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Developmental continuity in the processes that underlie spatial recall

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Abstract

This study investigated whether children's spatial recall performance shows three separable characteristics: (1) biases away from symmetry axes (geometric effects); (2) systematic drift over delays; and (3) biases toward the exemplar distribution experienced in the task (experience-dependent effects). In Experiment 1, the location of one target within each geometric category was varied. Children's responses showed biases away from a midline axis that increased over delays. In Experiment 2, multiple targets were placed within each category at the same locations used in Experiment 1. After removing geometric effects, 6-year-olds'—but not 11-year-olds'—responses were biased toward the average remembered location over learning. In Experiment 3, children responded to one target more frequently than the others. Both 6- and 11-year-olds showed biases toward the most frequent target over learning. These results provide a bridge between the performance of younger children and adults, demonstrating continuity in the processes that underlie spatial memory abilities across development.

Keywords: Spatial cognition; Location memory; Working memory; Spatial recall; Cognitive development; Spatial prototypes; Memory models; Models of development; Developmental continuity; Developmental discontinuity

1. Introduction

The complexity of development is often revealed by children's performance in the simplest of tasks. Consider infants' and children's performance when they are asked to find an object that was hidden a few seconds ago. Eight- to 10-month-old infants

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succeed in simple hiding and finding games when the memory delay is short and the object is hidden at a very salient location (e.g., Diedrich, Highlands, Thelen, & Smith, 2001; Piaget, 1954). If, however, infants have searched at an "A" location repeatedly, and now the toy is hidden at a nearby "B" location that is *not* perceptually salient, 8- to 10-month-olds will search at Location A, making the classic Piagetian A-not-B error (Piaget, 1954). Infants clear this hurdle around 12 months (e.g., Marcovitch & Zelazo, 1999; Thelen, Schöner, Scheier, & Smith, 2001). By 18 months, children are relatively good at hiding and finding games, even in taxing situations such as when a toy is hidden within a large rectangular sandbox (Huttenlocher, Newcombe, & Sandberg, 1994), and by 22 months, children begin using distal landmarks in these challenging situations (Newcombe, Huttenlocher, Drummey, & Wiley, 1998). Beyond 22 months, more intricate changes in children' spatial memory abilities emerge. For example, around 7 years, children start to use subtle cues such as the midline symmetry axis of a sandbox to carve up space into smaller spatial categories (Huttenlocher et al., 1994; for related results, see Sandberg, 1999; Sandberg, Huttenlocher, & Newcombe, 1996). These examples—although not an exhaustive list—illustrate some of the developmental changes that have been revealed by asking children to find hidden toys in different situations (see also, Bremner & Bryant, 1977; DeLoache, 1991; Plumert & Hund, 2001).

Given this complex set of developmental effects, a fundamental question is whether these results reflect qualitative changes in the processes that underlie spatial memory or more gradual, quantitative changes in memory processes. This is, of course, a variant of a core question in developmental psychology—is development discontinuous or continuous? Recent microgenetic approaches to this question have focused on particular transitions in development in great detail (e.g., Siegler, 1995; Siegler & Chen, 1998). Although this approach has successfully characterized the nature of developmental change in a variety of domains (e.g., in motor development: Hartelman, van der Maas, & Molenaar, 1998; Thelen & Ulrich, 1991; van der Maas & Hopkins, 1998; in mathematical reasoning: Siegler, 1995; in conservation tasks: van Geert, 1994; van der Maas & Molenaar, 1992), it does not address the issue of *long-term* continuity (or discontinuity) in developmental process.

Spatial memory is an ideal model system for investigating this issue for two reasons. First, there is a wealth of data from simple spatial memory tasks that spans development from infancy into adulthood. Second, it is often difficult to test claims of long-term continuity because such claims are poorly specified, in particular, the processes that underlie performance are only vaguely articulated (see Chi, 1978; Kail, 1991 for exceptions). This is not the case in the spatial domain where two mathematical models have emerged to explain developmental changes in location memory—the Category Adjustment (CA) model (Huttenlocher, Hedges, & Duncan, 1991) and the Dynamic Field Theory (DFT) (Schutte & Spencer, 2002; Schutte, Spencer, & Schöner, in press; Spencer & Schöner, 2003; Thelen et al., 2001). Importantly, proponents of both models have made claims of long-term continuity in process. Newcombe and Huttenlocher (2000) proposed that different spatial systems are in place very early—including the spatial processes captured by the CA model—but children learn to use or "weight" these systems differently over development.

Similarly, Spencer and colleagues (Schutte & Spencer, 2002; Spencer & Hund, 2002; Spencer & Schöner, 2003; Spencer, Smith, & Thelen, 2001) have argued that the same spatial memory processes that underlie performance in early development underlie the performance of older children and adults. The present study tested these claims of continuity by investigating whether three classes of effects captured by the CA and DFT models—geometric category biases, delay-dependent biases, and experience-dependent (i.e., long-term memory) biases—are separable aspects of performance across the span from early development to adulthood.

1.1. Developmental changes in spatial recall

The present study focuses on developmental changes in spatial recall. In spatial recall tasks, participants are shown a single target location inside an otherwise blank geometrical figure (e.g., Huttenlocher et al., 1991, 1994; Laeng, Peters, & McCabe, 1998). The target is then removed, there is a short delay, and participants are asked to reproduce the target location. Spatial recall tasks have revealed three central aspects of children's and adults' location memory abilities: (1) "geometric" effects, that is, biases toward or away from visible boundaries and symmetry axes (Huttenlocher et al., 1994; Schutte & Spencer, 2002; Spencer et al., 2001); (2) systematic spatial drift over short-term memory delays (Schutte & Spencer, 2002; Spencer & Hund, 2002); and (3) "experience-dependent" effects, that is, biases toward a long-term memory of the target locations (Schutte & Spencer, 2002; Spencer et al., 2001) or toward a distribution of previously experienced exemplars (Huttenlocher, Hedges, & Vevea, 2000; Spencer & Hund, 2002). In the sections that follow, we address each characteristic in turn, highlighting how the CA and DFT models have accounted for these different phenomena.

1.1.1. Geometric category biases

One of the better-known results from spatial recall tasks is that children and adults show systematic biases near visible boundaries and symmetry axes. For instance, when asked to find toys hidden within a large rectangular sandbox, 2- to 6-year-olds' responses are biased *toward* the midline axis of the sandbox (Huttenlocher et al., 1994; Spencer et al., 2001). Interestingly, 10- to 11-year-olds show a different pattern of error. These children show biases *away from* the midline axis and toward the centers of the left and right halves of the sandbox (Huttenlocher et al., 1994). Similarly, 7- and 9-year-olds show biases away from the midline axis of an inverted "V" frame and toward the centers of the left and right halves of the "V" (Sandberg et al., 1996). Adults show this same pattern (Engebretson & Huttenlocher, 1996; for related results, see Huttenlocher et al., 1991; Plumert & Hund, 2001; Schiano & Tversky, 1992; Spencer & Hund, 2002; Tversky & Schiano, 1989). Thus, younger children, older children, and adults all show systematic response biases near midline, but there is a shift in how children use this axis in early development. Although the exact ages of this shift are not clear, biases away from midline appear to be consistent across tasks by 6–7 years of age (Hund & Spencer, 2003; Sandberg et al., 1996).

To explain these response biases, Huttenlocher and colleagues (1991) proposed that people represent locations at two levels of detail. According to their CA model, people represent the *fine-grained* location of a target—the direction and distance of the target from a reference location—and the *category* in which the target is located. Categories are formed by dividing space using boundaries such as the visible edges and midline symmetry axis of the sandbox. These category boundaries, along with the central, or prototypical, member of each category are stored in memory. When asked to reproduce a target location, people combine their fine-grained and categorical representations. This leads to errors away from category boundaries and toward spatial prototypes, because people weight their estimates using prototypical information. Huttenlocher and colleagues explained the developmental shift in the direction of response bias near midline by speculating that children's ability to sub-divide space changes during the preschool years. Young children (e.g., 2-year-olds) treat large geometric figures as one spatial category with a prototype at the center of the space. By contrast, older children (e.g., 10- to 11-year-olds) divide space into multiple categories. This creates "left" and "right" categories with a prototype at the center of each category.

1.1.2. Delay-dependent biases in spatial recall

One of the central ideas of the CA model is that categorical information facilitates memory for fine-grained, metric information, particularly under conditions of uncertainty (Huttenlocher et al., 1991). To test this idea, Engebretson and Huttenlocher (1996) asked adults to remember a target angle in a "V" frame while performing an interference task during the memory delay. These researchers predicted that participants would show stronger prototypical biases in the interference task than in a standard condition: when faced with greater uncertainty, adults would rely more heavily on prototypical information. This was indeed the case—adults showed significantly larger biases toward the centers of the left and right halves of the "V" than participants in a non-interference condition. More recently, we re-examined this issue with adults in a "spaceship" task (Spencer & Hund, 2002). Rather than asking adults to remember intervening items, we simply asked them to remember a single target (a spaceship) on each trial and varied the memory delay. If memory becomes less certain over delays, then, according to the CA model, there should be a systematic shift in responses toward prototypical locations. This prediction was confirmed: adults responses drifted systematically away from midline as delays increased from 0 to 20 s (see also Hund & Plumert, 2002; Huttenlocher et al., 1991).

Although the CA model predicted the direction of drift in this study, its explanatory power is limited because it is not a process model that evolves through time. Thus, more recent work from our laboratory has focused on a new model of spatial memory—the dynamic field theory (DFT) (Schutte & Spencer, 2002; Spencer et al., 2001; Thelen et al., 2001). The DFT is a neural network model of spatial working memory that captures how location-related activation in a network of neurons can be sustained from second-to-second in spatial recall tasks. As such, this model offers new insights into the processes that might underlie delay-dependent biases in spatial memory.

To illustrate the basic principles of the DFT, consider the typical sequence of events in a spatial recall task. First, a target is displayed at a particular location. In the field model, this "target input" would activate a population of neurons in spatial working memory that is spatially tuned to respond to stimulation at the target location. This would include neurons that respond maximally to the stimulated location—neurons whose "preferred" location matches the target—as well as neurons that respond less vigorously to the stimulated location (for data showing spatially tuned neural activity in dorsal cortical areas, see, e.g., Andersen, 1995; Constantinidis & Steinmetz, 1996; di Pellegrino & Wise, 1993; Georgopoulos, Kettner, & Schwartz, 1988). Next, the target is hidden, removing the target input. Now, the activated neurons must remain active to retain an accurate representation of the target location during the delay. After the memory delay, this activation must be translated into a recall response, for instance, by responding to the location associated with the maximally active subset of neurons.

The DFT offers two central insights into delay-dependent biases in spatial memory. First, this model explains how a population of neurons can actively maintain location-related information when a target is hidden. Sustained activation is possible in the model because "neighboring" neurons influence one another through a local excitation/lateral inhibition interaction function. According to this function, an activated neuron will *excite* neurons that "code" similar spatial locations (i.e., locations spatially close to the activated neuron's preferred location), and *inhibit* neurons that code for locations far from the neuron's preferred location. Importantly, if local excitation is strong and focused, dynamic fields can enter a *self-sustaining state* in which peaks of activation are maintained even after the input is removed (see Amari, 1977; Thelen et al., 2001).

The second insight provided by the DFT addresses why memory drifts during delays. Simulations of the DFT have revealed that in the absence of strong input, a local, self-sustaining population of neurons can drift such that, after a delay, the population comes to represent a location a few centimeters away from the original target location. For instance, Schutte and Spencer (2002) asked 3-year-olds to repeatedly search for an object hidden at an "A" location. After several trials to this location, the object was hidden at a nearby "B" location. Three-year-olds showed biases toward location A on the B trials, and these biases increased systematically as the memory delays increased from 0 to 10 s (for related results with 2-year-olds, see Spencer et al., 2001). According to the DFT, this occurs because the long-term memory of A recruits new neurons on the A-ward side of B into the locally excitatory interaction. This, in turn, causes neurons on the other edge of the population to drop out due to lateral inhibition. As this process continues during the delay, the population activity systematically drifts toward A.

1.1.3. Experience-dependent biases in spatial recall performance

In the original formulation of the CA model, prototypical locations were generally linked to the centers of geometrically defined spatial regions. Nevertheless, Huttenlocher et al. (1991) suggested that prototypical locations might be influenced by the distribution of target locations in the task space, that is, recall performance might be influenced by participants' trial-by-trial experience in the task (for related results, see Nosofsky, 1986; Posner & Keele, 1968). We recently examined this possibility with adults by manipulating the distribution of targets in the spaceship task (Spencer & Hund, 2002). In particular, subsets of targets were positioned at different locations within the left and right geometric categories (i.e., on either side of the midline symmetry axis). When prototype effects were removed, adults showed a bias toward the center of the exemplar distribution to which they had been exposed.

These data are generally consistent with a modified version of the CA model proposed to account for *induced category* effects in the object categorization domain (Huttenlocher et al., 2000). Induced categories are formed by representing the distribution of exemplars experienced in a task. Such categories have a graded structure with instances that vary from good—near the central value of the distribution—to poor—near the boundaries of the category (see also Kay & McDaniel, 1978; Rosch, 1975). As in the spatial domain, Huttenlocher et al. proposed that people encode objects at a fine-grained level (i.e., the exact size of an object) and at a categorical level (i.e., the induced category to which a stimulus belongs). At the time of stimulus estimation, people combine these two sources of information. This produces a bias toward the center of the induced category because all stimulus values within a category are weighted with the same mean.

A recent dynamic field model of the Piagetian A-not-B error offers a related, process-based account of experience-dependent effects (Thelen et al., 2001). This model includes a long-term memory field that is coupled to working memory. Activation in working memory leaves a trace of activation in long-term memory, which decays quite slowly. Reversely, activation in long-term memory can serve as input to working memory. This reciprocal process can construct a type of induced category or exemplar-based distribution from trial-to-trial. For instance, in the canonical Piagetian A-not-B task, the repeated trials to the A location can build-up a long-term memory of A. Consequently, when the toy is hidden at the B location, activation in working memory can become biased toward A during memory delays (Smith, Thelen, Titzer, & McLin, 1999; Thelen et al., 2001). But with repeated trials to the B location, a long-term memory of B can build-up, limiting the bias toward A. As discussed above, this same long-term memory process has been used to explain trial-to-trial changes in 2- to 6-year-olds' spatial recall errors (Schutte & Spencer, 2002; Schutte et al., in press; Spencer et al., 2001).

1.2. Testing for developmental continuity between early childhood and adulthood

The CA model and DFT provide accounts of the processes that underlie three separable characteristics of spatial recall. Given that proponents of these models have claimed that there is continuity of process over development, we can ask whether the processes instantiated in these models are operative across the span from early development to adulthood. One way to address this issue is to ask if geometric category biases, delay-dependent biases, and experience-dependent biases are clearly separable aspects of performance across development. To date, the question has only been answered in early development (i.e., 3 years of age) and adulthood. Thus, the present study tested whether these three characteristics are clearly separable aspects of older children's recall responses.

Although no studies with older children have effectively separated all three characteristics of spatial memory, one study provides an initial look at these issues (Hund & Spencer, 2003). Six- and 11-year-old children remembered two locations located close to one another within the same geometric category. In one condition, children responded more frequently to the inner of two targets relative to an equal-frequency control group. Results showed that children's responses to the infrequent target were pulled toward the frequent target after a long memory delay. Nevertheless, this effect was only apparent after three blocks of trials had been completed; it was not apparent in the overall analyses. These data demonstrate that, in some conditions, older children use a long-term memory of locations. It is not clear from this study, however, how pervasive such effects are. Thus, the present study sought to provide more extensive evidence that these three classes of effects are indeed separable and pervasive aspects of older children's recall performance.

