −18° to +18°. Thus, this positive input is broad enough to overlap with the edge of the target peak which initially is centered at 20°. This overlap results in greater activation on that side of the target peak, and the peak drifts toward the midline input at 0°.

According to DFT, the developmental transition in geometric biases is due to two changes over development: an improvement in the perception of the midline symmetry axis and an increase in the precision and stability of neural processes that underlie spatial memory (Schutte & Spencer, 2009, 2010). Figure 1a shows an exemplar simulation prior to the transition (the 3 years 6 months parameter set from Schutte & Spencer, 2009) and Figure 1c shows a simulation from after the transition (the 5 years 4 months parameter set from Schutte & Spencer, 2009). The only differences between these two parameter sets involve the midline axis input and the strength of neural interaction. First, to capture children's improved ability to accurately perceive the location of axes of symmetry (Ortmann & Schutte, 2010), Schutte and Spencer (2009) sharpened and strengthened the input associated with the midline symmetry axis. Second, to increase the stability of memory, Schutte and Spencer (2009) increased the strength of excitatory and inhibitory neural interactions across the three layers. The resulting change in peak shape can be seen by comparing the peak in the SWM field in Figure 1b to the peak in the SWM field in Figure 1d. The sustained peaks in SWM that result from the increases in interaction strength over development are more precise. They are also more stable, i.e., they do not drift as much during the delay (see difference between target location and center of peak in Figure 1b,d; see also, Schutte et al., 2003).

The increase in interaction strength also enables the model to simultaneously maintain a peak of activation at midline in the perceptual field (see top layer of Figure 1c) and a peak of activation near the target location in SWM (see bottom layer of Figure 1c). The stronger midline peak in the perceptual field results in the SWM peak being repelled from midline after a 10 seconds delay, due to overlapping inhibition in the shared inhibitory layer (see bias away from −20° in the bottom row of Figure 1b). Effectively, the midline peak in the perceptual field 'pushes' the peak in SWM away from 0°.

Based on simulations of the DFT model of SWM, Schutte and Spencer (2009) predicted that the developmental timing of the transition in geometric biases would depend on target location. To empirically test this prediction, they tested children in a simple spatial memory task, called the "spaceship task." In this task, children have to remember the location of a "spaceship" on a large monitor. Schutte and Spencer (2009) were able to quantitatively fit the empirical data with the DFT model by only changing the strength of neural interaction and the strength and width of the midline axis input parameters.

The goal of the current study is to test the prediction of DFT that spatial memory errors are related to the perception of the location of midline. This prediction, however, is not very specific. One advantage of a computational model is that simulations can be used to make a general prediction more precise and, therefore, more falsifiable. In order to generate a more precise prediction about the relationship between the perception of midline and spatial memory, we conducted a series of simulations of DFT with a variable midline reference axis input using the 3 years 6 months parameter set from Schutte and Spencer (2009). We chose the 3 years 6 months parameter set because Schutte and Spencer (2009) found that children at this age are just starting the transition and are highly variable. In particular, some children have started the transition and some have not. Thus, testing the hypothesis in this age group allowed for variability in performance across children while holding age constant. It should also be noted that Schutte and Spencer found that the fitting the model to the data from the two 3-year-old groups (3 years, 6 months and 3 years, 8 months) only required changing the width of the midline input and not the strength (see Schutte & Spencer, 2009, Experiment 3). Therefore, we only varied one parameter: the width of the midline input.

2.1. *Method and results of simulations*

All simulations were conducted using MATLAB software. The simulations used a 10 second delay, and the model ran 15 simulations to each target location for each parameter set. Fifteen simulations were chosen to prevent small correlations from being significant due to the large number of degrees of freedom. Also, the mean error did not change significantly after 15 runs. The target locations were 0°, 10°, 20°, 30°, 40°, 50°, and 60° from the reference axis. For specifics of the model equations and a complete list of parameters see the appendix and Table A2 in Schutte & Spencer (2009); a copy of the Matlab code is available from the corresponding author).

We varied the width of the reference axis input, σ_{ref}, from 10.64 (partway between the 3 years model and 3 years 6 months) to 4.16 (partway between 3 years 6 months model and 3 years 8 months model). We used a total of 15 different widths (see Table A2 and appendix in Schutte & Spencer, 2009, for details of the other parameter settings and the equations). Figure 2 shows the midline input for a sampling of the 15 widths from the widest (bold, solid line) to the narrowest (bold, dashed line).

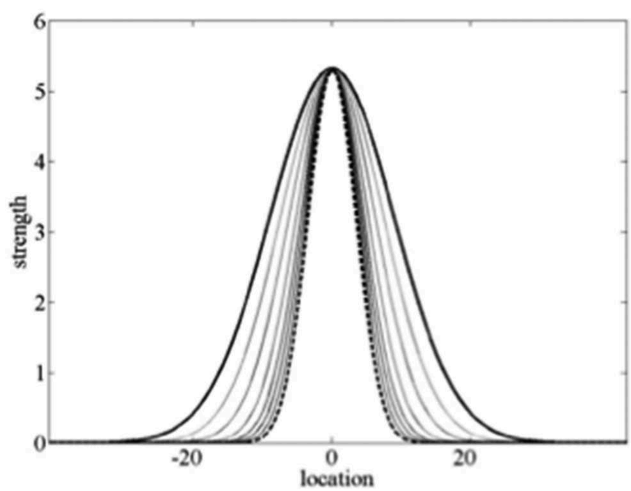

Figure 2. Graph of the midline input for a sampling of the 15 widths used in the simulations. Location is on the x-axis and strength is on the y-axis. The solid bold line is the widest input used, and the dashed bold line is the narrowest input used.

To determine if the midline input width was related to the models' mean constant error, we computed the correlation between the model's mean error and the midline input width parameter coded as 1 = to the widest width (10.664) up to 15 = to the narrowest width (4.160). Note that the correlations between the actual input width used and mean error were similar in magnitude, but in the opposite direction. The correlations between the model's memory errors and input widths for five different target locations are presented in Table 1. As can be seen in the table, the only significant correlations were at 10° and 20°. The model's mean error to each target location for each reference input width is shown in Figure 3. As can be seen in the figure, the

Table 1. Correlations between midline input width parameter and model's mean constant error.

Target Location (spatial memory simulation)	Correlation	p-value (two-tailed)
5°	.04	.591
10°	.25	<.001
20°	.61	<.001
40°	.13	.056
60°	.10	.138

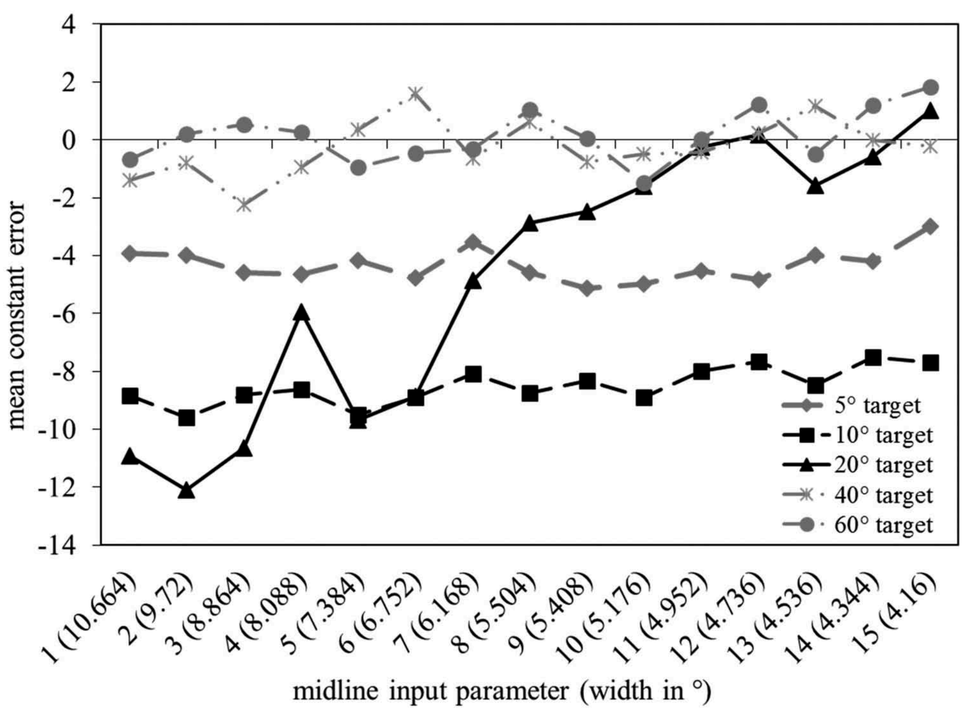

Figure 3. The model's mean error to each target location for each reference input width. Negative errors are toward the midline input, and positive errors are away from the midline input.