1.3. Overview of the present study

Given that previous studies from our laboratory have examined the recall performance of 3-year-olds and adults, we are in a unique situation to test the claim of long-term continuity in the spatial domain. In particular, we can examine older children's performance in the *same* task using the *same* target locations as in previous studies (see, Hund & Spencer, 2003; Schutte & Spencer, 2002; Spencer et al., 2001). Moreover, we can use the same basic strategy adopted in our earlier studies to separate geometric, delay-dependent, and experience-dependent effects. The general idea is to separate these effects by placing a subset of targets on one side of midline (i.e., within the same category) and varying memory delays and the location of the target sets relative to the category boundary. For instance, in one condition, targets were located 20°, 40°, and 60° from midline (see "near" category in Fig. 1a), whereas in another condition, targets were located 40°, 60°, and 80° from midline (see "far" category in Fig. 1b). If older children's responses are subject to delay-dependent spatial drift, responses to these target locations should become systematically biased over delays. Furthermore, if children's recall responses are affected by a long-term memory of the target locations, responses to the "left" and "right" targets in each of these conditions should be biased toward the "center" target over delays.

These predictions are complicated, however, by the presence of geometric effects. Specifically, we would expect to see significant differences across these two conditions *solely due to biases away from midline*. Based on previous studies (e.g., Engebretson & Huttenlocher, 1996; Hund & Spencer, 2003), participants in these conditions should make greater outward errors at 20° than at 40° because 20° is closer to midline and farther from the category center at 90°. Similarly, participants should make greater outward errors at 40° than at 60°, and greater outward errors at 60° than at 80°. As a consequence, response biases should be larger in the first condition when the target set is near midline than in the far condition. This would lead to significant

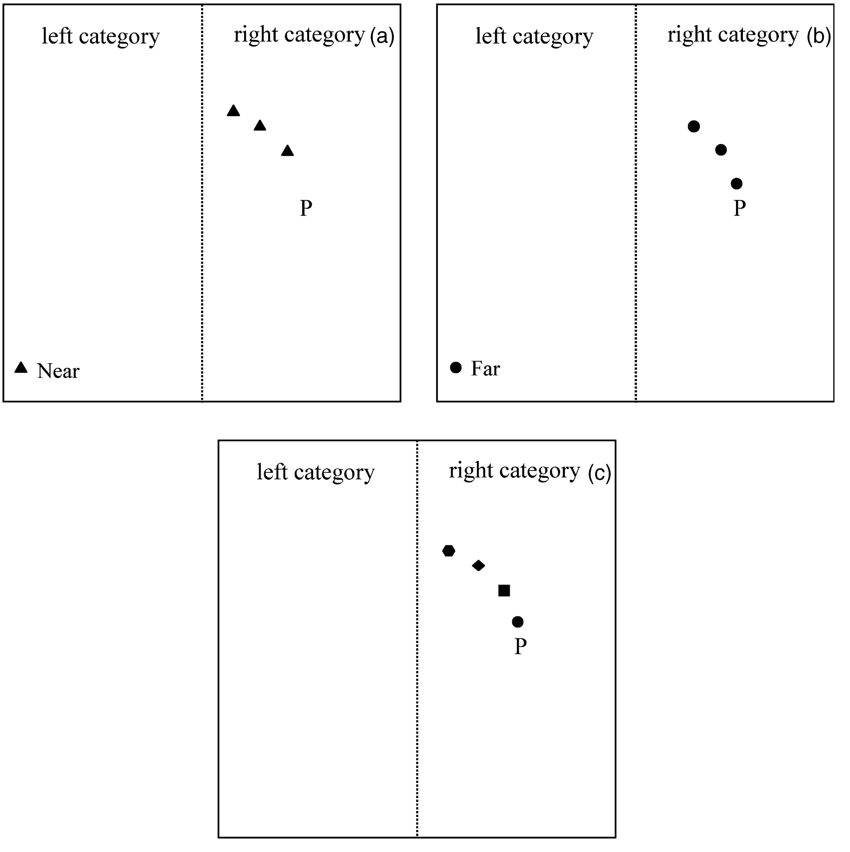

Fig. 1. (a) Set of target locations near the midline category boundary. (b) Set of target locations far from the midline category boundary. (c) Different symbols indicate the single target presented in each experimental condition. Dotted line shows the position of the midline category boundary. Geometric prototypes are marked by Ps.

condition effects, making it difficult to tease apart experience-dependent and geometric biases.

We adopted three strategies to handle this complication. First, we used a subtraction technique across Experiments 1 and 2 (see, Spencer & Hund, 2002, for use of this technique with adults). In the first experiment, we obtained a measure of geometric effects at individual locations within a category (e.g., the right category) by placing one item in the category and measuring the bias away from midline. We varied the placement of these single targets across conditions (see Fig. 1c). In Experiment 2, we varied the spatial position of three targets within a category such that the set of targets was near or far from midline (Figs. 1a and b). Importantly, these target sets were composed of items at the same absolute spatial locations used in Experiment 1. The central question was whether participants showed biases toward the centers of the target sets after geometric effects measured in Experiment 1 were removed.

The second strategy used to separate geometric and experience-dependent effects was to examine changes in performance across learning. According to both the CA model and the DFT, geometric biases should be present throughout the testing session. By contrast, experience-dependent effects should only emerge after participants have constructed a long-term memory of the target locations. Consistent with this prediction, Hund and Spencer (2003) reported that experience-dependent biases were evident only after several blocks of trials. Here, we conducted the same type of block-by-block analyses to investigate the generality of these learning effects.

As a final strategy, we investigated the separability of geometric and experience-dependent effects without using the subtraction technique. In particular, we biased how often children moved to each target location in Experiment 3. If children use a long-term memory of the target locations, they should construct a strong, accurate memory of the "biased," or most frequent, location. This, in turn, should create a pull toward the biased location apparent in responses to the unbiased locations.

2. Experiment 1

The first goal of this experiment was to assess the magnitude of children's response biases away from a midline symmetry axis (toward spatial prototypes) when a single target was placed at different locations within a category. These data provided a baseline measure of geometric effects used in Experiment 2. Rather than having children estimate the location of only one target across all trials as in Fig. 1c (which could create task demand effects relative to later experiments with multiple items in each category), *three* targets were included in each condition. One target was in the left category (i.e., to the left of the midline axis), whereas a second target was in the right category. The location of these targets within each category varied across conditions. We also included a third target that was aligned with the midline category boundary. Responses to this target provided an index of the certainty of the boundary.

A second goal of the present study was to examine the extent to which older children's responses are affected by delay-dependent spatial drift as is the case with 3-year-olds (Schutte & Spencer, 2002) and adults (Spencer & Hund, 2002). Hund and Spencer (2003) showed that 6- and 11-year-olds' recall responses show an increase in spatial drift over short and long delays. However, these researchers only examined performance across two delays that differed for the two age groups (6-year-olds: 5 and 10 s; 11-year-olds: 10 and 15 s). Thus, in the present experiment, children remembered target locations across delays of 0–20 s.

Before turning to the methods, it is important to note a possible confound in our experimental design that could influence responses in the 20° condition (i.e., the condition in which children responded to targets at ±20° and 0°). If children use a long-term memory of the target locations—one of the central questions of this study—then our measure of geometric effects at these locations might be systematically underestimated. That is, the pull toward an average remembered location at 0° might counteract the bias away from midline. This might make it more likely for us to find differences for targets close to midline across Experiments 1 and 2 using the subtraction technique. Note that such effects would be less likely in the other conditions because the targets are farther apart and, therefore, less likely to interact (see Erlhagen & Schöner, 2002; Spencer et al., 2001).

Although our baseline measure of geometric effects at ±20° might be systematically underestimated, we retained the experimental design used here for several reasons. First, the hypothetical result described above is precisely the effect we sought to document in the present study, because it would indicate that geometric and experience-dependent effects are separable. An important question is whether such effects are only found to the ±20° targets, or whether such effects generalize to the other locations as well. As the reader will see, experience-dependent effects were evident across multiple locations.

Second, we retained this experimental design for practical reasons. We thought it was important to include the same number of targets across experiments, because children might be strongly influenced by such task demands. As an alternative design, we considered moving the 0° target to 180°. This would allow us to include three targets (with one aligned with the category boundary), but would reduce potential interactions among targets because adjacent targets would be farther apart. Unfortunately, this was not possible because, given the starting location and target distances used in previous studies (Hund & Spencer, 2003; Schutte & Spencer, 2002), there was not enough physical space to present a target at 180°.

2.1. Method

2.1.1. Participants

Thirty 5–7-year-olds ($M = 6$ years 8.04 months; $SD = 5.3$ months) and 30 10–11-year-olds ($M = 10$ years 10.6 months; $SD = 5.6$ months) participated in this study. Data from five additional 6-year-olds were excluded from analyses because the participants stopped data collection early. Data from one additional 11-year-old were excluded because the participant was missing data from more than 10% of the trials following the outlier analysis (see below). Children were recruited from participant databases maintained by Indiana University and the University of Iowa and via referrals from other participants. Thirty-two participants completed the experiment at Indiana University, whereas the remaining 30 participated at the University of Iowa. Children received a small gift for participation. All participants were right-handed. The number of females and males was roughly balanced across experimental conditions.

2.1.2. Apparatus and materials

Participants sat at a 1.22 m × 1.22 m horizontal table, the top of which was a uniform piece of plexiglas. An arc was removed from one side of the table, and participants were seated in a chair positioned within this arc with the tabletop at belly height (see Fig. 2a). The plexiglas tabletop was covered with black tinting to prevent participants from seeing the small LEDs positioned below. In addition, the room lights were dimmed and black cloth was hung across the ceiling and down the walls

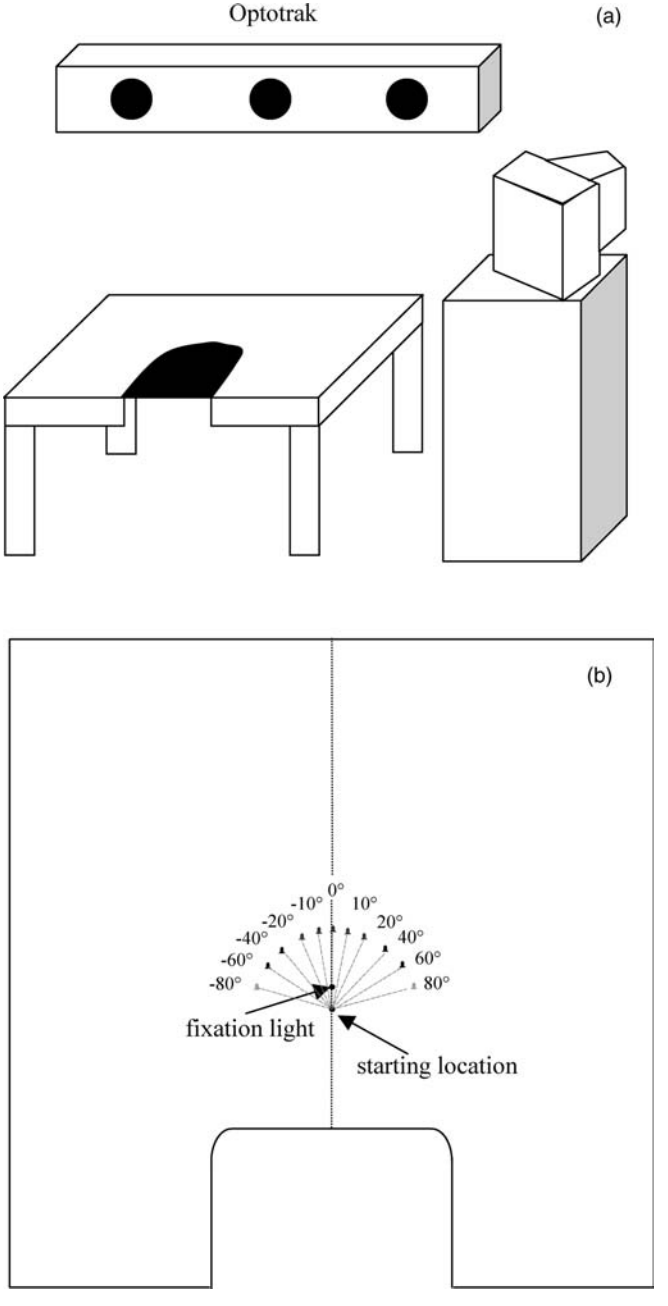

Fig. 2. (a) Diagram of the experimental table, Optotrak cameras, and feedback monitor (the monitor was not used in Experiment 3). (b) Overhead view of the table top with a diagram of the target locations used across experiments. Dotted line shows the midline category boundary.

to prevent reflections from appearing on the tabletop. After these adjustments, the top of the table appeared to be a smooth, black, homogeneous surface.

A small (1 cm radius) yellow sticker was placed along the midline axis of the table to mark the starting location. The starting location was 15 cm from the front edge of the table for the 6-year-olds and 20 cm for the 11-year-olds. An electro-magnetic switch was positioned below the starting location (under the plexiglas tabletop). This was used to ensure that participants were ready to begin each trial, remained at the starting location during the delays, and started moving at the correct time. Targets were illuminated using a bank of LEDs with diodes every 10° from −80° to 80° (see Fig. 2b). The diodes were located 15 cm from the starting location, and a fixation light diode was placed 4 cm in front of the starting location. The LED board was covered by a black X-ray film with spaceship-shaped cutouts aligned with the LEDs and a circle-shaped (0.5 cm radius) cutout aligned with the fixation light. The spaceships were 1.25 cm from the tip to the base, 1.25 cm across the base, and 0.65 cm at the midsection. LED voltage was chosen to avoid visual afterimages.

The lights and switch were controlled by a computer, which was able to trigger the LEDs with better than 10 ms precision. The computer controlled the type and timing of all stimuli using customized software. In addition, the computer's monitor was used to present visual feedback after each trial. The monitor was positioned to the right of the table at a comfortable viewing distance (see Fig. 2a). The experimenter sat to the right of the experimental table. Pre-recorded messages were played through two speakers. These messages led participants through the spaceship game and gave them praise or warning messages after each trial.

Participants' movements were recorded using an optical-electronic motion analysis system (Optotrak, Northern Digital, Inc.). Optotrak tracks small (radius = 3.5 mm), individually pulsed infrared emitting diodes (IREDs) within a specified three-dimensional volume with better than 1 mm precision. Pointing data were collected in a pre-defined coordinate system: the $(0, 0)$ coordinate was positioned at the starting location; the "x" coordinate axis was defined as the left–right dimension; the "y" coordinate axis was defined as the front–back dimension.

2.1.3. Task and procedure

Participants were told that spaceships would appear and then disappear somewhere on the tabletop in front of them. Their task was to remember where each spaceship was and to move to the remembered location at the end of a "ready, set, go" sequence spoken by the computer. Participants moved to the target locations by sliding a magnetic disk with their right index finger along the tabletop. Three IREDs were placed on the participant's right index finger to ensure good IRED visibility. The IRED placed directly above the fingernail always had the best visibility, so data from this IRED were used in all analyses.