20° target is the only target to show a large change in error as the reference input width changes. The 20° target is also the first target to transition from being biased toward midline to being biased away from midline (Schutte & Spencer, 2009).

The 10° target showed a small decrease in bias toward midline. SWM errors to both the 10° and the 20° targets were positively correlated with the midline input.

Therefore, according to DFT, at 3 years 6 months of age memory errors to targets at intermediate distances from midline (i.e., the targets that are at or near the transition point) will be correlated with children's perception of midline. This pattern of correlation occurs due to the overlap between the midline input and the peak generated by the target in the SWM field. As can be seen in Figure 2, the widest midline input is quite wide and goes beyond the 20° target location, while the narrowest input does not reach as far as 20°. Thus, only the widest midline inputs will attract the peak at 20° toward midline. In contrast, peaks for targets close to midline (e.g., a target at 5°) will always overlap with the midline input, and, therefore, the different midline widths will have little differential effect on the model's memory errors to the 5° target. Likewise, targets far from midline (e.g., a target at 60°) may not overlap with even the widest midline input, so the midline input will also have little effect on the errors to those targets.

3. Experiment 1

To test the prediction that spatial memory errors to intermediate target locations would be related to the perception of the midline symmetry axis, children 3 years 6 months of age completed the spatial memory task used by Schutte and Spencer (2009) and the midline perception task used by Ortmann and Schutte (2010). We tested the prediction that performance on the symmetry axis perception task would be correlated with SWM errors to targets that were an intermediate distance from the symmetry axis.

3.1. *Method*

3.1.1. *Participants*

Eighteen 3-year-olds (*M* = 42.3 months, *SD* = 1.4 months, range: 40.6–-45.6 months, 9 males) participated in the study. As part of a larger study, children came in for a visit once a week for 5 weeks. One additional 3-year-old did not complete all of the sessions so data from that 3-year-old were not included in any of the analyses. Each child's parent gave consent and each child gave oral assent. The experiment was approved by the University Institutional Review Board.

3.1.2. *Apparatus*

The spatial memory task and the symmetry axis perception task used a 29 × 42 inch (74 x 107 cm) LCD monitor. The monitor was tilted 15 degrees up from horizontal, and the screen resolution was 1024 × 768 pixels. A low platform placed in front of the monitor allowed the children to stand in front of the monitor such that the monitor was approximately waist high. E-Prime 1.0 was used to run both of the tasks on the computer. For the spatial memory task, the stimuli were small, triangular, "spaceship shaped" targets. The stimuli for the discrimination task were small smiley faces (1.5 × 1 cm). A Smarttech touchscreen placed over the monitor recorded responses in the spatial memory task. Children used a joystick that moved only right and left to respond in the perception task. The experimenter then entered their response on the computer.

3.1.3. *Procedure*

Children participated in five sessions. The sessions were scheduled approximately one week apart. In sessions 1 and 5, children completed the Spaceship spatial memory task and a sandbox spatial memory task. Data from the sandbox spatial memory task were not analyzed as part of this study. In Sessions 2, 3, and 4, children completed the symmetry axis perception task. Multiple sessions resulted in a more robust measure of their ability to localize the symmetry axis of the space.

3.1.4. *Tasks*

3.1.4.1 *Spaceship spatial memory task*

The child played a warm-up game to help "Buzz Lightyear" find lost spaceships. The experimenter gave the child a stylus 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 while the child watched. The experimenter waited for a brief delay and then said, "go." When the experimenter said "go," the child was encouraged to use the stylus to touch the spaceship card, i.e., to "find" the spaceship. Trials of the warm-up game were repeated until the child successfully found at least two spaceships in a row. Generally, children needed only 2–3 trials of the warm-up game. Next, the child moved to stand on the platform in front of the monitor. The session began with a demo trial that was identical to the test trials except the experimenter performed the task. Following the demo, children completed two practice trials and then the test trials. Each trial began when the computer said, "Let's look for a spaceship." A spaceship appeared for 2 seconds followed by either a 1 or 10 second delay. When the computer said "go, go, go" the child touched the screen with the stylus where the spaceship was "hiding." After each trial, the target was re-illuminated for 4 s. 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). The feedback served two purposes: to help teach children the purpose of the game (i.e., that they should try to respond "close" to where they saw the spaceship), and to help keep them interested in the game. See Figure 4.

Children were randomly assigned to one of two conditions in the Spaceship spatial memory task. In the "left" condition, targets were located 5° (1.31 cm), 10° (2.61 cm), 20° (5.13 cm), 40° (9.64 cm), and 60° (12.99 cm) to the left of midline. Targets in the "right" condition were located 5° (1.31 cm), 10° (2.61 cm), 20° (5.13 cm), 40° (9.64 cm), and 60° (12.99 cm) to the right of midline. Note that the distance from a target to the bottom center of the touchscreen was always 15 centimeters. In these tasks 3-year-olds are biased toward both the center of the space and toward their longer-term memory of the previous target locations (Schutte & Spencer, 2002). Putting all of the targets on one side of the monitor meant that for targets near the center of the monitor, the bias toward the center and the bias toward previous targets would be in opposition to each other, and any bias toward midline, at least for the targets near midline, would not be a bias toward the memory of other target locations. Children completed 4 trials to each target for a total of 20 test trials. One trial to each target had a 1 second delay and three trials had a 10 seconds delay. The 1 second delay trials were used to keep children's interest in the task and were not included in the analyses.

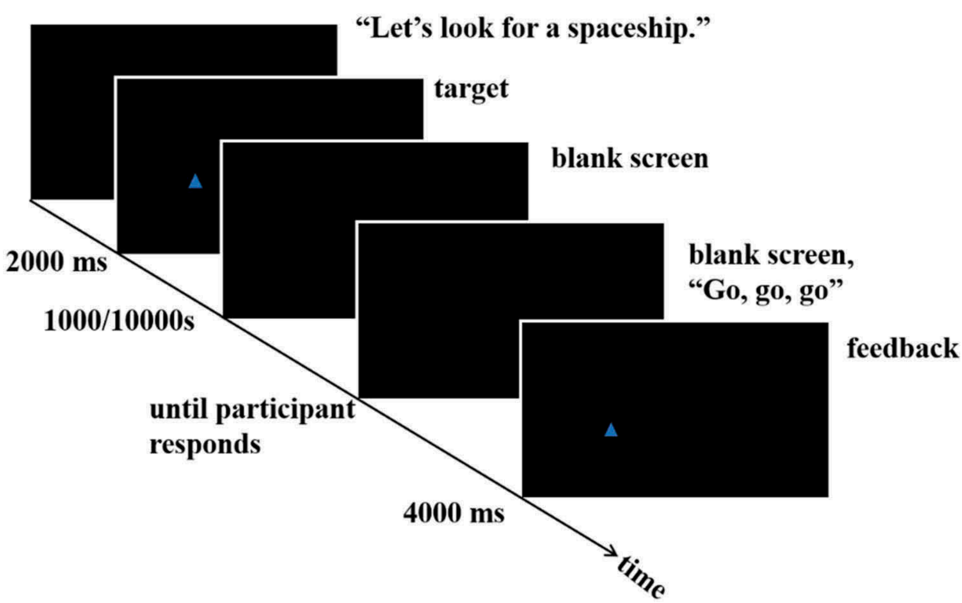

Figure 4. The Spaceship spatial memory task from the onset of a trial, i.e., the computer prompts a child to look for a spaceship, to the end of a trial, i.e., the computer gives feedback to a memory response.

3.1.4.2. ***Symmetry axis perception task.*** The task began with a warm-up game that introduced the discrimination task to the children. The children were shown two small cards with smiley faces on them and were told that they were identical twins (Bill and Ted). The children were then shown a black piece of paper and told that each twin lived in their own yard, which was one half of the paper. The twins did not cross into each other's yards. The children were told that, "Ted and Bill like to play a game where you have to try and figure out which one of them is which." A transparency sheet with a red line drawn down the center was laid over the black paper to divide the space and show the child how each twin had their own yard and they did not cross over the center line, and that they could tell whether a smiley face was Bill or Ted by where they were on the paper. The transparency was then removed and the experimenter took the two smiley faces and mixed them around behind his or her back. The experimenter placed a smiley face on one side of the sheet of paper, and the participant was asked to identify which twin the smiley face was by moving a joystick to the left or right. After the child responded, the transparency was laid back down to give them visual feedback about the location of the smiley face.

Children completed a minimum of three training trials during the warm-up game. The order of the training trials was random, and each side of the paper was used at least once. If the child did not get at least two of the three training trials correct, more trials were added until the child answered at least two in a row correctly. Generally, children did not require more than three training trials.

After the training trials, the child moved to the platform in front of the monitor. The experimenter completed a demonstration trial for the child. The demonstration trial was followed by two practice trials and then the test trials. The smiley face appeared on the monitor and the child moved the "joystick" to the given side. The smiley face stayed on the monitor until the participant responded. After each trial, a yellow line at midline and the smiley face appeared on the screen. The computer then told the child whether or not he/she identified the correct side. If the child was incorrect, they were told "nice try" and encouraged to try again. The purpose of the feedback was to help children understand the game and keep them motivated.

There were two trials to each target location. The target locations were ±.65, ±1.307, ±2.61, ±3.88, ±5.13, and ±11.49 cm from midline with positive locations to the right of midline and negative locations to the left. These locations corresponded to the following locations in degrees: ±2.5°, ±5°, ±10°, ±15°, ±20°, and ±50°. Children completed a total of 24 trials. The ±50° target was a control location that was used to check for children's understanding of the game. All children were correct on at least 75% of the control trials. The control location was not included in the analyses.

3.1.5. *Analytic strategy*

For each trial in the Spaceship spatial memory task, E-prime 1.0 recorded two touches of the touchscreen following the go signal. Occasionally children would touch the monitor with one hand while reaching with the stylus with the other hand. The touch that was closest to the target location was used in the analyses. In addition, children occasionally grabbed the lower edge of the monitor while reaching. If both touches were at the lower edge of the monitor, the trial was not included in the analyses (42 trials, 5.5% of trials). Outliers were also removed by removing any trials with errors larger than 2.5 standard deviations from the mean. This resulted in the removal of 78 trials (10.3% of the trials). Across sessions, 367 test trials were included in the analyses (84.0% of the total number of trials). For each trial, the computer calculated the difference in degrees between the target and the response. Directional errors away from the midline symmetry axis were positive and errors toward the midline symmetry axis were negative, i.e., on the right half of the monitor errors to the right of the target location were positive and errors to the left were negative, and on the left half of the monitor errors to the right were negative and errors to the left were positive. See Figure 5 for a schematic of the touchscreen.

In the Symmetry axis perception task, the proportion correct for each participant for each target location was computed across all sessions. There were no significant effects of side of the monitor, so targets were averaged relative to the midline symmetry axis: 2.5°, 5°, 10°, 15°, 20°, and 50° from midline. In addition, there was no significant main effect of session, $F(2, 51) = 0.84$, $p = 0.438$, and no significant session x target interaction, $F(18, 504) = 0.79$, $p = 0.711$, so proportion correct was averaged across session.

We examined whether the relationship between SWM constant directional errors and perception of the symmetry axis varied by target locations in Multilevel models. We dummy-coded the variable target location. The 20° target was set as the reference target, i.e., coded 0, because the DFT simulations predicted that responses to 20° would be most strongly correlated with the perception task. In the model building stage, we first tested whether variance in constant direction errors significantly varied across individuals in an intercept only model, u_0: variance component = 24.81, $\chi^2(17) = 26.06$, $p = 0.073$, suggesting that SWM constant directional errors varied across children at a marginal level of significance. We then added the variable target location to level-1 of the model and tested whether the relationship between constant directional errors and target location varied across individuals. Target locations were uncentered. Model comparisons showed that the relationship between constant directional errors and target locations did not vary across individuals.

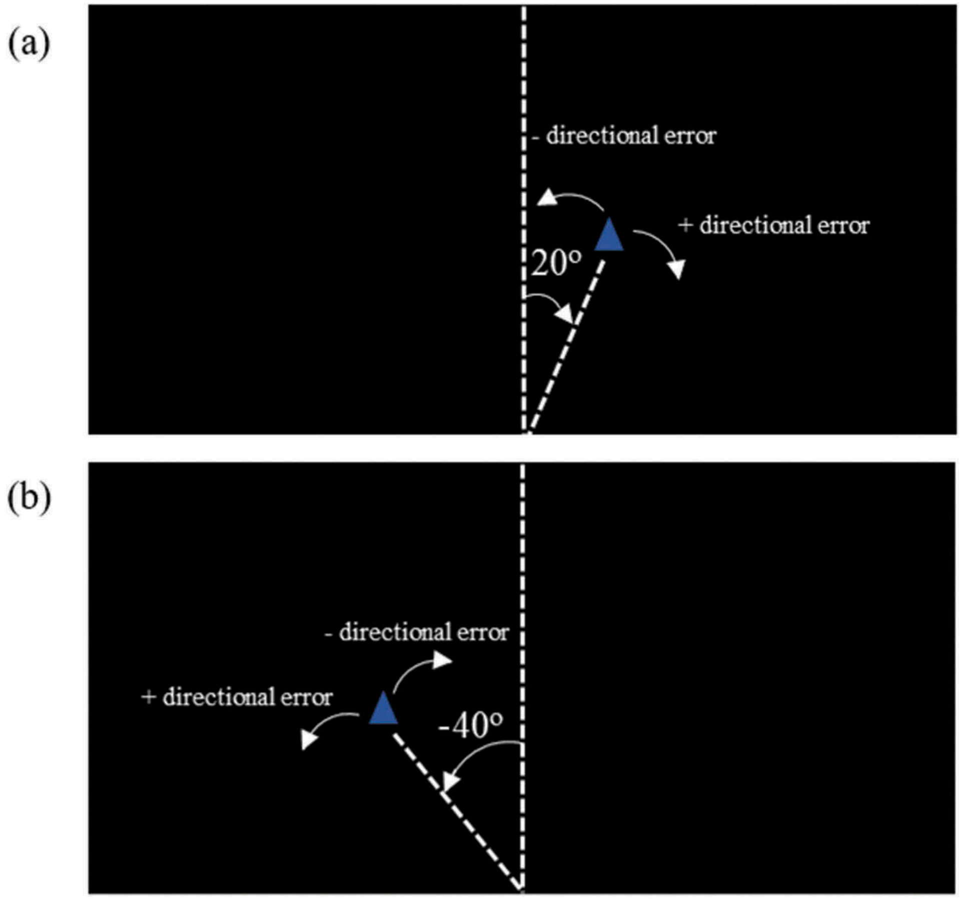

Figure 5. Diagrams of target layout on monitor with directional errors marked. The sample targets are the 20° and -40° targets. Constant directional errors away from midline, relative to the target, were coded as positive. Errors toward midline, relative to the target, were coded as negative. Note that this diagram is not to scale.

We added scores on the perception of symmetry axis task to level-2 of the model. The predictors are proportion correct on the perception of symmetry axis task at the 20°, 15°, 10°, 5°, and 2.5° locations. Level 2 predictors were grand-mean centered. The final multilevel model is presented below.