The specific task and types of feedback were explained during a brief practice session. Each trial began when the computer said, "beginning search for enemy spaceships." Participants then moved the magnet to the starting location and attended to the task space in front of them. After a random pre-trial delay ranging from 2 to 4 s, a "spaceship" light was illuminated for 2 s. Next, participants heard a "ready, set, go" sequence. This sequence ended 0, 5, 10, 15, or 20 s after the target disappeared. To control participants' looking direction during the 5–20 s delays, a fixation light appeared after the target disappeared. Participants were asked to look at this light, rather than looking at the spaceship's location. The experimenter made sure participants looked at the fixation light on each trial. The fixation light was turned off at the start of the "ready, set, go" sequence.

Participants were instructed to move directly to where they thought the spaceship was when they heard "go." Movement speed was not emphasized; however, initiation time relative to the go signal was. This ensured that the length of the delays remained relatively constant across trials and participants. Participants were also told that they could make small corrections at the end of the movement. They were asked to maintain this final position until they received feedback from the computer. At the end of each 3.5 s trial, the target was re-illuminated for 1.5 s (2 s during the practice phase of session 1). This allowed participants to compare the location of their finger (the remembered target location) with the actual target location. Then, feedback information was displayed on the computer monitor for 3 s. After feedback, the screen was blanked, there was a short delay, and the computer began the next trial.

Computer feedback on each trial was based on two sources of information. First, the magnetic switch was triggered when participants started moving, providing a measure of initiation time. To receive the highest initiation time score (5 pts), 6-year-olds had to begin moving within 150 ms of the "go" signal and 11-year-olds had to begin moving within 70 ms of "go." Second, the computer determined the spatial location at the end of each movement using the Optotrak data. These data were used to compute a spatial accuracy score based on pre-specified accuracy zones (concentric circles surrounding the target location). The accuracy zones and scores were as follows: 0–1.5 cm from the target = 5 pts, 1.5–3 cm = 4 pts, 3–5 cm = 3 pts, 5–7.5 cm = 2 pts, 7.5–10.5 cm = 1 pt, and >10.5 cm = 0 pts. This scale was chosen to ensure that children needed to be very accurate to receive maximal points, but did not become frustrated on trials during which their responses were inaccurate.

Four types of feedback information were displayed after each trial: (1) a graphic display of the initiation time, (2) the sum of the initiation time and accuracy scores, (3) the total accumulated points, and (4) a "flight rank." The computer warned participants if their initiation times were at the boundaries of the acceptable initiation time range. Point scores of 10 and 9 were accompanied by a "direct hit!" and "good job" message, respectively. Participants received 1 new star for each 80 total points. They also heard a verbal message describing their new rank for every two stars earned.

2.1.4. Experimental design

Participants in each age group were randomly assigned to one of five experimental conditions. In each condition, participants moved to three target locations—a left, center, and right location. One target was presented to the left of the midline axis of the table (i.e., in the left category) and one target was presented to the right of midline (i.e., in the right category). The angular distance of the left and right targets from midline varied across separation conditions: targets were 10°, 20°, 40°, 60°, or

80° from the midline axis (see Fig. 2b). The center target was always aligned with the midline category boundary (0°), regardless of separation condition.

Each participant came into the laboratory for two experimental sessions. At the start of the first session, children completed 15 practice trials—5 to each target location at randomly selected delays. At the start of the second session, participants completed 6 practice trials—2 to each target at randomly selected delays. Following practice, children completed 57 trials in blocks of 15 trials each (the final trial block contained 12 trials). There were 4 trials to each target at each of four delays (5, 10, 15, and 20 s). In addition, children completed 3 trials to each target with a 0 s delay during which the target remained illuminated after the "ready, set, go" sequence. The purpose of these trials was to determine how accurate movements to visible targets could be. Across the two sessions, then, participants completed 8 trials to each target at each memory delay, and 6 trials to each target at the 0 s delay. All trials were randomized with the constraint that movements to the same target location never occurred more than twice in a row.

2.1.5. Method of analysis

Optotrak data from each trial were analyzed using customized computer software. First, the computer selected three kinematic events that identified potentially valid x and y coordinates at the end of each movement—the end of the "transport" phase, the end of the "correction" phase, and the end of the "extra" correction phase. These kinematic events were selected based on rules described in Hund and Spencer (2003). The most accurate of these kinematic events was included in the final analyses. This was the most conservative choice because it maximized participants' accuracy, which was counter to the goal of investigating memory errors.

After the computer selected the x–y coordinate associated with the most accurate kinematic event on each trial (i.e., the x–y coordinate at the remembered location), directional errors were computed. For each response, we computed the angle between the line connecting the starting location and the remembered location and the line connecting the starting location and the actual location of the target. Given that our primary goal was to measure biases away from midline (toward spatial prototypes), directional errors were computed such that positive directional errors indicated errors *away from the midline axis of the table* relative to the target direction, whereas negative errors indicated errors *toward the midline axis*. Thus, for responses to targets on the left side of the table, a clockwise error would produce a negative directional error (i.e., toward midline). Conversely, a clockwise error to a target on the right side of the table would yield a positive directional error (i.e., away from midline). Recall that the center target was always aligned with the midline axis. Consequently, directional errors to this location could only be coded as clockwise or counterclockwise (the toward or away from midline measure would not distinguish errors on either side of midline). *Positive directional errors to the center target indicated counterclockwise errors.*

In the next analysis step, we checked for computer selection mistakes by manually re-analyzing all trials with directional errors larger than the median error ± 2 *SD* for movements to each target location at each delay. Small *SD*s were set to a minimum value of 5°, and large *SD*s were set to a maximum value of 10° (see also, Hund &

Table 1
Directional error for responses to each target at the 0 s delay in each experiment

Experiment	Left/inner target	Center target	Right/outer target
1	−1.83° (.20°)	−1.58° (.15°)	−.85° (.14°)
2	.44° (.12°)	.51° (.11°)	.09° (.12°)
3	.73° (.24°)	−.67° (.24°)	−1.00° (.27°)

Note. Standard errors are listed in parentheses.

Spencer, 2003; Spencer & Hund, 2002). After this manual check, all remaining trials with directional errors larger than the median error ±2 *SD* were eliminated. Trials with initiation times >1 s were also eliminated. Nine trials did not meet the initiation time criterion. Overall, 2.26% of all trials were eliminated for the 6-year-olds and 0.61% of all trials for the 11-year-olds.

Finally, we noticed that participants' responses on the 0 s delay trials were rotated slightly, even though the targets were visible. Table 1 shows the mean error to each target location at the 0 s delay. Inspection of Table 1 reveals that the errors at 0 s were quite small across targets and experiments. In the final analysis step, we removed these systematic errors by subtracting the mean directional error on the 0 s delay trials from the directional errors on the 5–20 s delays for each target and participant. These adjusted directional errors were used in all analyses.[1]

2.2. Results

The primary goal of this experiment was to examine how children's biases away from the midline category boundary (toward prototypes) varied over delays when individual targets were presented at different angular separations from midline. Thus, we analyzed constant directional errors to the left and right targets at each delay for each age. In addition, we analyzed variable errors to these targets to determine whether memory became less certain over delays. In a final set of analyses, we examined responses to the center target (0°) to provide an index of the certainty of the midline category boundary.

Our emphasis on directional error is consistent with previous studies of children's and adults' memory errors in tasks where target direction was the only spatial dimension varied (e.g., Engebretson & Huttenlocher, 1996; Hund & Spencer, 2003; Sandberg et al., 1996; Schiano & Tversky, 1992; Schutte & Spencer, 2002; Spencer & Hund, 2002; Tversky & Schiano, 1989). Moreover, data from studies of adults' location reproduction errors suggest that direction and distance are encoded independently (e.g., Ghez et al., 1997; Gordon, Ghilardi, Cooper, & Ghez, 1994a; Gordon, Ghilardi, & Ghez, 1994b; Huttenlocher et al., 1991). Given these results, we expected to find evidence of geometric effects only in analyses of directional error. This expectation was supported by analyses of distance error, which showed no systematic effects with regard to the midline of the task space (see Appendix A).

[1] The MANOVAs described in the Results sections were conducted using both adjusted and non-adjusted data. There were few substantive differences; thus, only analyses of adjusted data are reported.

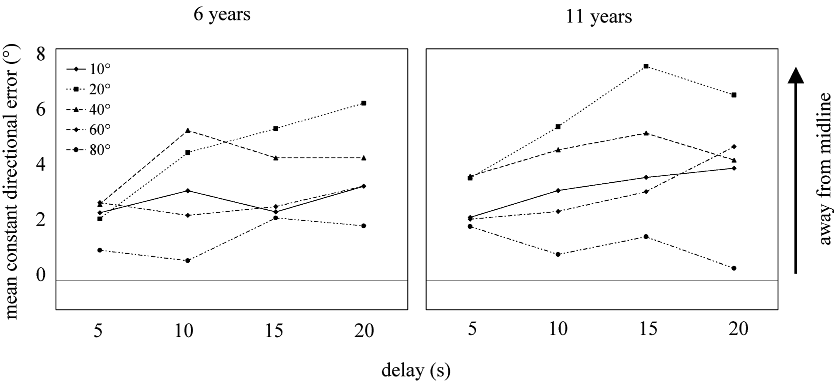

Fig. 3. Mean constant directional errors (averaged across responses to targets in the left and right categories) for 6- and 11-year-olds in each separation condition (see legend) at each delay (Experiment 1). Positive values reflect errors away from the midline category boundary (toward spatial prototypes).

2.2.1. Biases away from midline: Responses to the left and right targets

2.2.1.1. Constant directional error. Fig. 3 shows mean constant directional errors for 6- and 11-year-olds at each delay to targets located at each angular separation from midline. Given the symmetry of the left and right spatial categories in our task, errors to identical locations in these categories (e.g., −20° and +20°) have been averaged in this figure. Inspection of Fig. 3 reveals that, in general, children showed geometric category biases: responses were biased away from the midline category boundary and toward the spatial prototypes. Moreover, bias was largest at 20°, and decreased in magnitude as targets were moved closer (i.e., 10°) and further (i.e., 60°, 80°) from the midline category boundary. In addition, children's errors increased systematically over delays. This suggests that 6- and 11-year-olds' responses—like those of younger children (e.g., Schutte & Spencer, 2002) and adults (Spencer & Hund, 2002)—are subject to delay-dependent spatial drift.

Mean constant directional errors were analyzed using a four-way Multivariate Analysis of Variance (MANOVA) with Age (6 years, 11 years) and Separation (10°, 20°, 40°, 60°, 80°) as between-subjects factors and Delay (5 s, 10 s, 15 s, 20 s) and Side (left, right) as within-subjects factors.[2] Results revealed significant main effects of Delay, Wilks' $\Lambda = .76$, $F(3, 48) = 5.19$, $p < .005$, and Separation, $F(4, 50) = 3.45$, $p < .05$, which were subsumed by a significant Delay × Separation interaction, Wilks' $\Lambda = .64$, $F(12, 127) = 1.99$, $p < .05$. Tests of simple effects indicated that constant directional error increased significantly over delays in the 20° condition, $F(3, 33) = 8.74$, $p < .05$, the 40° condition, $F(3, 33) = 2.95$, $p < .05$, and the 60° condition,

[2] We used multivariate tests of within-subjects factors (Wilks' Λ) in all overall analyses because these tests do not require the assumption of sphericity. Thus, they are more conservative than conventional univariate tests of within-subjects factors.

$F(3,33) = 2.97, p < .05$, but not in the 10°, $F(3,33) = .85$, *ns*, and 80°, $F(3,33) = .87$, *ns*, conditions. Additional tests of simple effects indicated that constant errors differed significantly across separations at the 10 s delay, $F(4,55) = 4.53$, $p < .05$, the 15 s delay, $F(4,55) = 3.67$, $p < .05$, and the 20 s delay, $F(4,55) = 3.28$, $p < .05$, but not at the 5 s delay, $F(4,55) = .97$, *ns*. As can be seen in Fig. 3, directional biases at the longer delays were generally greatest in the 20° condition and smallest in the 80° condition. Taken together, these results reveal systematic delay-dependent and geometric biases in children's memory for locations.

Results of the overall MANOVA also revealed a significant main effect of Side, Wilks' $\Lambda = .84$, $F(1,50) = 9.34$, $p < .005$, and a significant Side × Separation interaction, Wilks' $\Lambda = .79$, $F(4,50) = 3.37$, $p < .05$. Tests of simple effects indicated that constant errors were larger on the left side than on the right side at 10°, $F(1,11) = 8.84$, $p < .05$ (left: $M = 4.51°$, right: $M = 1.45°$), 40°, $F(1,11) = 14.49$, $p < .05$ (left: $M = 5.48°$, right: $M = 2.93°$), and 80°, $F(1,11) = 4.94$, $p < .05$ (left: $M = 2.15°$, right: $M = .48°$), but not at the other separations, all $F\text{s}(1,11) < 1.17$, *ns*. It is possible that this effect is related to handedness, given that all of our participants were right handed. No other results from the overall MANOVA reached statistical significance.

2.2.1.2. Variable directional error. Next, we examined the variability (standard deviation) of 6- and 11-year-olds' responses to the left and right targets across delays and separations. Fig. 4 shows mean variable directional errors for both ages averaged across the left and right targets in each separation condition at each delay. As can be seen in this figure, variability was higher for 6-year-olds than for 11-year-olds. In addition, variability generally increased over delays. This is consistent with the increase in variability over delays reported with adult participants (Spencer & Hund, 2002).

Mean variable directional errors were analyzed in a four-way MANOVA with Age and Separation as between-subjects factors and Delay and Side as within-

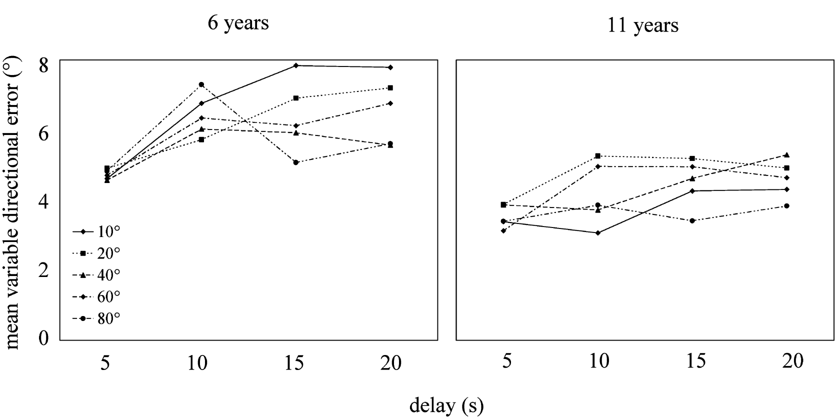

Fig. 4. Mean variable (standard deviation) directional errors (averaged across responses to targets in the left and right categories) for 6- and 11-year-olds in each separation condition (see legend) at each delay (Experiment 1).

subjects factors. Results revealed significant main effects of Age, $F(1,50) = 26.07$, $p < .001$, Delay, Wilks' $\Lambda = .43$, $F(3,48) = 20.99$, $p < .001$, and Side, Wilks' $\Lambda = .92$, $F(1,50) = 4.18$, $p < .05$. As can be seen in Fig. 4, variability was significantly greater for the 6-year-olds ($M = 6.03°$) than for the 11-year-olds ($M = 4.20°$). Moreover, variability increased over delays (5 s: $M = 4.13°$; 10 s: $M = 5.30°$; 15 s: $M = 5.43°$; 20 s: $M = 5.59°$). Finally, variability was greater on the left side of the table ($M = 5.31°$) than on the right side ($M = 4.92°$), suggesting that memory for locations in the left category is less certain than memory for targets in the right category. These findings parallel the larger constant directional errors in the left category reported above. No other results reached significance.

2.2.2. *The certainty of the category boundary: Responses to the center target*

In a final set of analyses, we examined children's responses to the center target (0°) to assess the certainty of the midline category boundary. If midline is a relatively certain category boundary, then we would expect constant and variable directional errors to the center target to be small (e.g., Engebretson & Huttenlocher, 1996). Fig. 5 depicts mean constant directional errors to this target at each delay in each condition. Inspection of this figure reveals that constant directional errors to the center target were quite small across delays in all conditions. This replicates effects reported by Hund and Spencer (2003) and is consistent with the small errors to the center target reported with 3-year-olds (Schutte & Spencer, 2002) and adults (Spencer & Hund, 2002). It is not clear why children showed a small positive (counterclockwise) bias to the center location.

Mean constant directional errors to the center target were entered into a three-way MANOVA with Age and Separation as between-subjects factors and Delay as a within-subjects factor. Results revealed a significant Delay × Age interaction, Wilks' $\Lambda = .85$, $F(3,48) = 2.84$, $p < .05$, and a significant Delay × Separation × Age interaction, Wilks' $\Lambda = .65$, $F(12,127) = 1.85$, $p < .05$ (see Fig. 5). Tests of simple effects revealed that 6-year-olds made larger counterclockwise (i.e., positive) errors

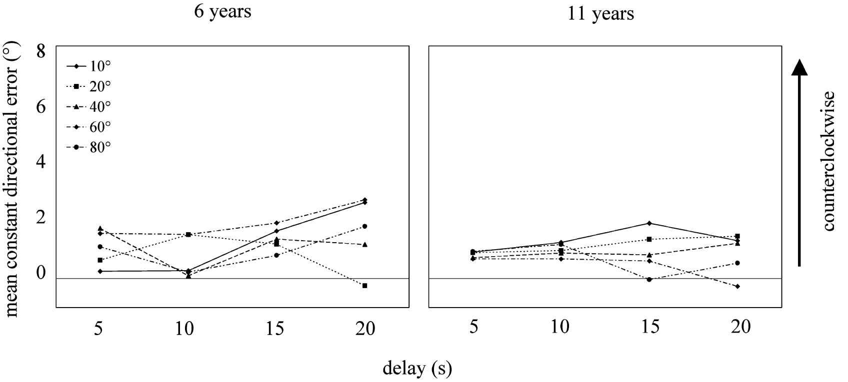

Fig. 5. Mean constant directional errors for responses to the center target for 6- and 11-year-olds in each separation condition (see legend) at each delay (Experiment 1). Positive values reflect counterclockwise errors.

than did 11-year-olds in the 60° condition, $F(1,150) = 14.93$, $p < .025$. Additional tests of simple effects revealed that counterclockwise errors increased significantly across delays in the 10° condition, $F(3,150) = 3.24$, $p < .025$. There were no other significant Delay, Age, or Delay × Age effects at any other separations. Thus, children's responses were generally quite accurate to the center target, and the three-way interaction was the result of an isolated age effect in the 60° condition and a delay effect in the 10° condition.

Fig. 6 shows mean variable directional errors to the 0° target across delays and conditions for both age groups. As can be seen in this figure, variable errors to the center target were generally quite small, suggesting that the midline axis is a relatively certain boundary. Nevertheless, 6-year-olds' responses were more variable than were 11-year-olds' responses. Variable errors also tended to increase across delays in a manner similar to the delay-dependent increase in variability for responses to the left and right targets. Mean variable directional errors to the center target were entered into a three-way MANOVA with Age and Separation as between-subjects factors and Delay as a within-subjects factor. Results revealed a significant main effect of Age, $F(1,50) = 21.67, p < .05$. As with responses to the left and right targets, variable errors to the center target were larger for the 6-year-olds ($M = 4.67°$) than for the 11-year-olds ($M = 3.23°$). Results also revealed a significant main effect of Delay, Wilks' $\Lambda = .70$, $F(3,48) = 7.00$, $p < .005$ (5 s: $M = 3.69°$; 10 s: $M = 4.66°$; 15 s: $M = 4.90°$; 20 s: $M = 5.00°$). Finally, there was a significant main effect of Separation, $F(4,50) = 2.87$, $p < .05$. Variability was lower for targets further from midline (10°: $M = 4.23°$; 20°: $M = 4.22°$; 40°: $M = 3.87°$; 60°: $M = 3.82°$; 80°: $M = 3.60°$).

2.3. Discussion

The first goal of the present study was to examine the magnitude of geometric category biases in 6- and 11-year-olds' recall responses. Both age groups showed strong geometric effects—responses to the left and right targets were biased away from

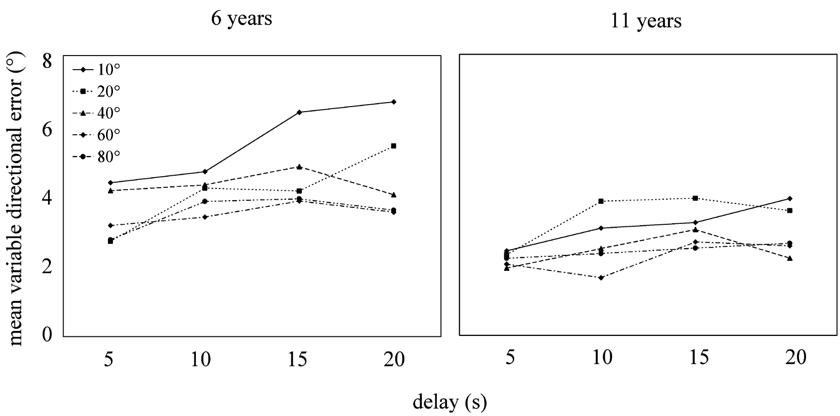

Fig. 6. Mean variable directional errors for responses to the center target for 6- and 11-year-olds in each separation condition (see legend) at each delay (Experiment 1).

midline (toward spatial prototypes). In addition, these biases varied systematically depending on the location of the target within each category. Directional errors were largest at 20° and decreased systematically across conditions as the targets were moved away from midline. Furthermore, performance to the target aligned with the category boundary (0°) was consistently accurate with low variability, suggesting that the midline category boundary was relatively certain. Taken together, these data provide a baseline measure of children's biases away from midline (toward spatial prototypes) when remembering individual locations to the left and right of this category boundary.

Interestingly, directional errors were largest to the ±20° locations, the locations at which we thought geometric effects might be underestimated. Although this could still be the case, the pattern of results across locations is consistent with previous studies of geometric effects (Engebretson & Huttenlocher, 1996; Huttenlocher et al., 1991, 1994; Spencer & Hund, 2002). There was some suggestion that targets close to midline might be underestimated. Specifically, there was a reduction in constant directional error at 10° relative to errors to the 20° location. Although this might be related to children's use of a long-term memory of the target locations, it could also result from occasionally mis-categorizing items close to the category boundary (see Huttenlocher et al., 1991). We suspect that both factors might influence responses at 10°, particularly for 6-year-olds (see Hund & Spencer, 2003 for a discussion of related effects).

The second goal of the present study was to examine whether 6- and 11-year-olds—like 3-year-olds and adults—show systematic delay-dependent spatial drift. This was indeed the case. Directional bias away from midline increased significantly over delays at the 20°, 40°, and 60° locations. By contrast, children's responses to the targets very close to (10°) and very far from (80°) midline did not show a significant increase in error over delays. Thus, the magnitude of delay-dependent effects varied systematically with the magnitude of bias away from midline—the greater the geometric bias to a particular location, the stronger the delay-dependent spatial drift. It is important to note that there were no significant age-related differences in spatial drift over delays. By contrast, there was a significant reduction in variable error across ages. This suggests that between 6 and 11 years memory becomes more stable, but is still prone to large biases.

One final result is worthy of note: children's constant and variable errors were generally larger when they moved to targets to the left of midline versus to the right of midline. Given that all of the children in this experiment were right-handed, it is likely that these results are related to differences in skill when right-handed children attempt to remember locations in the contralateral task space (Carnahan, 1998; Fisk & Goodale, 1985).[3]

[3] It is possible that children used the feedback screen located to the right of the experimental table as a landmark to facilitate memory during the delay. We think this is unlikely given that children and adults show no noticeable differences in performance with versus without this screen present (see Hund & Spencer, 2003; Schutte & Spencer, 2002; Spencer & Hund, 2002).

3. Experiment 2

The goal of the present experiment was to determine whether children's biases away from midline were separable from experience-dependent biases as the claim of developmental continuity suggests. Toward this end, we examined whether the geometric effects measured in Experiment 1 were modulated by the relative position of targets within a spatial category. A schematic of the design of this experiment is shown in Fig. 1. In each condition, children estimated the locations of three targets separated by 20° following delays of 0–20 s. Across conditions, we varied the layout of the target sets with respect to midline: one set of targets was close to midline, one set was further from midline, and one set was very far from midline. We also varied whether the targets were within the left or right category.

If 6- and 11-year-old children do *not* use experience-dependent spatial information in a manner comparable to younger children (Schutte & Spencer, 2002) and adults (Spencer & Hund, 2002), then biases at each absolute location should depend solely on the target's position relative to midline, that is, results to each absolute location should be identical to results from Experiment 1. If, however, there is developmental continuity in spatial memory processes and children's estimates are modulated by experience-dependent information, then directional errors across conditions should diverge systematically from the results of Experiment 1. Specifically, responses to the "inner" target (i.e., the target closest to midline) in each target set should be biased outward—toward the average remembered location—relative to the geometric biases reported in Experiment 1. By contrast, responses to the "outer" target in each target set should be biased inward—toward the average remembered location. Moreover, such effects should be constructed via trial-to-trial experience in the task. To test these predictions, we examined the overall pattern of error in children's responses and changes in error over learning.

3.1. Method

3.1.1. Participants

Thirty-six 6–7-year-olds ($M = 6$ years 3.08 months; $SD = 3.22$ months) and 36 10–11-year-olds ($M = 10$ years 6.89 months; $SD = 2.38$ months) participated in this experiment. Data from one additional 6-year-old were not included in the final analyses because a high percentage of data (>8%) was missing following initial data processing. Data from one additional 11-year-old were also excluded because IRED visibility to the −80° target was poor. Children were recruited from a child participant database maintained by the Department of Psychology at the University of Iowa and via referrals from other participants. Children received a $4 gift certificate for each experimental session. All participants were right-handed. Approximately equal numbers of females and males participated in each condition.

3.1.2. Apparatus, materials, task, and procedure

The apparatus, materials, task, and procedure were identical to those used in Experiment 1.

3.1.3. Experimental design

Participants in each age group were randomly assigned to one of six experimental conditions in a full-factorial design, crossing rotation condition and side. Participants in all conditions moved equally often to three target locations separated by 20°—an inner, center, and outer location. The target closest to the midline of the table was designated as the inner target, while the target furthest from midline was designated as the outer target. Targets were always presented within one spatial category—to the left of midline or to the right of midline. In addition, the layout of target locations within each category varied across three rotation conditions designated by the center target's location. Participants in the Center20° condition responded to targets at 0°, 20°, and 40° for the right side condition and 0°, −20°, and −40° for the left side condition. Participants in the Center40° condition responded to targets at 20°, 40°, and 60° (or −20°, −40°, and −60°). Participants in the Center60° condition responded to targets at 40°, 60°, and 80° (or −40°, −60°, and −80°). All other design details were identical to Experiment 1.

3.1.4. Method of analysis

The method of analysis was identical to Experiment 1. As a result of the outlier analysis, an average of 5.83% of all trials were eliminated for the 6-year-olds and 1.61% for the 11-year-olds.

3.2. Results

3.2.1. Constant directional error and directional difference scores

We began our analyses by examining geometric biases in children's responses. Fig. 7 shows mean constant directional errors to the inner, center, and outer targets in the Center20°, Center40°, and Center60° conditions across delays for the 6-year-olds and 11-year-olds. For comparison, Fig. 7 also shows mean constant directional errors to the same absolute spatial locations in Experiment 1. As in previous figures, directional errors were averaged across targets in the left and right spatial categories. As can be seen in Fig. 7, effects in the present experiment generally replicated findings from Experiment 1. Children made outward directional errors when moving to non-0° targets, and these errors increased in magnitude over delays. Furthermore, the magnitude of error was quite large for targets near midline (i.e., 20°) and decreased for targets further from midline (i.e., 80°). Finally, responses to the target aligned with the category boundary (0°) were quite accurate across delays. There was one exception to the general pattern of geometric effects, however: 6-year-olds' responses to the outer target (60°) in the Center40° condition were slightly biased inward over delays (see Fig. 7e).

The central question of interest was whether children showed experience-dependent biases. Thus, we examined whether the layout of targets within a category

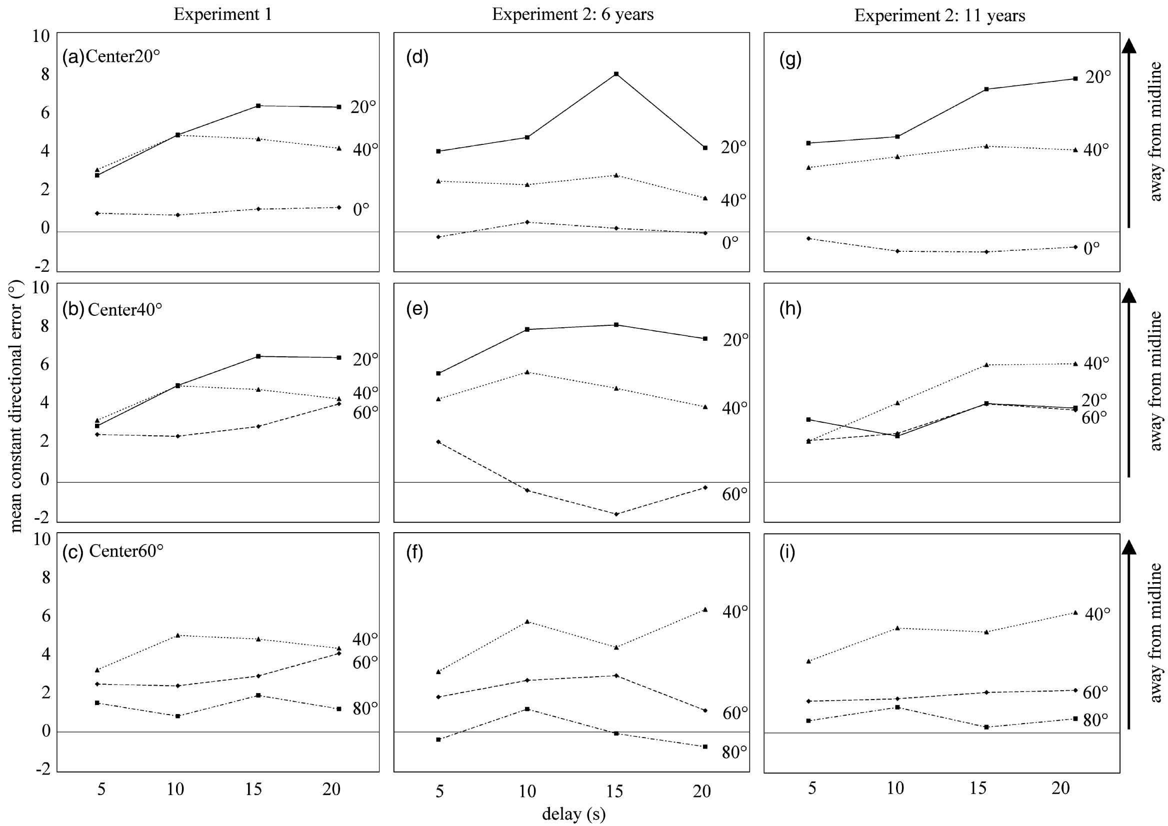

Fig. 7. (a, b, c) Mean constant directional errors over delays from Experiment 1 for responses to the target locations included in Experiment 2. Note that data from the 20°, 40°, and 60° locations are duplicated in these panels. Remaining panels display mean constant directional errors over delays for 6-year-olds' (d, e, f) and 11-year-olds' (g, h, i) responses to the inner, center, and outer targets in the Center20° (d, g), Center40° (e, h), and Center60° (f, i) conditions (Experiment 2).

modified geometric biases. Specifically, we removed geometric effects from children's responses by subtracting the mean constant directional error to each target location at each delay in Experiment 1 from directional errors to the associated targets and delays in Experiment 2 for each age group and side separately. Positive directional difference scores reflect outward biases (i.e., *away from* midline) relative to Experiment 1, whereas negative scores reflect inward biases (i.e., *toward* midline) relative to Experiment 1. If children's responses were not influenced by the distribution of exemplars experienced in the task, then difference scores should be zero. Conversely, if older children used the exemplar distribution in a manner comparable to younger children and adults, then difference scores to the inner and outer targets should be biased toward the center target.