Level-1 Model

$$SWM\ constant\ directional\ errors_{ij} = \beta_{0j} + \beta_{1j} * (Target\ 20^\circ vs\ 60^\circ{}_{ij}) + \beta_{2j} * (Target\ 20^\circ vs\ 40^\circ{}_{ij}) + \beta_{3j} * (Target\ 20^\circ vs\ 10^\circ{}_{ij}) + \beta_{4j} * (Target\ 20^\circ vs\ 5^\circ{}_{ij}) + r_{ij}$$

Level-2 Model

$$\beta_{0j} = \gamma_{00} + \gamma_{01} * (20^{\circ}_{j}) + \gamma_{02} * (15^{\circ}_{j}) + \gamma_{03} * (10^{\circ}_{j}) + \gamma_{04} * (5^{\circ}_{j}) + \gamma_{05} * (2.5^{\circ}_{j}) + u_{0j}$$
$$\beta_{1j} = \gamma_{10} + \gamma_{11} * (20^{\circ}_{j}) + \gamma_{12} * (15^{\circ}_{j}) + \gamma_{13} * (10^{\circ}_{j}) + \gamma_{14} * (5^{\circ}_{j}) + \gamma_{15} * (2.5^{\circ}_{j})$$
$$\beta_{2j} = \gamma_{20} + \gamma_{21} * (20^{\circ}_{j}) + \gamma_{22} * (15^{\circ}_{j}) + \gamma_{23} * (10^{\circ}_{j}) + \gamma_{24} * (5^{\circ}_{j}) + \gamma_{25} * (2.5^{\circ}_{j})$$
$$\beta_{3j} = \gamma_{30} + \gamma_{31} * (20^{\circ}_{j}) + \gamma_{22} * (15^{\circ}_{j}) + \gamma_{33} * (10^{\circ}_{j}) + \gamma_{34} * (5^{\circ}_{j}) + \gamma_{35} * (2.5^{\circ}_{j})$$
$$\beta_{4j} = \gamma_{40} + \gamma_{41} * (20^{\circ}_{j}) + \gamma_{42} * (15^{\circ}_{j}) + \gamma_{43} * (10^{\circ}_{j}) + \gamma_{44} * (5^{\circ}_{j}) + \gamma_{45} * (2.5^{\circ}_{j})$$

3.2. *Results*

Children's performance on the Spaceship spatial memory task, i.e., constant directional errors, are shown in Figure 6. We conducted an ANOVA with target (5°, 10°, 20°, 40°, 60°) as a within-subjects variable and condition (left, right) was a between-subjects variable. There was no significant effect of target, $\Lambda = 0.62$, $F(4,13) = 1.97$, $p = 0.159$, $\eta^2 = 0.38$, or significant effect of condition, $F(1,16) = 0.11$, $p = 0.744$, $\eta^2 = 0.01$, or an interaction between target and condition, $\Lambda = 0.96$, $F(4,13) = 0.15$, $p = 0.958$, $\eta^2 = 0.05$. One-sample t-tests showed that 3-year-olds' spatial memory were not significantly biased at any target location (5° target, $t(17) = 0.41$, $p = 0.686$; 10° target, $t(17) = 1.98$, $p = 0.065$; 20° target, $t(17) = 1.80$, $p = 0.09$; 40° target, $t(17) = 0.77$, $p = 0.451$ and 60° target, $t(17) = -0.64$, $p = 0.529$). Performance on the perception of symmetry axis task, i.e., proportion correct

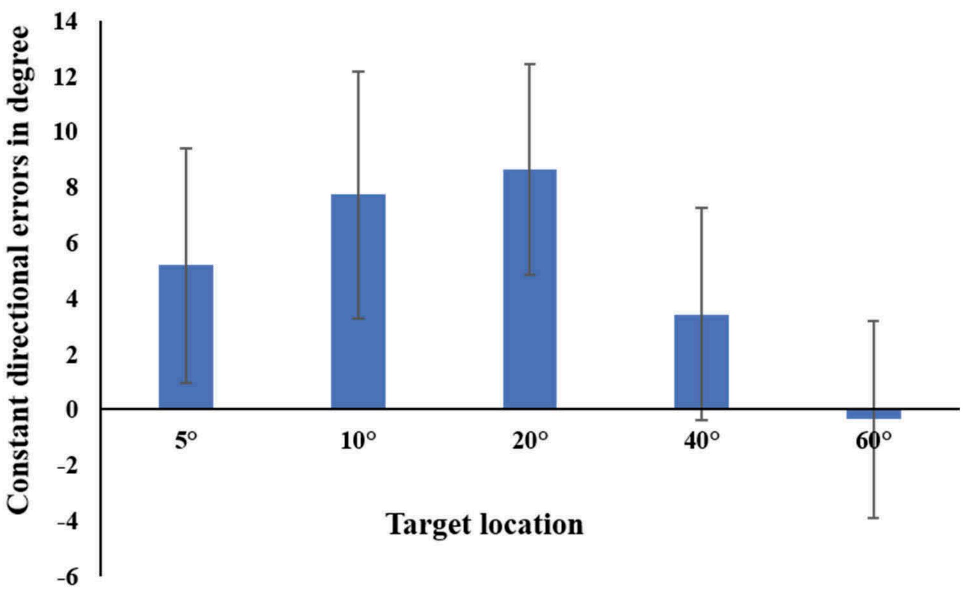

Figure 6. Means of constant directional errors at each target location in 3-year-olds (Experiment 1). Error bars are standard error.

at the 20º, 15º, 10º, 5º and 2.5º locations, are presented in Figure 7. One-sample t-tests of proportion correct at each location revealed that 3-year-olds' performance was above chance at all locations except at the location closest to midline (2.5° location, $t(17) = 1.94$, $p = 0.068$; 20° location, $t(17) = 11.93$, $p < 0.001$; 15° location, $t(17) = 8.58$, $p < 0.001$; 10° location, $t(17) = 10.91$, $p < 0.001$; and 5° location, $t(17) = 3.30$, $p = 0.004$).

Results of the multilevel model are presented in Table 2. Perception of the symmetry axis at the 10° location was a significant predictor of SWM constant directional errors at the 20º target, $t\ (12) = 3.36$, $p = 0.006$, suggesting that 3-year-olds who had a better perception of midline score displayed more SWM constant directional errors biased away from the midline at the 20º target. Additionally, the relationship between SWM constant directional errors and perception of symmetry axis at the 10° location varied between the 20º and 5º targets, $t\ (196) = -3.96$, $p = 0.001$. Exploring this moderation effect showed that 3-year-olds who performed better on the perception of symmetry axis task at the 10° location displayed more SWM biases away from midline at the 20º target and more SWM biases toward midline at the 5º target. Furthermore, the relationship between SWM constant directional errors and perception of symmetry axis at the 2.5° location varied between the 20º and 40º targets, $t\ (196) = 2.27$, $p = 0.025$. Further explorations of this moderation effect showed that 3-year-olds who performed better on the perception of symmetry axis task at the 2.5° location displayed more SWM biases away from midline at the 40º target. The relationship between SWM constant directional errors and perception of symmetry axis at the 2.5° location was non-significant at the 20º target.