Mean constant directional difference scores were analyzed using a five-way MANOVA with Age (6 years, 11 years), Rotation (Center20°, Center40°, Center60°), and Side (left, right) as between-subjects factors and Delay (5, 10, 15, and 20 s) and Target (inner, center, and outer) as within-subjects factors. Results showed a significant Target × Age interaction, Wilks' $\Lambda = .89$, $F(2, 59) = 3.79$, $p < .05$. Tests of simple effects revealed a significant Target effect for the 6-year-olds, $F(2, 120) = 7.51$, $p < .05$, but not for the 11-year-olds, $F(2, 120) = .89$, *ns*. This interaction is shown in Fig. 8. For the 6-year-olds, difference scores for the inner targets were biased outward (i.e., toward the center target), whereas difference scores for the outer targets were biased inward (i.e., toward the center target). Thus, 6-year-olds showed experience-dependent biases after geometric effects were removed. Follow-up t tests indicated that errors to the outer target differed significantly from zero error, $t(35) = -2.60$, $p < .05$, whereas errors to the inner target did not. It is possible that experience-dependent effects were smaller to the inner target because the inner target in the Center20° condition (0°) was aligned with the category boundary (see Fig. 7d). We return to this possibility in Discussion. In contrast to the 6-year-olds' performance, difference scores to the center and outer targets hovered near zero for the 11-year-olds, while difference scores to the inner target were biased slightly inward (see Fig. 8). Follow-up t tests indicated that 11-year-olds' difference scores to each target did not differ significantly from zero. Thus, 11-year-olds did not show evidence of experience-dependent effects.

Results also revealed a significant Delay × Age interaction, Wilks' $\Lambda = .85$, $F(3, 58) = 3.31$, $p < .05$. Tests of simple effects indicated that difference scores increased significantly across delays for the 6-year-olds, $F(3, 180) = 6.31$, $p < .05$, but not for the 11-year-olds, $F(3, 180) = .63$, *ns*. The 6-year-olds' response biases became increasingly negative (i.e., inward relative to baseline) over delays (5 s: $M = .31°$; 10 s: $M = .07°$; 15 s: $M = -.32°$; 20 s: $M = -1.32°$), reflecting the larger experience-dependent effects to the outer targets relative to the inner targets (see Fig. 8).

A final set of effects were consistent with the Target effects described above, but showed some modulation of errors to the inner and outer targets across the three targets sets. Specifically, the MANOVA revealed a significant main effect of Target, Wilks' $\Lambda = .89$, $F(2, 59) = 3.72$, $p < .05$, a significant Delay × Condition interaction, Wilks' $\Lambda = .69$, $F(6, 116) = 4.01$, $p < .005$, and a significant Target × Condition interaction, Wilks' $\Lambda = .81$, $F(4, 118) = 3.34$, $p < .05$. These effects were subsumed

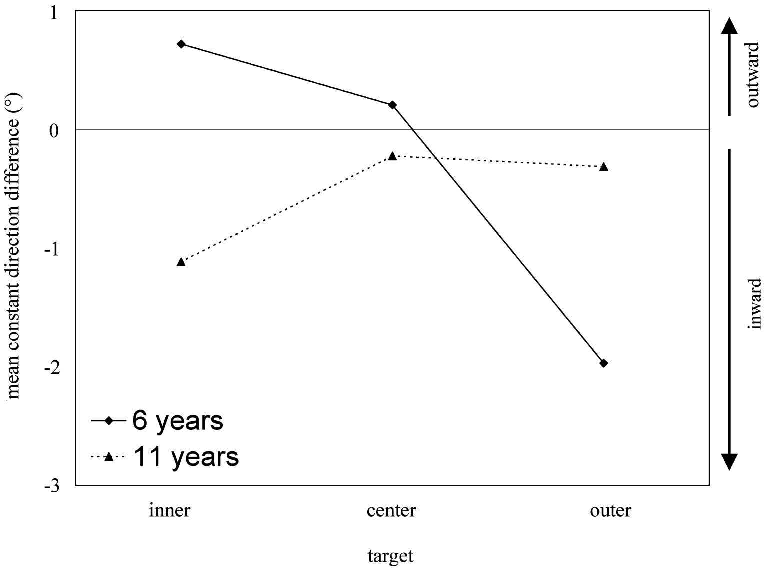

Fig. 8. Mean constant directional difference scores for 6-year-olds' (solid line) and 11-year-olds' (dotted line) responses to the inner, center, and outer targets (Experiment 2).

by a significant Target × Delay × Condition interaction, Wilks' $\Lambda = .64$, $F(12, 110) = 2.27$, $p < .05$. Tests of simple effects revealed significant Target effects in all three Conditions: Center20° condition, $F(2, 360) = 15.44$, $p < .025$ (inner: $M = -1.38°$; center: $M = .55°$, outer: $M = -1.1°$), Center40° condition, $F(2, 360) = 12.14$, $p < .025$ (inner: $M = .11°$; center: $M = .31°$; outer: $M = -1.38°$), and Center60° condition, $F(2, 360) = 11.98$, $p < .025$. However, there was also a Delay × Target interaction, $F(6, 360) = 3.53$, $p < .025$ in the Center60° condition. Additional tests of simple effects revealed a significant Target effect at the 20 s delay in this condition, $F(3, 360) = 16.97$, $p < .025$ (inner: $M = 1.90°$; center: $M = -2.33°$; outer: $M = -1.16°$), but not at the other delays, all Fs $(3, 360) < 2.95$, *ns*.

The significant Target effects evident in these simple effects tests reflect experience-dependent biases: responses to the outer target were biased inward (i.e., negative) in all three conditions, and responses to the inner target in the Center60° condition were biased outward at the 20 s delay. There was, however, one result contrary to this general pattern: the inner target (0°) in the Center20° condition was biased inward. As can be seen in Figs. 7a and g, responses to the 0° location in Experiment 1 were biased in a clockwise direction, whereas responses to the same location in Experiment 2 were near zero error or biased in a counterclockwise direction. It is not clear why this difference existed across experiments.

3.2.1.1. Analyses of difference scores over learning. If children's ability to remember location information is affected by a long-term memory of the exemplar distribution, then the build up of this long-term memory should be evident across trials.

To investigate this possibility, we analyzed how children's responses to each target location changed across four blocks of trials relative to performance to the same absolute locations in Experiment 1. The four blocks of trials were early during Session 1 (Block 1), late during Session 1 (Block 2), early during Session 2 (Block 3), and late during Session 2 (Block 4). Trial 30 divided the early and late blocks in each session. Due to the randomization of trial order, there were some cases in which children did not move to one of the targets at a particular delay during one of the trial blocks. Thus, we collapsed across delays, and computed the median directional error to each target in each block of trials for each age group and side separately. Median errors were used because of the small number of trials in some blocks. In the final analysis step, we subtracted geometric biases from children's responses. In particular, we subtracted the median constant directional error to each target location in each block of trials in Experiment 1 from analogous responses in the present experiment. As above, this was done separately for each age group and side.

Median directional difference scores were analyzed in a four-way MANOVA with Age and Rotation as between-subjects factors and Block (1, 2, 3, 4) and Target as within-subjects factors. Only Block effects are reported below since the critical question was whether children's responses showed an increase in experience-dependent biases over learning. There was a significant Block $\times$ Target $\times$ Age interaction, Wilks' $\Lambda = .79$, $F(6, 61) = 2.68$, $p < .05$. Tests of simple effects revealed a significant Block $\times$ Target interaction for the 6-year-olds, $F(6, 396) = 3.13$, $p < .01$. Additional simple effects tests for the 6-year-olds showed a significant Block effect at the inner target, $F(3, 105) = 4.02$, $p < .01$, but not at the other targets, all $F\text{s}(3, 105) < .46$, *ns*. There were no significant Block effects for the 11-year-olds. This is consistent with the analyses of constant directional errors, which showed no significant experience-dependent effects for this age group.

Fig. 9 shows median directional difference scores across the four trial blocks to each target location for both age groups. As can be seen in this figure, 6-year-olds' responses to the inner target became increasingly biased outward over blocks of trials, whereas their responses to the outer target became increasingly biased inward over blocks. The direction of these block effects is consistent with a build-up of experience-dependent biases over learning: responses became increasingly biased toward an average remembered location over blocks. In contrast to the 6-year-olds' responses, 11-year-olds did not show consistent changes in response bias over blocks. Rather, their responses remained near zero, indicating that response biases across blocks were comparable to biases in Experiment 1.

3.2.2. Variable directional error

As in Experiment 1, we examined how variable children's responses were over delays across the different target sets. Mean variable directional errors were analyzed in a five-way MANOVA with Rotation, Age, and Side as between-subjects factors and Delay and Target as within-subjects factors. Results revealed significant main effects of Age, $F(1, 60) = 60.75$, $p < .001$, and Delay, Wilks' $\Lambda = .22$, $F(3, 58) = 67.85$, $p < .001$. These main effects were subsumed by a significant Delay $\times$ Age interaction,

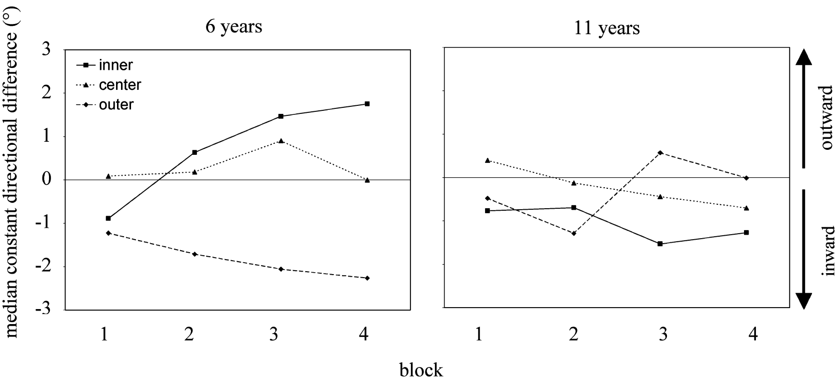

Fig. 9. Median constant directional difference scores over four blocks of trials for 6- and 11-year-olds' responses to the inner, center, and outer targets (Experiment 2).

Wilks' $\Lambda = .86$, $F(3, 58) = 3.08$, $p < .05$. Results of simple effects tests indicated that the increase in variability over delay was significant for both age groups (6-year-olds: $F(3, 180) = 43.08$, $p < .01$; 11-year-olds: $F(3, 180) = 21.46$, $p < .01$). As in Experiment 1, the increase in variability over delay was greater for 6-year-olds (5 s $M = 5.15°$; 10 s $M = 6.81°$; 15 s $M = 7.27°$; 20 s $M = 8.14°$) than for 11-year-olds (5 s $M = 3.70°$; 10 s $M = 4.52°$; 15 s $M = 5.07°$; 20 s $M = 5.80°$).

Results also revealed a significant main effect of Target, Wilks' $\Lambda = .64$, $F(2, 59) = 16.61$, $p < .001$. Variability to the inner target ($M = 5.22°$) was less than variability to the center ($M = 5.86°$) and outer ($M = 6.34°$) targets. As in Experiment 1, these effects were primarily driven by low variability to the target aligned with the category boundary (0°). Specifically, variability to the inner target in the Center20° condition (0°) was quite low ($M = 3.99°$), whereas variability to the inner targets in the Center40° ($M = 5.76°$) and Center60° ($M = 5.91°$) conditions was higher, comparable to the mean variability to the center and outer targets across conditions (see above).

3.3. Discussion

Results generally replicated the pattern of geometric and delay effects from Experiment 1. Children's responses to the non-0° targets were biased away from the midline category boundary (toward spatial prototypes) as the memory delay increased. These outward biases were generally largest when children responded to the 20° target and smaller for targets further from the midline axis. In addition, children's responses to the 0° location—the target aligned with the category boundary—were accurate over delays with low variability, and 6-year-olds' responses were more variable over delays than were 11-year-olds' responses.

The central question of interest was whether geometric and delay-dependent effects could be separated from biases toward the center of the exemplar distribution children experienced in the task. To this end, we examined whether responses to the inner and outer targets in each target set were biased toward the center target, above and beyond the geometric biases reported in Experiment 1. This was indeed the case for the 6-year-olds, but not for the 11-year-olds. Six-year-olds' responses to the outer targets showed a clear inward bias relative to geometric effects in Experiment 1. Similarly, responses to the inner target in the Center60° condition were biased outward relative to geometric effects in Experiment 1. Analyses of learning effects provided strong evidence that these response biases were due to attraction toward the center of the exemplar distribution constructed over trial blocks. Similar trial-by-trial effects have been reported with younger children (Schutte & Spencer, 2002; Spencer et al., 2001), suggesting that the same long-term memory processes operate between early (2–3 years) and later (6 years) development.

In contrast, 11-year-olds did not show experience-dependent effects. Their difference scores were generally near zero, indicating that 11-year-olds' responses were largely dominated by geometric and delay-dependent biases. Analyses of learning effects also failed to show experience-dependent biases. The qualitative developmental difference in experience-dependent effects between 6 and 11 years contrasts sharply with developmental similarities in geometric and delay-dependent effects reported in Experiment 1. These results suggest that there is a developmental *discontinuity* in experience-dependent effects between 6 and 11 years.

It is also possible, however, that developmental continuity was masked by the particulars of the manipulation we used. Consider, for example, the mechanism that underlies long-term memory effects in the DFT: on each trial, activation in spatial working memory leaves an activation trace in long-term memory (see Erlhagen & Schöner, 2002; Kopecz & Schöner, 1995; Schöner, Dose, & Engels, 1995; Thelen et al., 2001). From trial to trial, these memory traces build distributions of activation in long-term memory centered at each target location. For instance, in Fig. 10a, each of the dotted distributions indicates how a child might represent a target location in long-term memory following several trials to that location. Given the graded and overlapping nature of these distributions, activation across the three locations will blend together, producing the summed activation profile captured by the solid line. This profile can lead to the type of experience-dependent effects reported here. When the 6-year-olds responded to the outer target, for example, activation in spatial working memory was biased toward the center target because the long-term memory input at this location was stronger than at the outer location.