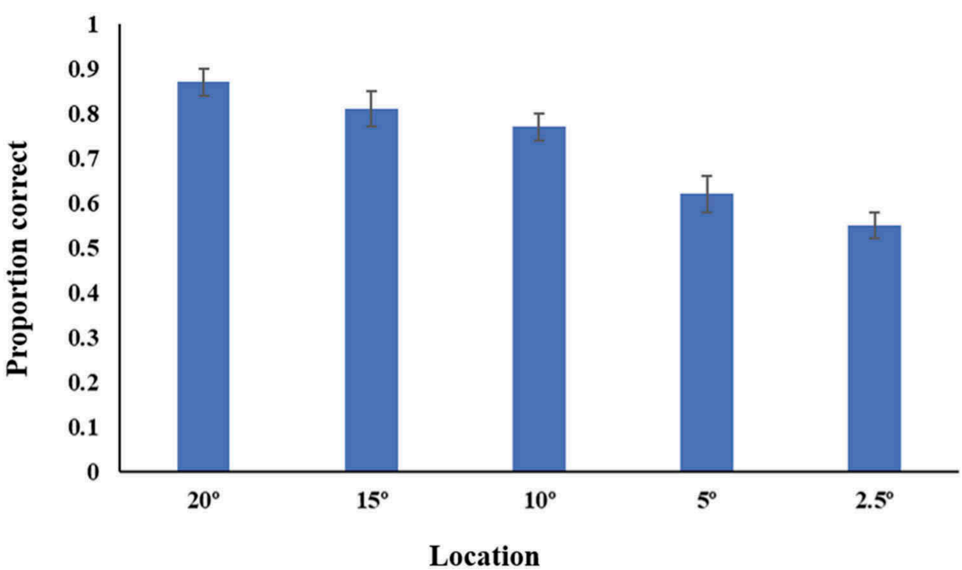

Figure 7. Mean of proportion correct at each location on the perception of midline task in 3-year-olds (Experiment 1). Error bars are standard error.

Table 2. Results of multilevel model for 3-year-olds in Experiment 1.

Fixed Effect	Coefficient	SE	*t*-ratio	*df*	*p*-value
Intercept, β_0					
γ_{00}	8.24	3.53	2.33	12	0.038
γ_{01} (20°)	−39.36	45.88	−0.86	12	0.408
γ_{02} (15°)	−25.55	29.99	−0.85	12	0.411
γ_{03} (10°)	145.29	43.22	3.36	12	0.006
γ_{04} (5°)	15.64	37.67	0.42	12	0.685
γ_{05} (2.5°)	18.70	32.78	0.57	12	0.579
Target 20° vs 60° slope, β_1					
γ_{10}	−9.95	5.05	−1.97	196	0.05
γ_{11} (20°)	−15.38	62.50	−0.25	196	0.806
γ_{12} (15°)	−17.63	42.83	−0.41	196	0.681
γ_{13} (10°)	−108.28	61.72	−1.75	196	0.081
γ_{14} (5°)	74.79	51.17	1.46	196	0.146
γ_{15} (2.5°)	13.00	46.37	0.28	196	0.780
Target 20° vs 40° slope, β_2					
γ_{20}	−3.27	5.22	−0.63	196	0.531
γ_{21} (20°)	98.26	65.69	1.50	196	0.136
γ_{22} (15°)	−15.90	44.51	−0.36	196	0.721
γ_{23} (10°)	−71.57	66.67	−1.07	196	0.284
γ_{24} (5°)	−59.11	52.60	−1.12	196	0.262
γ_{25} (2.5°)	107.82	47.58	2.27	196	0.025
Target 20° vs 10° slope, β_3					
γ_{30}	−0.96	4.98	−0.19	196	0.848
γ_{31} (20°)	79.61	63.75	1.25	196	0.213
γ_{32} (15°)	6.87	41.88	0.164	196	0.870
γ_{33} (10°)	−67.02	63.44	−1.06	196	0.292
γ_{34} (5°)	−32.36	50.90	−0.64	196	0.526
γ_{35} (2.5°)	−42.93	46.70	−0.92	196	0.359
Target 20° vs 5° slope, β_4					
γ_{40}	−3.38	4.99	−0.68	196	0.499
γ_{41} (20°)	64.87	63.02	1.03	196	0.305
γ_{42} (15°)	48.76	42.06	1.16	196	0.248
γ_{43} (10°)	−256.76	64.84	−3.96	196	0.001
γ_{44} (5°)	−20.88	50.55	−0.41	196	0.680
γ_{45} (2.5°)	−30.33	46.93	−0.65	196	0.519

3.3. *Discussion*

The study presented here tested the hypothesis that 3-year-olds' spatial memory biases would be related to their ability to perceive symmetry axes. Running simulations of DFT and varying the width of the midline symmetry axis input generated a more specific hypothesis. Specifically, errors to the targets that were farthest from midline (i.e., 40° and 60°) and closest to midline (i.e., 5°) were not correlated in the simulations. Only the model's errors to the targets that were an intermediate distance (i.e., 10° and 20°) were significantly correlated with the midline input. Thus, the specific hypothesis was that children's spatial memory errors to targets an intermediate distance from the midline symmetry axis would be correlated with their ability to perceive the location of the symmetry axis.

The hypothesis was supported, although the specific targets were slightly different. Biases away from midline at the 20º and 40º targets were significantly related to the symmetry axis perception task, rather than 10º and 20º. Specifically, discrimination performance at the 10° location was positively related to spatial memory bias at the 20º target, such that better performance in the symmetry axis task at that location predicted greater memory bias away from midline at the 20º target. In contrast, SWM bias and discrimination performance was negatively related at the 5º target. That is, better performance in the perception of symmetry axis task at the 10° location was associated with greater SWM constant directional errors toward midline at the 5º target. Additionally, SWM biases at the 40º target and performance in the perception of the symmetry axis at the 2.5° location were positively associated, i.e., better perception of midline at the 2.5° location predicted greater SWM constant directional errors away from midline at the 40º target.

Only performance at the 10° and at 2.5° locations in the symmetry axis perception task was associated with spatial memory bias. The 10° location may be the most discriminating measure of the perception of midline for most 3-year-olds. Specifically, 3-year-old children performed closer to ceiling at locations that were farther away from midline, i.e., the 20° and 15° locations; and they performed closer to chance at locations that were closer to midline, i.e., the 5° and 2.5° locations. Performance at the 2.5° location, however, may have been the best measure of the symmetry axis perception for those children with the best perception of the symmetry axis, and, as a result, this location was predictive of bias at 40º, a location that generally transitions to being biased away at an older age than 20º (Schutte & Spencer, 2009).

Although the simulations predicted a positive relationship between spatial memory biases and perception at 10º and 20º, we found the relationship at 20º and 40º. Notably, the simulation parameters were based on the spatial memory results from Schutte and Spencer (2009). The difference between the results of the simulations and the children's performance may be due to differences between the task used by Schutte and Spencer (2009) and the task used here. The task space, i.e., the monitor, used for this experiment was slightly smaller than the task space used by Schutte and Spencer, which may have led to different pattern of memory biases. Schutte et al. (2017), however, used the same sized monitor as the one used in this experiment and found the same pattern of error as in Schutte and Spencer (2009), i.e., 3-year-olds' responses were biased toward midline at 20° and 6-year-olds were biased away from midline. Another difference between this study and Schutte and Spencer (2009) is the setup of the targets in the task space. Specifically, in order to separate bias toward midline from bias toward memory of other target locations for the target locations closest to midline, the targets in the SWM task were all on one side of the monitor with side randomized between children. This setup may have caused memory responses to the inner targets (5° and 10°) to be biased away from the midline of the computer monitor and toward the long-term memory of the other target locations (Schutte & Spencer, 2002). Schutte and Spencer (2009) minimized the influence of the memory of other target locations by having target as a between-participant variable with only two target locations that were separated by 80° in each condition. In order to test the relationship between the perception of midline and memory bias to different target locations, we included a wider range of target locations.

The target setup may have also caused the negative relationship between performance in the perception task and spatial memory biases at the 5° target, which was not predicted by the model. Children who have a weaker perception of midline, may also have a less precise memory of the target location and be more influenced by memory of previous trials. As a result, they are more biased toward previously remembered locations, which, for the 5° target, results in a bias away from midline. In Experiment 2 we minimized the influence of the memory of other target locations by spreading out the target locations as much as possible across both sides of the monitor.