Central to this account is the overlap among the individual activation profiles. If this overlap is eliminated, then there should no longer be stronger input at the center location, *and there should no longer be experience-dependent effects*. This is shown in Fig. 10b where we have made the individual activation profiles more spatially precise (i.e., narrower). This change produces a balanced long-term memory input around each target location. As a consequence, memory for the outer location would not be biased toward an average remembered location because spatial working memory receives balanced long-term memory input. This may explain why 11-year-olds failed to show experience-dependent effects—these children represented locations in long-term memory in a relatively precise manner. Thus, the manipulation used in

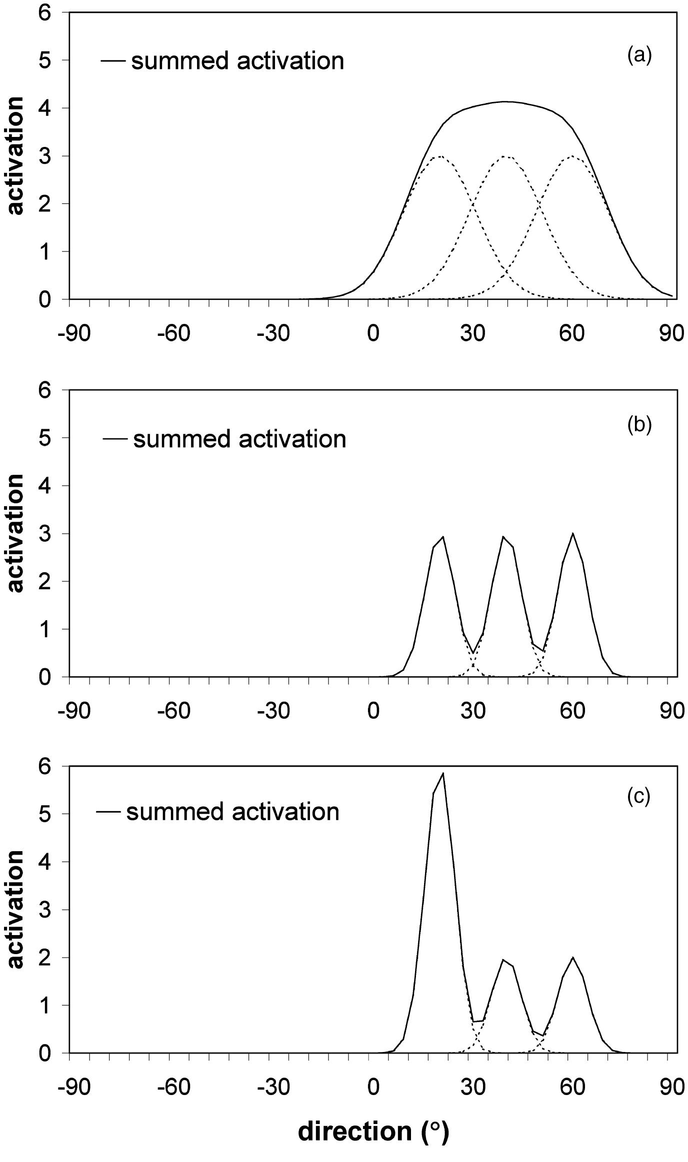

Fig. 10. (a) Dotted lines represent relatively broad activation associated with the long-term memory of each target location (i.e., 20°, 40°, 60°). Solid line depicts summed activation across the three individual activation profiles. (b) Dotted lines represent narrower activation associated with each target location (i.e., 20°, 40°, 60°). Solid line depicts summed activation across the three individual activation profiles. (c) Dotted lines represent narrower activation associated with each target location (i.e., 20°, 40°, 60°). Higher activation to the 20° target reflects the increase in response frequency to that location, while lower activation to 40° and 60° targets reflects the decrease in response frequency to these locations. Solid line depicts summed activation across the three targets.

the present experiment might not have effectively tapped into long-term memory processes for the 11-year-olds.

4. Experiment 3

In the present experiment, we re-examined evidence for developmental discontinuity in experience-dependent effects by using a second manipulation of long-term memory. In particular, we manipulated how often children responded to each target location using one of the target sets from Experiment 2 (Center40°). In a bias inward (BI) condition, children responded 2/3rds of the time to the inner target, and 1/6th of the time to the center and outer targets, respectively. In a bias outward (BO) condition, children responded more often to the outer target relative to the other two. According to the DFT, this should lead to greater activation in long-term memory associated with the biased target (see Fig. 10c). Consequently, when children are asked to remember the unbiased locations, activation in spatial working memory should be differentially pulled toward the biased location. Importantly, this prediction holds even if 11-year-olds' long-term memory for the targets is relatively precise as in Fig. 10c. Moreover, this hypothesis can be tested without using the subtraction technique from Experiment 2. This allowed us to examine whether the subtraction technique might have contributed to the developmental differences reported previously.

4.1. Method

4.1.1. Participants

Twenty-four 6–7-year-olds ($M = 6$ years 8.04 months; $SD = 1.73$ months) and 24 10–12-year-olds ($M = 10$ years 6.87 months; $SD = 2.10$ months) participated in this study. Data from nine additional children were excluded from final analyses: seven 6-year-olds did not complete data collection,[4] there was an experimenter error for one 6-year-old, and we experienced equipment problems for one 11-year-old. Children were recruited and compensated in the same manner as in Experiment 2. All participants were right-handed. Approximately equal numbers of females and males participated in each experimental condition.

4.1.2. Apparatus and materials

Although the apparatus used in the present experiment was nearly identical to that used in Experiments 1 and 2 from the participants' perspective, several changes made the apparatus easier to use. First, the table size was increased to $1.22\,\text{m} \times 1.83\,\text{m}$, and the plexiglas top was replaced by a rear-projection surface.

[4] Three of these children's sessions occurred during a brief period when we were experiencing minor equipment problems. Although these equipment problems did not result in the loss of data, they were somewhat disruptive to the overall flow of the task and might have contributed to these participants' decision to halt data collection early.

Next, a Barco 708 Data Projector (Barco, Inc.) was used to project images onto the table's surface. These images—a yellow start circle, a white fixation circle, and the target spaceships—were similar to those used in Experiments 1 and 2 in size and luminance. Third, real-time Optotrak analyses of participants' finger position replaced the electro-magnetic switch. Finally, visual feedback was presented on the surface of the table after each trial. Thus, the computer monitor (see Fig. 2) was not visible during the experimental sessions.

4.1.3. Task and procedure

The task and procedures were identical to those used in Experiments 1 and 2.

4.1.4. Experimental design

Participants in each age group were randomly assigned to one of four experimental conditions in a full factorial design, crossing bias condition and side. Participants in all conditions moved to the same three target locations used in the Center40° condition from Experiment 2. Thus, targets were presented at 20°, 40°, and 60° on the right side of the table and at −20°, −40°, and −60° on the left side of the table. To assess long-term memory effects without using the subtraction technique, we altered how often children moved to each location. Participants in a bias inner (BI) condition moved to the inner target (±20°) on 2/3 of all trials, whereas they moved to the center and outer targets on 1/6 of all trials. Participants in a bias outer (BO) condition moved to the outer target (±60°) on 2/3 of all trials, whereas they moved to the center and inner targets on 1/6 of all trials.

Participants came into the laboratory for two sessions. During the first session, participants completed 15 practice trials—5 to each target at randomly selected delays. During the second session, participants completed 6 practice trials—3 to each target at randomly selected delays. Following practice, children in each session completed 65 trials in blocks of 15 trials each (the final block contained 20 trials). There were 20 trials to the biased target (inner or outer) at each of two delays, and 4 trials to each of the non-biased targets at each of two delays. In addition, children completed three 0 s delay trials to each target during each session. Across the two sessions, then, participants completed 40 trials to the biased target and 8 trials to each non-biased target at each of two delays. We only used two age-appropriate delays to keep the total number of trials comparable across Experiments 1–3. Six-year-olds recalled the target locations following delays of 5 and 10 s, whereas 11-year-olds recalled the target locations following delays of 10 and 15 s (see also, Hund & Spencer, 2003). All trials were randomized with the constraint that trials to the non-biased targets never occurred more than twice in a row.

4.1.5. Method of analysis

The method of analysis was identical to that used in the previous experiments. As a result of the outlier analysis, an average of 5.94% of all trials were eliminated for the 6-year-olds and 4.18% of all trials for the 11-year-olds.

4.2. Results

4.2.1. Constant directional error

Fig. 11 shows mean constant directional errors to the inner, center, and outer targets across the short and long delays for children in both bias conditions. For comparison, Fig. 11a shows mean constant directional errors from the analogous targets and delays in Experiment 1. As in previous figures, directional errors were averaged across targets in the left and right spatial categories. Children generally made errors away from midline over delays. However, these midline effects were modulated by experience-dependent biases, that is, responses differed across the two bias conditions. In the BI condition, 6-year-olds' responses to the outer target were biased *inward* at the long delay—toward the biased location. Eleven-year-olds' responses in the BI condition also showed a bias-related effect: responses to the center target (40°) were biased inward relative to directional errors in Experiment 1. In the BO condition, both 6- and 11-year-olds showed large outward biases to the inner and center targets relative to the geometric effects in Experiment 1.

Children's mean constant directional errors were analyzed in a five-way MANOVA with Condition (BI, BO), Age (6 years, 11 years), and Side (left, right) as between-subjects factors and Delay (short, long) and Target (inner, center, outer) as within-subjects factors. The central question was whether children's responses were affected by the bias manipulation, that is, were there significant Condition effects. The five-way MANOVA revealed a significant Target × Condition interaction, Wilks' $\Lambda = .76$, $F(2,39) = 6.04$, $p < .01$. Results of simple effects tests indicated that errors to the center target differed significantly depending on condition, $F(1,96) = 7.6$, $p < .01$, whereas errors to the inner, $F(1,96) = 1.53$, *ns*, and outer, $F(1,96) = .07$, *ns*, targets did not differ. The Target × Condition interaction is shown in Fig. 12a. Participants generally made larger outward errors in the BO condition than in the BI condition. Of particular note, errors to the center target were strongly biased outward in the BO condition and showed a smaller outward bias in the BI condition. This was the case even though the center target was in the same absolute spatial location in both conditions. These data suggest that children's responses to the center target were attracted toward the long-term memory of the biased target.

To examine whether the experience-dependent effects shown in Fig. 12a were primarily driven by the 6-year-olds—a question germane to the developmental continuity claim—we conducted a follow-up analysis to determine whether the Condition effect at the center target was significant for each age group. This analysis revealed a significant Condition effect for the 6-year-olds, $F(1,22) = 7.96$, $p < .01$, and a trend for the 11-year-olds, $F(1,22) = 3.36$, $p < .08$. Thus, it appears that there is developmental continuity in experience-dependent effects, although the magnitude of such effects is larger for the 6-year-olds.

In addition to the condition effects, two additional sets of main effects and interactions reached significance in the overall MANOVA. These effects were largely driven by the geometric and delay-dependent biases evident in Fig. 11. In particular, there was a significant main effect of Delay, Wilks' $\Lambda = .91$, $F(1,40) = 4.07$, $p < .05$, and a significant Delay × Target interaction, Wilks' $\Lambda = .69$, $F(2,39) = 8.69$,

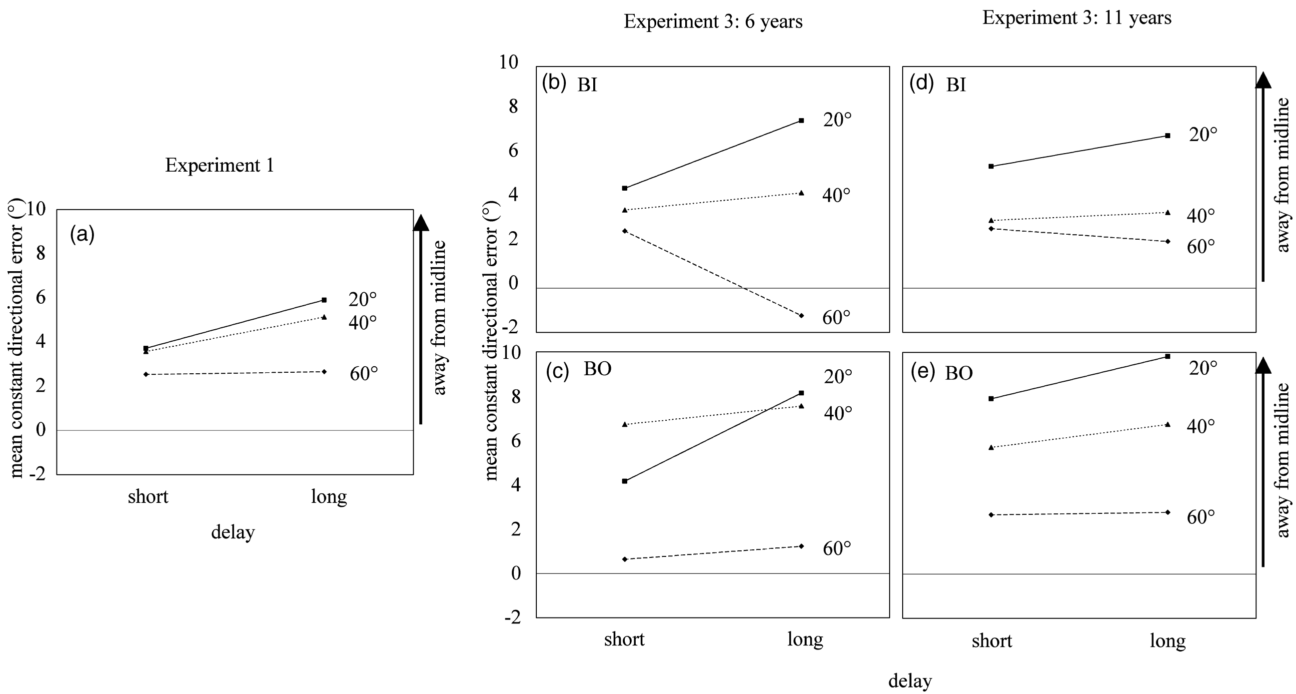

Fig. 11. (a) Mean constant directional errors for the short and long delays from Experiment 1 for responses to the target locations and delays included in Experiment 3. (b, c) Mean constant directional errors over delays for 6-year-olds' responses to the 20°, 40°, and 60° targets in the BI (b) and BO (c) conditions (Experiment 3). (d, e) Mean constant directional errors over delays for 11-year-olds' responses to the three targets in the BI (d) and BO (e) conditions (Experiment 3).

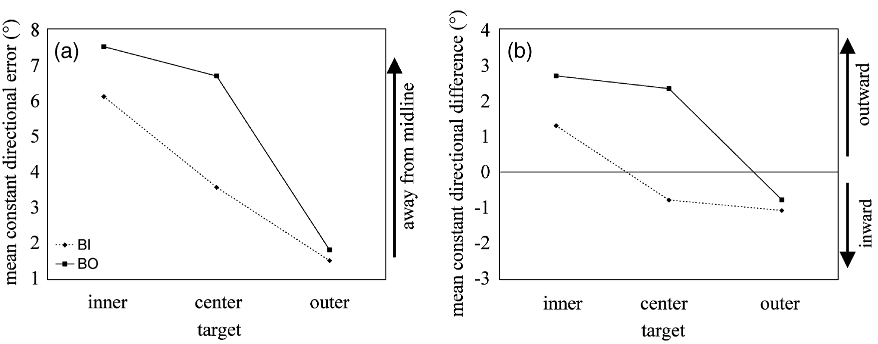

Fig. 12. (a) Mean constant directional errors to the inner (20°), center (40°), and outer (60°) targets in the BI (dotted line) and BO (solid line) conditions (Experiment 3). (b) Mean constant directional difference scores for children's responses to the inner, center, and outer targets in the BI (dotted line) and BO (solid line) conditions.