4. Experiment 2

Experiment 1 provided some support for a relationship between SWM biases and perception of midline in young children near the cusp of the transition. If the perception of midline is influencing SWM biases, we should continue to see a relationship in children 4 to 6 years of age, who are still within the developmental transition in geometric biases (Schutte & Spencer, 2009). Schutte and Spencer (2009) found that the transition was gradual between 3 and 6 years of age with biases to the targets closest to midline and farthest from midline still transitioning between 4 and 6 years of age. In Experiment 2, we tested the relationship between the perception of midline and SWM directional error in children 4 to 6 years of age. Our first hypothesis was that the relationship between SWM errors of 4- to 6-year-olds and their perception of the symmetry axis would vary by target location. Specifically, we did not predict a relationship between SWM biases and perception of midline at 20° due to the majority of children's memory responses being biased away at this location (Schutte & Spencer, 2009). We hypothesized a positive association between SWM biases and perception of midline at targets that were in transition from being biased toward to being biased away, i.e., targets that were closer to the midline such as the 5° target, and targets that were farther away from the midline such as the 60° target. That is, better perception of the symmetry axis would be related to greater spatial memory bias away from the midline at these target locations. It is important to note that we included a small age range of children (3-year-olds) in Experiment 1, but we included a larger age range of children (4- to 6-year-olds) in Experiment 2. Thus, our second hypothesis was that child age would moderate the relationship between target location and spatial memory biases, after controlling for performance on the perception of symmetry axis task. In the DFT model of SWM, changes across this age range are due to both changes in the perception of the symmetry axis and changes in neural interaction. Therefore, after controlling for perception of the axis, there should still be age differences in spatial memory. We predicted that after controlling for performance on the symmetry axis perception task, there would still be a significant relationship between age and SWM biases.

4.1. *Methods*

4.1.1. *Participants*

Sixty-six 4- to 6-year old children (*M* = 5 years, 6.4 months, *SD* = 9.4 months; 38 girls) participated in the study. An additional three children came into lab but were not included due to not completing the tasks. Experiment 2 was approved by the University Institutional Review Board.

4.1.2. *Procedure*

Children participated in one session in the lab. They completed two SWM tasks and one perception of symmetry axis task. The order of tasks was counterbalanced.

4.1.3. *Tasks*

4.1.3.1. ***Spatial memory task.*** This task was the same as in Experiment 1, except that the target was either a spaceship, a treasure chest, or a bubble. Each child completed two of these tasks. In one task, targets appeared 60°, 20°, and 5° to the left of the midline of the monitor and 40° and 10° to the right. In the other task, targets appeared 40° and 10° to the left of midline and 60°, 20°, and 5° to the right. Children completed 4 trials (3 with a 10 seconds delay and one with a 1 second delay) to each target location for a total of 20 test trials in each task. Therefore, children completed 8 trials per distance from midline for a total of 40 test trials. Note that we only analyzed trials had a 10 second delay. Using this design, we were able to collect more responses to each target location from children and still keep children engaged in the tasks.

4.1.3.2. ***Symmetry axis perception task.*** The task was the same as in Experiment 1.

4.1.4. *Analytic strategy*

As in Experiment 1, participants made large errors on a few trials in the SWM task. We removed any outliers that were greater than 2.5 standard deviations from the mean error. We removed a total of 74 trials (2.75% of the total number of trials).

We tested multilevel models to examine the relationship between SWM bias and the perception of the symmetry axis. In model building stage, we first tested an intercept only model to examine whether mean SWM constant directional error varied across children. Mean SWM constant directional error varied randomly across children, u_0: variance component = 24.82, χ^2 (64) = 85.80, p = 0.036.

We then added target locations as level-1 predictors. Target locations were dummy-coded. The 20º target was set as the reference target. Thus, level-1 predictors were target 20° vs 60°, target 20° vs 40°, target 20° vs 10°, and target 20° vs 5°. Level-1 predictors were uncentered. We examined whether the relationship between target location and SWM constant directional error varied across children. Model comparison showed that a model with the relationship between target location and SWM constant directional error significantly varied across children was a better fitting model, χ^2 (2) = 6.55, p = 0.037

Level-2 predictors were grand-mean centered and included age (as a control variable), and scores for the five locations in the symmetry axis perception task. We measured age from children's date of birth, and then subtracted a child's date of birth from his/her date of participation and created age in years that was a continuous variable. The following final model was the best fitting model. See Table 4 for results from the final multilevel model.

Level-1 Model:

$$SWM\ Bias_{ij} = \beta_{0j} + \beta_{1j} * \left(T\arg et\ 20^\circ\ vs\ 60^\circ_{ij}\right) + \beta_{2j} * \left(T\arg et\ 20^\circ\ vs\ 40^\circ_{ij}\right) + \beta_{3j} * \left(T\arg et\ 20^\circ\ vs\ 10^\circ_{ij}\right) + \beta_{4j} * \left(T\arg et\ 20^\circ\ vs\ 5^\circ_{ij}\right) + r_{ij}$$

Level-2 Model:

$$\beta_{0j} = \gamma_{00} + \gamma_{01} * (Age_j) + \gamma_{02} * (20^\circ_j) + \gamma_{03} * (15^\circ_j) + \gamma_{04} * (10^\circ_j) + \gamma_{05} * (5^\circ_j) + \gamma_{06} * (2.5^\circ_j) + u_{0j}$$
$$\beta_{1j} = \gamma_{10} + \gamma_{11} * (Age_j) + \gamma_{12} * (20^\circ_j) + \gamma_{13} * (15^\circ_j) + \gamma_{14} * (10^\circ_j) + \gamma_{15} * (5^\circ_j) + \gamma_{16} * (2.5^\circ_j)$$
$$\beta_{2j} = \gamma_{20} + \gamma_{21} * (Age_j) + \gamma_{22} * (20^\circ_j) + \gamma_{23} * (15^\circ_j) + \gamma_{24} * (10^\circ_j) + \gamma_{25} * (5^\circ_j) + \gamma_{26} * (2.5^\circ_j)$$
$$\beta_{3j} = \gamma_{30} + \gamma_{31} * (Age_j) + \gamma_{32} * (20^\circ_j) + \gamma_{33} * (15^\circ_j) + \gamma_{34} * (10^\circ_j) + \gamma_{35} * (5^\circ_j) + \gamma_{36} * (2.5^\circ_j)$$
$$\beta_{4j} = \gamma_{40} + \gamma_{41} * (Age_j) + \gamma_{42} * (20^\circ_j) + \gamma_{43} * (15^\circ_j) + \gamma_{44} * (10^\circ_j) + \gamma_{45} * (5^\circ_j) + \gamma_{46} * (2.5^\circ_j)$$

4.2. *Results*

Table 3 summarizes the means and standard deviations of SWM constant directional error by target location for each age group. Note that age was treated as a categorical variable in ANOVA analyses, where the three groups in the age variable were 4, 5, and 6 year olds. A positive score in constant directional error means that SWM response error was biased away from

Table 3. Mean and standard deviations of SWM constant directional error in degree for 4-to 6-year-olds in Experiment 2.

Age	n	5°	10°	20°	40°	60°
4 years old	20	14.91(30.14)	5.79(35.66)	12.06(39.50)	11.19(33.74)	11.05(28.45)
5 years old	25	−4.47(23.57)	2.07(25.53)	8.84(22.52)	10.85(31.25)	7.60(30.58)
6 years old	21	3.25(20.91)	9.46(27.59)	12.83(22.93)	18.19(24.03)	8.71(25.06)
Total	66	1.92(25.16)	5.52(29.41)	11.09(28.31)	11.38(30.22)	8.90(28.20)

Table 4. Proportion correct and standard deviations for 4- to 6-year-olds in the perception of the symmetry axis task in Experiment 2.

Age	n	2.5°	5°	10°	15°	20°
4 years old	20	0.47(0.38)	0.53(0.41)	0.75(0.35)	0.86(0.29)	0.81(0.33)
5 years old	25	0.68(0.40)	0.68(0.36)	0.85(0.24)	0.93(0.20)	0.95(0.16)
6 years old	21	0.69(0.31)	0.71(0.38)	0.93(0.14)	0.98(0.11)	0.97(0.13)
Total	66	0.56(0.38)	0.64(0.39)	0.85(0.27)	0.93(0.22)	0.91(0.23)

midline relative to the target, and a negative score means that error was biased toward midline relative to the target. Mean SWM directional errors were analyzed in a 2-way ANOVA with age (4, 5, 6) as a between-subject factor and target location (60°, 40°, 20°, 10°, 5°) as a within-subject factor. There was a main effect of target location, $F\ (4,\ 315) = 2.96$, $p = 0.02$. Children's memory responses were biased more strongly away from midline at the 40° target than the 5° target, $t\ (128) = 3.4$, $p = 0.01$. There was no main effect of age or interaction effect between age and target location.

The means and standard deviations of proportion of correct trials on the perception of symmetry axis task by target location for each age group are in Table 4. We conducted an ANOVA with age as a between-subject factor and location (20°, 15°, 10°, 5°, and 2.5°) as a within-subject factor. There was a main effect of age, $F\ (2,\ 315) = 17.94$, $p < 0.001$. Five-year-olds and 6-year-olds performed significantly better than 4-year-olds in the perception of symmetry axis task, $t\ (43) = 4.09$, $p < 0.001$, and $t\ (44) = 5.93$, $p < 0.001$, respectively. There was also a main effect of location, $F\ (4,\ 315) = 33.81$, $p < 0.001$. Children performed significantly better at the 20°, 15°, and 10° locations than at the 5° and 2.5° locations, $t\ (130)$(20° vs 5°) = 6.83, $t\ (130)$(20° vs 2.5°) = 8.78, $t\ (130)$(15° vs 5°) = 7.12, $t\ (130)$(15° vs 2.5°) = 9.07, $t\ (130)$(10° vs 5°) = 5.07, $t\ (130)$(10° vs 2.5°) = 7.02, all ps <0.001.

Results of the multilevel model are presented in Table 5. After controlling for age, SWM constant directional errors at the 20° vs. 60° targets were positively associated with perception of symmetry axis at the 10° location, $t\ (559) = 2.37$, $p = 0.018$. Further explorations of this relationship revealed that at the 60° target, the memory responses of children who scored higher in the perception of symmetry axis task at the 10° location, were biased more away from midline. This relationship, however, was not significant at the 20° target. Moreover, SWM constant directional errors at the 20° vs 60° targets

Table 5. Results of multilevel model for 4- to 6-year-olds in Experiment 2.

Fixed Effect	Coefficient	SE	*t*-ratio	*df*	*p*-value
Intercept, β_0					
γ_{00}	9.11	1.80	5.05	59	0.001
γ_{01} (Age)	1.84	2.56	0.72	59	0.476
γ_{02} (20°)	10.86	15.15	0.72	59	0.476
γ_{03} (15°)	−8.13	17.65	−0.46	59	0.647
γ_{04} (10°)	14.71	11.87	1.24	59	0.220
γ_{05} (5°)	11.90	6.82	1.745	59	0.086
γ_{06} (2.5°)	−5.49	9.49	−0.58	59	0.565
Target 20° vs 60° slope, β_1					
γ_{10}	−0.39	2.80	−0.14	559	0.888
γ_{11} (Age)	−7.18	3.18	−2.26	559	0.024
γ_{12} (20°)	−34.65	22.04	−1.57	559	0.116
γ_{13} (15°)	27.23	25.01	1.09	559	0.277
γ_{14} (10°)	37.66	15.87	2.37	559	0.018
γ_{15} (5°)	−28.99	10.72	−2.71	559	0.007
γ_{16} (2.5°)	23.12	12.58	1.84	559	0.067
Target 20° vs 40° slope, β_2					
γ_{20}	4.14	2.68	1.55	559	0.123
γ_{21} (Age)	2.76	3.87	0.71	559	0.476
γ_{22} (20°)	−30.29	28.31	−1.07	559	0.285
γ_{23} (15°)	20.56	26.01	0.79	559	0.430
γ_{24} (10°)	10.90	17.94	0.61	559	0.544
γ_{25} (5°)	−12.15	10.12	−1.20	559	0.231
γ_{26} (2.5°)	−2.29	9.84	−0.233	559	0.816
Target 20° vs 10° slope, β_3					
γ_{30}	−3.65	2.67	−1.37	559	0.173
γ_{31} (Age)	−2.18	4.29	−0.51	559	0.612
γ_{32} (20°)	−5.99	22.77	−0.26	559	0.792
γ_{33} (15°)	56.12	28.49	1.97	559	0.049
γ_{34} (10°)	−1.87	17.62	−0.11	559	0.915
γ_{35} (5°)	−16.95	10.02	−1.69	559	0.091
γ_{36} (2.5°)	−11.96	13.00	−0.920	559	0.358
Target 20° vs 5° slope, β_4					
γ_{40}	−7.13	2.69	−2.646	559	0.008
γ_{41} (Age)	−2.89	3.28	−0.881	559	0.379
γ_{42} (20°)	−58.22	26.84	−2.17	559	0.031
γ_{43} (15°)	43.94	28.91	1.52	559	0.129
γ_{44} (10°)	−4.35	18.83	−0.23	559	0.82
γ_{45} (5°)	−13.23	9.73	−1.36	559	0.174
γ_{46} (2.5°)	1.93	13.38	0.14	559	0.885

were negatively associated with performance in the perception task at the 5° location, t (559) = −2.71, p = 0.002. Exploring to this relationship indicated that spatial memory bias and perception of midline at 5° location was marginally negatively related at the 60° target, coefficient = −17.09, SE = 9.28, p = 0.066, and marginally positively related at the 20° target, coefficient = 11.90, SE = 6.82, p = 0.081. Therefore, results suggested that the relationship between spatial memory bias and perception of midline differed at the 20° and 60° targets. Specifically, children who were better at localizing the symmetry axis at 5° location were marginally more biased away at 20° target, and less biased away at the 60° target.

SWM constant directional errors at the 20° vs 10° targets and perception of the symmetry axis at the 15° location were positively associated, t (559) = 1.97, p = 0.049. Explorations of the relationship between SWM constant directional errors and perception of the symmetry axis at the 15° location showed that, although the relationship was not significantly associated at either the 20° target, coefficient = −8.13, SE = 17.65, p = 0.645, or the 10° target, coefficient = 47.99, SE = 33.41, p = 0.151, the coefficients were in the opposite direction, suggesting a more positive relationship at 10° than at 20°. Furthermore, the relationship between SWM constant directional errors at the 20° vs 5° targets was negatively associated with perception of the symmetry axis at the 20° location, t (559) = −2.17, p = 0.031. Specifically, children who performed better in the perception of symmetry axis task at the 20° location, displayed greater spatial memory biases toward midline at the 5° target, coefficient = −47.36, SE = 18.97, p = 0.012. This relationship, however, was not significant at the 20° target, coefficient = 10.86, SE = 17.31, p = 0.530. This may mean that children who were better at discriminating the symmetry axis at the 20° location showed less bias away at the 5° target, and those children displayed more bias away from midline at the 20° target. See Figure 8.

We also found an age effect in the relationship between target location and spatial memory biases, after controlling for children's performance on the symmetry axis perception task. That is, SWM constant directional errors at

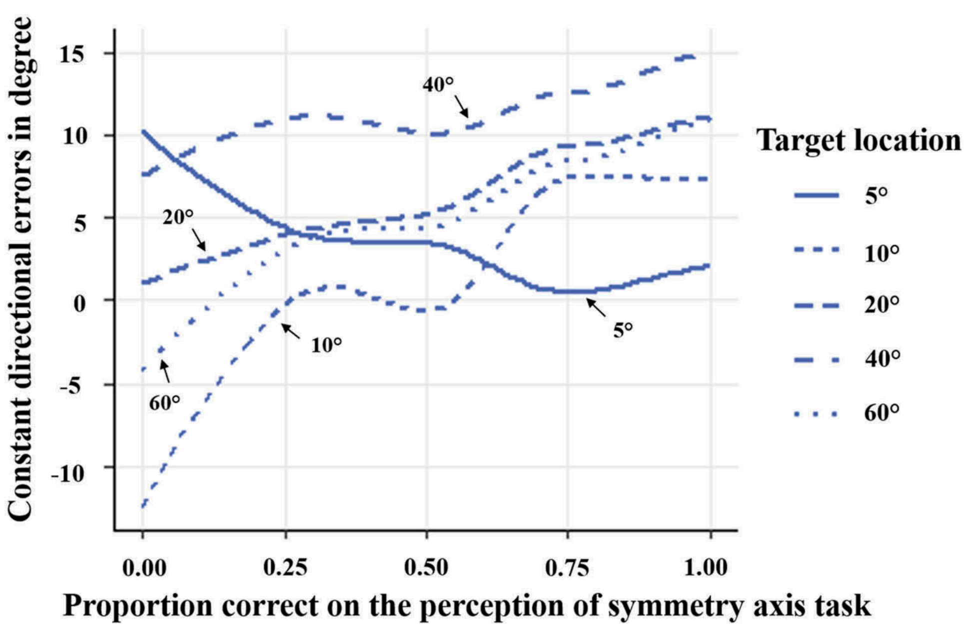

Figure 8. The relationship between constant directional errors and perception of midline performance for each target location in Experiment 2. Positive errors are errors away from midline relative to the target location and negative errors are toward midline.