$p < .005$. Tests of simple effects revealed a significant increase in error over delays for the inner target, $F(1,47) = 15.95$, $p < .001$, but not for the other targets, all Fs $(1,47) < 2.6$, *ns*. (see Fig. 11). There was also a main effect of Target, Wilks' $\Lambda = .45$, $F(2,39) = 23.73$, $p < .001$, and a significant Target × Age interaction, Wilks' $\Lambda = .75$, $F(2,39) = 6.38$, $p < .005$. Tests of simple effects revealed a significant Target effect for both age groups: 6-year-olds, $F(2,80) = 20.65$, $p < .05$, and 11-year-olds, $F(2,80) = 15.11$, $p < .05$. In both cases, these target effects largely reflect the geometric biases reported in the previous experiments. Specifically, 6-year-olds' responses to the inner target ($M = 6.09°$) were more strongly biased away from midline than were responses to the center target ($M = 5.43°$) and outer target ($M = .8°$). Similarly, 11-year-olds' responses were more strongly biased away from midline closer to this axis (inner: $M = 7.52°$; center: $M = 4.73°$; and outer: $M = 2.56°$).

4.2.1.1. Directional difference scores. An important focus of this experiment was whether geometric and experience-dependent effects could be separated without using the subtraction technique. The analyses of constant error above demonstrate that this is the case. Here we asked whether the subtraction technique introduces biases relative to the results reported above. As in Experiment 2, we removed geometric effects by subtracting the mean constant directional error to each target location at each delay in Experiment 1 from the data from the associated targets and delays in the present experiment for each age group and side separately. The resulting constant directional difference scores were analyzed in a five-way MANOVA with Condition, Age, and Side as between-subjects factors and Delay and Target as within-subjects factors. The central question was whether there were significant Condition effects, paralleling results from the analyses reported above. This was indeed the case. Results from the five-way MANOVA revealed a significant Target × Condition interaction, Wilks' $\Lambda = .76$, $F(2,39) = 6.04$, $p < .01$. Simple effects tests indicated that errors to the center target differed significantly depending on condition, $F(1,46) = 9.56$, $p < .005$, whereas errors to the inner, $F(1,46) = 1.08$, *ns*, and outer, $F(1,46) = .09$, *ns*, targets did not differ across conditions. Additional simple effects tests indicated that responses across the three targets differed significantly in both the BI condition, $F(2,80) = 4.07$, $p < .05$, and the BO condition, $F(2,80) = 8.85$, $p < .001$.

The Target × Condition interaction is shown in Fig. 12b. Relative to the geometric effects measured in Experiment 1, responses to the inner targets were biased outward, whereas responses to the outer targets were biased inward. Most dramatically, response errors to the center target *changed sign depending on the bias condition*. Children in the BO condition made outward errors to the center target relative to the geometric effects in Experiment 1, whereas children in the BI condition made inward errors to the center target relative to errors in Experiment 1. These results once again point toward children's use of long-term memory cues.

4.2.1.2. Analyses of directional error over learning. As in Experiment 2, we examined whether biases toward a long-term memory of the target locations increased across blocks of trials; however, we did not use the subtraction technique in these analyses. Rather, we computed median directional errors to each target location in each block of trials. Median directional errors were analyzed in a four-way MANOVA with Age and Condition as between-subjects factors and Block (1, 2, 3, 4) and Target as within-subjects factors. Only Block effects are reported below. There was a significant Block × Target × Condition interaction, Wilks' $\Lambda = .46$, $F(6,19) = 3.71$, $p < .025$. This interaction is shown in Fig. 13. Tests of simple effects revealed a significant Block effect, $F(3,144) = 3.59$, $p < .05$, and a significant Block × Target interaction, $F(6,144) = 3.61$, $p < .05$, in the BI condition. Additional tests of simple effects revealed a significant Block effect to the center target, $F(3,144) = 6.08$, $p < .025$, and the outer target, $F(3,144) = 7.9$, $p < .01$, but not the inner (biased) target, $F(3,144) = .08$, *ns*. As can be seen in Fig. 13a, children showed a decrease in

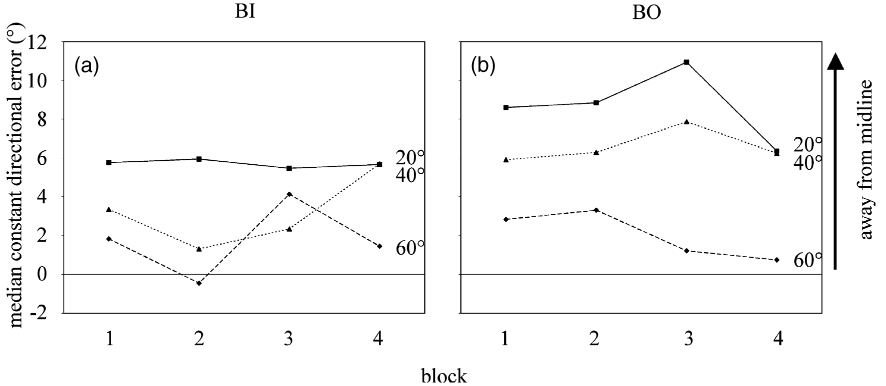

Fig. 13. Median constant directional errors for children's responses to the inner (20°), center (40°), and outer (60°) targets across the four blocks of trials in the BI condition (a) and BO condition (b) (Experiment 3).

outward bias across Blocks 1 and 2 to both the center and outer targets in the BI condition, that is, responses to both targets were pulled inward toward the biased location. In Blocks 3 and 4, however, there was some recovery from this effect. There was also a significant Block effect in the BO condition, $F(3,144) = 3.18$, $p < .05$ (Block 1: $M = 5.78°$; Block 2: $M = 6.14°$; Block 3: $M = 6.67°$; and Block 4: $M = 4.49°$). As can be seen in Fig. 13b, outward directional errors generally increased across Blocks 1–3, particularly to the inner and center targets. In Block 4, however, directional errors were smaller, once again suggesting some recovery from the pull toward the biased location.

As in the analyses of constant directional error above, we examined whether these Block-related effects were statistically reliable for each age group. We conducted a three-way MANOVA for each age group separately with Block and Target as within-subjects factors and Condition as a between-subjects factor. There was a marginally significant Block × Target × Condition interaction for the 6-year-olds, $F(6,72) = 2.17$, $p = .055$, and a significant Block × Target × Condition interaction for the 11-year-olds, $F(6,72) = 2.64$, $p < .025$. Thus, both age groups contributed to the three-way interaction reported above.

4.2.2. Variable directional error

In a final set of analyses, we examined the variability of children's responses over delays to the different targets in the two bias conditions. Mean variable directional error was analyzed using a five-way MANOVA with Condition, Age, and Side as between-subjects factors and Delay and Target as within-subjects factors. As in Experiments 1 and 2, variability increased significantly across Delays, Wilks' $\Lambda = .67$, $F(1,40) = 19.53$, $p < .001$ (short: $M = 5.59°$; long: $M = 6.62°$). Results also revealed a significant Target × Condition interaction, Wilks' $\Lambda = .63$, $F(2,39) = 11.38$, $p < .001$. Tests of simple effects indicated that variability differed significantly across conditions for the inner target, $F(1,46) = 8.12$, $p < .01$ (BI: $M = 5.28°$; BO: $M = 6.67°$), the center target, $F(1,46) = 5.06$, $p < .05$ (BI: $M = 6.84°$; BO: $M = 5.62°$), and the outer target, $F(1,46) = 12.41$, $p < .005$ (BI: $M = 6.79°$; BO: $M = 5.44°$). This interaction was largely due to a reduction in variability to the biased location in each condition relative to the non-biased locations, suggesting that children benefited from repeated practice to the biased location.

4.3. Discussion

As in the previous two experiments, children's responses generally showed large geometric biases—responses were biased away from midline (toward spatial prototypes). Moreover, responses became more variable over delays. Of central importance here, however, responses were systematically biased toward the most frequent target, particularly for responses to the center target. In the BI condition, responses to this target were pulled inward, and in the BO condition, responses to this target were pulled outward. These effects generalized across analyses of both constant directional errors and directional difference scores. In addition, analyses of learning effects indicated that experience-dependent biases were constructed across the first two blocks of trials. Thus, responses to the same absolute location in space shifted systematically depending on children's trial-to-trial experience in the task.

Importantly, experience-dependent effects were evident in the responses of children in both age groups. There were significant differences in 6-year-olds' responses to the center target across bias conditions, and 11-year-olds' responses showed a trend in this direction. Moreover, both age groups showed significant changes in response errors over learning. These data demonstrate that there is developmental *continuity* in experience-dependent effects. And, together with results from Experiments 1 and 2, these data show that geometric category biases, delay-dependent biases, and experience-dependent biases are separable aspects of older children's recall responses.

5. General discussion

The goal of this study was to examine whether there is long-term continuity in the processes that underlie spatial memory performance over development, as proponents of the CA model and DFT have proposed. In particular, we tested whether three characteristics of 3-year-olds' and adults' spatial recall responses—geometric effects, delay-dependent effects, and experience-dependent effects—were also separable aspects of 6- and 11-year-olds' responses. Convergent results from three experiments provide strong evidence of developmental continuity. In Experiment 1, we obtained a measure of geometric effects at individual locations in the task space. As expected based on previous experiments (e.g., Hund & Spencer, 2003; Huttenlocher et al., 1994; Sandberg, 1999), children showed systematic biases away from the midline axis (for similar effects, see Engebretson & Huttenlocher, 1996; Sandberg et al., 1996; Schiano & Tversky, 1992; Tversky, Sattath, & Slovic, 1988). In addition, these geometric biases increased systematically over delays, demonstrating that 6- and 11-year-olds' memory for locations is subject to delay-dependent drift.

Having established a baseline measure of geometric effects, we then altered the spatial layout of the target set within each category in Experiment 2. We hypothesized that responses should be biased toward an average remembered location. Six-year-olds' responses showed the hypothesized experience-dependent effects in analyses of both mean responses over delays and median responses over learning, whereas 11-year-olds' responses did not. In the final experiment, we manipulated children's long-term memory of the target locations in a different way: we altered how often they responded to each location. Now, both age groups showed evidence of experience-dependent effects in analyses of mean responses and median responses over learning.

Taken together, results from Experiments 1 to 3, in conjunction with results from previous research with 3-year-olds (Schutte & Spencer, 2002) and adults (Spencer & Hund, 2002) using the *same* task and the *same* target locations across similar delays, strongly suggest developmental continuity in the processes that underlie spatial recall performance. This provides initial support for claims of continuity by proponents of the CA model and DFT. However, can we take these claims of continuity to a more detailed level of specificity? In particular, can the CA and DFT models capture the details of developmental change revealed in these studies via quantitative, continuous change of model parameters? And beyond this question, do the models make novel predictions regarding *how* continuous changes in model parameters occur? Clearly, these are challenging questions that few models in the literature have effectively addressed. Nevertheless, evaluating the models with regard to these issues provides an index of the current state of theory in the spatial domain and identifies concrete goals for the future.

5.1. Developmental changes in spatial memory

Before evaluating the two models, we first provide an overview of three developmental trends that each model must explain. First, children show a transition in geometric effects around 6 years of age (Huttenlocher et al., 1994; Sandberg, 1999; Sandberg et al., 1996). In the present study, both 6- and 11-year-old children showed consistent biases away from midline (see also Hund & Spencer, 2003; Sandberg, 1999). By contrast, when 3-year-old children responded to the same locations in the same task, they showed biases *toward* midline (Schutte & Spencer, 2002). Second, the models must account for a reduction in the magnitude of delay-dependent effects across development. Specifically, in our previous studies, 3-year-olds typically made 10–20° errors following delays of 5–10 s (Schutte & Spencer, 2002). By contrast, 6- and 11-year-old children typically made 6–8° errors over delays in the present report, whereas adults' errors generally ranged between 3° and 5° (Spencer & Hund, 2002).

The third developmental change in spatial recall is a reduction in the magnitude of experience-dependent effects. As discussed previously, young children are strongly influenced by long-term memory cues. At a very early age—8 to 10 months—infants fail to find an object clearly hidden at a "B" location after a 3 s delay in the A-not-B task (e.g., Marcovitch & Zelazo, 1999; Smith et al., 1999; Thelen et al., 2001; Wellman, Cross, & Bartsch, 1987). Similarly, in an A-not-B version of the spaceship task with A and B separated by 20°, 3-year-olds erred roughly 10° toward A on the B trials following a 10 s delay (Schutte & Spencer, 2002; see also Spencer et al., 2001). In the present study, we demonstrated that 6- and 11-year-old children show experience-dependent effects; however, the size of these effects was greatly reduced, typically, 2–4°. Moreover, comparison of results from Experiments 2 and 3 suggest that there are improvements in the precision of location information in long-term memory between 6 and 11 years. Despite these developmental improvements, even adults are sensitive to experience-dependent effects (Spencer & Hund, 2002). As might be expected from the results reported here, however, adults' errors were quite small—experience-dependent biases tended to be roughly 1–2°.

5.2. Evaluating the CA model

A clear strength of the CA model is its account of geometric biases. According to this model, the large bias when participants responded to targets near midline (e.g., 20°) in the present study reflects strong bias toward spatial prototypes, and the reduction in bias to targets close to spatial prototypes (e.g., 80°) reflects overlap between fine-grained and categorical information. The CA model also provides a strong account of delay-dependent biases. According to Huttenlocher et al. (1991), fine-grained information becomes less certain over delays. As this occurs, bias toward spatial prototypes increases, as does response variability. Recent simulations of the CA model using Bayesian approaches formalize this proposal: as fine-grained information becomes less certain, optimal performance requires an increase in both bias and variability (Huttenlocher et al., 2000).

The third class of effects reported here—experience-dependent biases—is less clearly handled by the CA model, in part, because a full model that incorporates fine-grained information, prototypical information, *and* induced category information has not been proposed. Conceptually, such a model could account for biases toward an average remembered location in Experiment 2 and toward the most frequent location in Experiment 3. These effects would emerge via the same type of weighting process described above for spatial prototypes (see Huttenlocher et al., 2000). Nevertheless, one result from the present study challenges the induced category view. According to the induced category version of the CA model proposed by Huttenlocher et al. (2000), responses to infrequent targets should be less biased toward the center of an induced category relative to responses to the same targets in an equal frequency condition. This occurs because category membership is less certain for the infrequent items; therefore, category information is weighted less heavily (Huttenlocher et al., 2000). We found the opposite results for 11-year-olds, who showed stronger induced category effects to the infrequent targets in our biased (Experiment 3) versus equal frequency (Experiment 2) conditions.

5.2.1. Capturing developmental change

Although the CA model provides an account for several key results of the present study, a fundamental question is whether this model can capture long-term continuity in process via quantitative, continuous change in the model over development. At the present time, the CA model provides an incomplete account of developmental change. According to proponents of this model, the transition in geometric effects is caused by a developmental change in children's ability to sub-divide space into smaller categories (e.g., Huttenlocher et al., 1994). But the processes that underlie this developmental change, and how these processes change across the transition, have not been specified in detail. One possibility is that the change in geometric effects is related to feedback children receive when finding hidden objects in different situations (Newcombe & Huttenlocher, 2000). Children who spontaneously use cues such as the midline axis of a table to subdivide space will, on average, find objects faster then children who do not, because subdivision limits the size of the spatial region considered during recall. Through repetition in different situations, children might discover that subdivision is a general strategy useful in a variety of tasks.