the 20° and 60° targets varied by age, after controlling for children's performance on the perception of midline task, t (559) = −2.26, p = 0.024. Specifically, younger children were less biased away at the 20° target than older children, whereas older children were less biased away at the 60° target than younger children. These results indicated that spatial memory biases are associated with both perception of midline and age.

4.3. *Discussion*

In Experiment 2, we examined how SWM biases at different target locations were related to the perception of symmetry axes among 4- to 6-year-old children. Consistent with the first hypothesis, we found a significant relationship between perception of the symmetry axis and SWM biases, and this relationship varied by target location. Specifically, at the 60° target, spatial memory biases were positively associated with perception of the symmetry axis, indicating that children who had better perception of midline were biased more away from the midline at the 60° target. Contrary to our prediction, but consistent with results of the first experiment, spatial memory bias and perception of midline was negatively related at the 5° target. This suggested that children who had better perception of midline were less biased away midline at the target that was closest to midline.

The memory responses of the 4- to 6-year-olds were biased significantly away from midline at the 20° target, and this bias away from midline at 20° was not related to their performance in the perception of symmetry axis task. Schutte and Spencer (2009) found that 4- to 6-year-olds were biased away from midline at the 20° target. Thus, all children's perception of midline appeared to be strong enough to elicit biases away from midline, resulting in there not being a significant relationship between perception and spatial memory at this target location even though there was a significant relationship for the 3-year-olds in Experiment 1.

Moreover, we also found some support for the second hypothesis. After controlling for performance on the symmetry axis perception task, the relationship between spatial memory biases and target location varied over age. Thus, perception of the symmetry axis could not account for all of the age differences, suggesting another mechanism was also influencing developmental changes in spatial memory bias.

Experiment 2 supports the idea that perception of the symmetry axis is related to SWM biases, and that across development, this relationship varies by target location. Findings also suggest that in this older age group a more accurate perception of the symmetry axis is related to greater SWM biases away from the midline symmetry axis at target locations that are farther away from midline. Overall, results support the proposal of the

DFT model of spatial memory that improvement in the perception of symmetry axes is one of the factors that relates to the transition in geometric biases in SWM.

5. General discussion

Both experiments provided some support for the proposal of DFT that there is a relationship between SWM biases and the perception of symmetry axis in children 3 to 6 years of age. In Experiment 1, SWM bias and perception of midline was positively associated at the 20° and 40° targets, such that three-year-olds who were better at perceiving the perception of midline displayed larger biases away from midline at 20° and 40°. In Experiment 2, the memory responses of 4- to 6-year-olds at the 20° target were not related to perception of the symmetry axis, and children displayed larger memory biases away from the midline at 20°. Memory responses at the 60° target, however, were associated with the perception of the symmetry axis, such that 4- to 6-year-olds who were better in the perception of symmetry axis task were biased more away from midline at the 60° target.

The finding that better perception of the symmetry axis is associated with great spatial memory bias away from midline provides evidence for DFT's proposal that stronger perception of the symmetry axes is related to spatial memory biases. Furthermore, the shift of the relationship between spatial memory bias and perception of midline from being significant at intermediate locations, i.e., the 20° and 40° targets, to being significant at a location that was farther away from midline, i.e., the 60° target, supports the DFT proposal that this relationship would appear first at intermediate locations and gradually shift to locations that are farther from midline.

In contrast, the spatial memory bias at the 5° target and perception of the symmetry axis were negatively related in both 3-year-olds and 4- to 6-year-olds, suggesting that children who performed better in the perception of the symmetry axis task showed less bias away from midline at the target closest to midline. This result was not expected. According to the DFT, improvement in the perception of the symmetry axis contributes to spatial memory being biased away from midline. Nevertheless, it is possible that because the 5° target is so close to midline, having a more accurate perception of midline results in a more stable memory of the target. In the DFT model, the greatest level of inhibition is near midline, which can lead to greater repulsion. Inhibition, however, can also stabilize memory. Thus, more accurate encoding of the symmetry axis may also lead to a more stable memory near the axis, and, therefore, less bias away from midline.

These results have implications for future research and theorizing about the development of SWM. Schutte and Spencer (2010) demonstrated that perception of a reference axis was related to spatial memory biases. This study takes it a step further and directly demonstrates that developmental changes in the perception of the symmetry axis and spatial memory bias are related even after controlling for age. This relationship between perception and spatial memory demonstrates that these processes are part of a dynamic system such that a change in one, i.e., perception, influences the other, i.e., spatial memory. Notably, the perceptual change is a relatively subtle change in the ability to localize an axis of symmetry, but it is related to a larger developmental change in spatial memory biases.

Although, these data provide some support for the DFT model of spatial memory, other theories may also be able to account for the results. According to the Category Adjustment model (CA model), the transition in the direction of bias is due to children dividing the space into two categories instead of just one (Huttenlocher et al., 1994). According to this theory, the change in subdivision is a result of changes in the ability to superimpose structure on the space (Huttenlocher & Lourenco, 2007); however, this theory does not specify the mechanisms underlying this change in ability, which makes it difficult to generate any specific predictions regarding the relationship between perception of the symmetry axis and spatial memory biases.

The relationship between visual perception and SWM emphasizes the importance of perception, in this case vision, for the development of other aspects of cognition, in particular for the development of spatial cognition. These results have implications for research involving populations with spatial memory deficits. Specifically, research with these populations should include tests of their visual perception to determine if their spatial memory deficits are due to perceptual differences. For example, both visual deficits (e.g., Hellerstein, Freed & Maples, 1995) and spatial memory deficits (e.g., Lehnung et al., 2001) are common following traumatic brain injury (TBI). Future research should examine whether the deficits in visual perception can account for the deficits in spatial memory, especially in children who suffer a TBI early in development, while spatial memory is developing.

This study has several limitations. First of all, giving the difficulty of recruiting participants at a very specific age, i.e., 3 years, 6 months, the sample size of children (n = 18) in Experiment 1 was relatively small. This may lead to study results not being robust. Future research should test the relationship between spatial memory bias and perception of midline in a larger sample. Second of all, in Experiment 1 the targets in the SWM task were all on one side of the computer monitor with side randomized between children, and in Experiment 2 the targets were spread across both sides. The differences in the setup may have caused the relationship between spatial memory biases and perception of the symmetry axis to be different from what we would get from 3- to 6-year-olds by using the same set up of the SWM task. Future research should test this relationship by using the same targets in the SWM task across ages. Lastly, we tested the association between spatial memory bias and perception of midline cross-sectionally. Longitudinal studies would provide more detailed information about the relationship between SWM bias and perception of symmetry across development.

5.1. *Conclusions*

Results of this study support the DFT. Improvement in the perception of midline is associated with greater spatial memory bias away from the midline, and, from 3 to 6 years of age, the relationship between spatial memory bias and perception of midline varies by target location, such that, as predicted by the DFT model, the relationship between perception of the midline axis and spatial memory biases is only significant for targets near the transition point in spatial memory bias. These results demonstrate the close relationship between developmental changes in perception and changes in memory.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, AS, upon reasonable request (aschutte2@unl.edu).

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