This proposal is consistent with a recent Bayesian description of the CA model (Huttenlocher et al., 2000). By this view, people pursue an optimal weighting of cues to produce maximally accurate responses. Importantly, the optimal solution depends on the certainty of the to-be-combined information. For instance, if both fine-grained and categorical information are uncertain early in development, treating large, empty spaces as one category might produce optimal—but biased—responses. Later in development when spatial information is more certain, two categories might produce optimal responses. Thus, it is possible that quantitative changes in the precision of spatial information drive the transition in geometric effects via a Bayesian process. This Bayesian description might provide insights into the reduced magnitude of delay- and experience-dependent effects as well. These reductions in error suggest that fine-grained information is becoming systematically more certain over development. As this occurs, optimal performance requires less reliance on categorical information and, consequently, responses become less biased and less variable.

In summary, the CA model provides a strong account of the geometric and delay-dependent results from the present study; however, our results pose challenges for a CA account of experience-dependent effects. With regard to development, the CA model provides only a limited account of developmental changes in spatial memory. Nevertheless, a recent Bayesian description of the model suggests that it is possible to account for at least some developmental changes in spatial recall performance via continuous changes in the precision of fine-grained and categorical information.

5.3. Evaluating the DFT

One strength of the DFT is that provides an account of the second-to-second details of spatial memory processes. Thus, the DFT has the potential to make precise time-dependent predictions (see, for example, Erlhagen & Schöner, 2002). Moreover, this model provides a mechanistic account for why delay-dependent spatial drift is such a challenge in tasks with homogeneous spaces (for related ideas, see Compte, Brunel, Goldman-Rakic, & Wang, 2000). In the absence of strong input, self-sustaining peaks of activation can drift due to attraction toward the few inputs available or simply due to random fluctuations in activation. Importantly, delay-dependent drift can be counteracted by changing the characteristics of the local excitation/lateral inhibition function. In particular, peaks with strong, narrow local excitation and strong lateral inhibition resist motion. This occurs because it is very unlikely that neurons at the edges of such peaks will enter into locally excitatory interactions.

In addition to this account of delay-dependent effects, the DFT provides a strong account of experience-dependent effects. Such effects arise in the model due to the interplay between activation in working memory and input from long-term memory. Importantly, these processes can capture central details of our results. Earlier, we described how this characteristic of the model explains why 11-year-olds failed to show experience-dependent effects in Experiment 2, but did show such effects in Experiment 3. The DFT also provides an account of the learning effects reported here. Early in learning, activation peaks associated with the infrequent targets are strongly biased toward the frequent location because there is only a weak long-term memory of the infrequent targets. Later in learning, this bias is reduced as a stronger long-term memory of the infrequent targets is constructed.

The central limitation of the DFT, at present, is that it cannot account for the geometric biases we observed. Schutte and Spencer (2002) were able to model young children's bias toward midline by including a midline input, that is, a perceptual input reflecting children's perception of the midline symmetry axis of the task space. It is not possible, however, with the current form of the DFT to transform this attraction toward midline into a bias away from midline (for a related interpretation of midline biases, see Schiano & Tversky, 1992; Tversky & Schiano, 1989). We are currently developing a new version of the DFT to overcome this limitation (see Spencer & Schöner, 2000 for a model that moves in this direction).

5.3.1. Capturing developmental change

Can the DFT capture long-term continuity of process? Changes in delay- and experience-dependent biases over development might both be related to quantitative and continuous changes in a global characteristic of the model—the stability and spatial precision of self-sustaining peaks. Central to this *spatial precision hypothesis* is the observation that self-sustaining peaks with strong neuronal interactions—strong, narrow local excitation and strong lateral inhibition—are more stable, that is, they are more resistant to forces that might drive them to new (and inaccurate) spatial locations. Thus, a gradual shift over development from weak to strong interactions could account for the gradual reduction in the size of delay- and experience-dependent effects.

Dynamic fields with strong interactions will also show weak delay- and experience-dependent effects because a narrower self-sustaining peak is less likely to spatially overlap with inputs to the model—a necessary condition for spatial drift (see Schutte et al., in press). Furthermore, this account explains why children's variable errors decrease between 6 years and adulthood (see Spencer & Hund, 2002): more stable peaks are more resistant to drift, which reduces the trial-to-trial variability in peak position during memory delays (see Spencer & Schöner, 2000). Finally, if sustained activation in working memory is more stable from trial to trial, that is, if there is less drift, then the DFT predicts that activation in long-term memory will be less variable and more spatially precise as well. This would result from the coupling between working memory and long-term memory. The developmental differences in experience-dependent biases across Experiments 2 and 3 are consistent with this proposal (see also Schutte et al., in press).

Two connections to the extant literature also make the spatial precision hypothesis appealing. First, Thelen et al. (2001) modeled developmental changes in infants' performance in the Piagetian A-not-B task by changing the strength of neuronal interactions in the DFT. Thus, our proposal is formally linked to this previous work. Second, the proposal that spatial memory biases are reduced over development due, in part, to stronger lateral inhibitory connections is consistent with developmental changes in dorsolateral prefrontal cortex—a cortical region implicated in working memory performance with pervasive inhibitory connections to other cortical areas (for related ideas, see Diamond, 1990a, 1990b; Diamond, Cruttenden, & Neiderman, 1994).

In summary, the DFT provides a strong account of delay- and experience-dependent biases from the present study, but, in its current form, this model is missing an account of geometric biases. With regard to development, we proposed a spatial precision hypothesis that links developmental changes in delay- and experience-dependent effects to quantitative changes in a global characteristic of the model—the strength of neuronal interactions. Thus, the DFT can effectively explain two classes of developmental effects via long-term continuity of process.

5.4. Comparison of the models

Given that this is the first paper in the literature to discuss both the CA model and DFT in depth, we conclude our evaluation of the models by highlighting points of theoretical convergence and divergence. Our evaluation of the CA and DFT models clearly has revealed considerable conceptual overlap. Both accounts provide similar explanations for delay- and experience-dependent effects, and both accounts point toward a similar view of developmental change—gradual, continuous change in the precision of spatial information might underlie many of the effects reported in the literature. As such, these models should be viewed as generally complementary. They are, however, different types of accounts: the CA model provides a general framework for thinking about critical aspects of spatial memory, whereas the DFT provides a process account of how particular biases arise.

With regard to developmental change, both models are faced with the tough challenge of formalizing and testing specific accounts of what is changing over development. Lurking on the horizon, of course, is the question of *how* these changes occur. One possible approach to this question is to borrow ideas from connectionist modeling. For instance, a central characteristic of many neural network models is their ability for self-modification over the longer time scales of learning and development (e.g., Elman, 2001; Munakata & McClelland, 2003). It might be possible to construct a self-modifying version of the DFT that closes the loop on development, demonstrating that the long-term developmental continuity reported here can, indeed, arise from continuous processes (see Spencer & Schöner, 2003, for a discussion of these possibilities).

6. Conclusions

To our knowledge, the present paper provides the first strong evidence of long-term continuity in process across the span from 2–3 years to adulthood. Moreover, this is the first paper to ground such continuity within the context of two formal models (for other evidence of long-term continuity, see Case, 1998; Chi, 1978; Kail, 1993). Although our data do not preclude the possibility that development is marked by both continuities and discontinuities in process, they strongly support claims of developmental continuity by proponents of the CA model and DFT (e.g., Hund & Spencer, 2003; Newcombe & Huttenlocher, 2000; Schutte & Spencer, 2002; Spencer & Hund, 2002; Spencer et al., 2001).

It is important to note that these findings revealing continuity contrast with other prominent accounts of the development of spatial memory. For instance, Piaget and

Inhelder (1956) contended that spatial cognitive development was marked by qualitative changes in the logical structures that underlie spatial reasoning. As an example, metric memory for location was viewed as a late development because metric distinctions require the use of formal systems of measurement.[5] The claim of continuity is also inconsistent with recent nativist views that development is marked by discontinuities resulting from the early use and later penetration of particular behavioral modules. For instance, Hermer and Spelke (1996) identified an apparent discontinuity in children's performance (see also Hermer-Vazquez, Moffet, & Munkholm, 2001) that they attributed to the early use of a geometric module, which was later penetrated through the use of spatial language (see Learmonth, Nadel, & Newcombe, 2002; Learmonth, Newcombe, & Huttenlocher, 2001 for evidence against this view).

More broadly, our evidence of continuity has implications for general theories of development. In particular, both models examined here have ties to domain general approaches to development. The weighting perspective proposed by Newcombe and Huttenlocher (2000) has also been applied to the study of early word learning (Hollich et al., 2000). The dynamic field theory is grounded in a general theoretical approach—dynamic systems theory (Newell & Molenaar, 1998; Thelen & Smith, 1994; van Geert, 1998). Thus, evidence of continuity not only supports claims made in the context of two specific models, but also more general claims about the nature of developmental change beyond the spatial domain.

In conclusion, the present investigation provides strong evidence for long-term continuity, which has important implications for how spatial memory is conceptualized. We suspect, for instance, that the three classes of effects identified here play a role *in every spatial memory situation*. Consider a child seated at a cluttered desk in an elementary school classroom trying to recall the location of the pencil she used recently. When searching for her pencil, the child might be influenced by the pencil's typical location (experience-dependent effects). Likewise, she might organize her search by geometric categories, searching inside the desk and then on top of the desk. And, undoubtedly, the child's recall performance will be affected by the length of the memory delay. Thus, the effects and theoretical processes reported here might yield new insights into how children organize their spatial activities in a diverse array of settings, providing a continuous bridge across situations and development.

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[5] It is important to note that Piaget did make some claims about continuity of process. For instance, he proposed that the processes of adaptation and organization operate across the life-span. Nevertheless, discontinuities in mental structures within particular domains of thinking (such as spatial reasoning) formed the core of his cognitive developmental theory.

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Appendix A

Distance errors were computed using the same *x–y* endpoint coordinates used in the analysis of directional error (see Method of Analysis). Positive distance errors indicate that children overshot a target, while negative distance errors indicate that children undershot a target. As with analyses of directional error, we removed distance errors associated with slight deviations in IRED position caused by the location of the IREDs on the top of the index finger. Specifically, the mean distance error for the 0 s delay trials to each target for each participant was subtracted from the distance errors to the corresponding target at the 5–20 s delays. These adjusted distance errors were used in all subsequent analyses. As with analyses of directional error in Experiment 1, we began our analyses by examining constant and variable distance errors to targets to the left and right of midline. These analyses were followed by analyses of distance error to the center (0°) target.

A.1. Responses to the left and right targets

A.1.1. Constant distance error

Mean constant distance errors were analyzed using a four-way Multivariate Analysis of Variance (MANOVA) with Age (6 years, 11 years) and Separation (10°, 20°, 40°, 60°, and 80°) as between-subjects factors and Delay (5, 10, 15, and 20 s) and Side (left, right) as within-subjects factors. Results revealed a main effect of Age, $F(1, 50) = 8.59$, $p < .005$, and a significant Delay × Age interaction, Wilks' $\Lambda = .79$, $F(3, 48) = 4.30$, $p < .01$. Tests of simple effects indicated that 6-year-olds consistently overshot the targets across all delays, $F(3, 150) = .93$, *ns* (5 s: $M = .66$ cm; 10 s: $M = .75$ cm; 15 s: $M = .60$ cm; 20 s: $M = .79$ cm), while the 11-year-olds overshot the targets less as the memory delays increased, $F(3, 150) = 6.07$, $p < .025$ (5 s: $M = .51$ cm; 10 s: $M = .23$ cm; 15 s: $M = .08$ cm; 20 s: $M = .02$ cm).

Results also showed a significant main effect of Separation, $F(4, 50) = 7.52$, $p < .001$. Children overshot the targets at 60° ($M = 1.29$ cm) to a greater extent than in the other conditions (10°: $M = -.10$ cm; 20°: $M = .23$ cm; 40°: $M = .49$ cm;

80°: $M = .36$ cm). Although it is not clear why children showed an increase in distance error in the 60° condition, this result might be related to how children compensate for differences in arm inertia for movements in different directions. Gordon et al. (1994a, 1994b) reported that adults made systematic distance errors that paralleled direction-dependent changes in arm inertia. Importantly, anisotropies in arm inertia follow an inertial ellipse with major axes oriented between 30° and 60° for planar reaching movements starting from body midline. It is possible that children, like adults, take into account maximal and minimal inertial forces acting at the tip of the finger when planning movement distances, and, in some cases, overcompensate for such forces leading to larger distance errors.

A.1.2. Variable distance error

Mean variable distance errors were analyzed in a four-way MANOVA with Age and Separation as between-subjects factors and Delay and Side as within-subjects factors. Results revealed a significant main effect of Delay, Wilks' $\Lambda = .72$, $F(3, 48) = 6.39$, $p < .01$. As with analyses of directional error, distance errors became more variable over delays (5 s: $M = 1.44$ cm; 10 s: $M = 1.49$ cm; 15 s: $M = 1.69$ cm; 20 s: $M = 1.70$ cm). Results also revealed a significant main effect of Age, $F(1, 50) = 17.21$, $p < .001$. Six-year-olds' distance responses were significantly more variable ($M = 1.80$ cm) than 11-year-olds' distance responses ($M = 1.36$ cm).

A.2. Responses to the center target

A.2.1. Constant distance error

Mean constant distance errors to the center (0°) target were analyzed using a three-way MANOVA with Age (6 years, 11 years) and Separation (10°, 20°, 40°, 60°, 80°) as between-subjects factors and Delay (5, 10, 15, and 20 s) as a within-subjects factor. Results revealed a significant main effect of Delay, Wilks' $\Lambda = .84$, $F(3, 48) = 3.13$, $p < .05$, and a significant Delay × Age interaction, Wilks' $\Lambda = .81$, $F(3, 48) = 3.87$, $p < .05$. Tests of simple effects indicated that, as with distance errors to the left and right targets, 6-year-olds consistently overshot the center target across all delays, $F(3, 150) = 2.98$, *ns* (5 s: $M = .46$ cm; 10 s: $M = .05$ cm; 15 s: $M = .44$ cm; 20 s: $M = .29$ cm), while 11-year-olds overshot the center target less as the memory delays increased, $F(3, 150) = 3.79$, $p < .025$ (5 s: $M = .34$ cm; 10 s: $M = .23$ cm; 15 s: $M = .02$ cm; 20 s: $M = -.14$ cm).

A.2.2. Variable distance error

Mean variable distance errors were analyzed in a 3-way MANOVA with Age and Separation as between-subjects factors and Delay as a within-subjects factor. Results revealed a significant main effect of Delay, Wilks' $\Lambda = .80$, $F(3, 48) = 3.96$, $p < .05$. As with variability to the left and right targets, variability in distance responses to the center target increased across delays (5 s: $M = 1.36$ cm; 10 s: $M = 1.48$ cm; 15 s: $M = 1.54$ cm; 20 s: $M = 1.59$ cm). Results also revealed a significant main effect of Age, $F(1, 50) = 13.26$, $p < .01$. As in the analyses above, variability was significantly greater for the 6-year-olds ($M = 1.66$ cm) than for the 11-year-olds ($M = 1.32$ cm).

A.3. Summary of distance error analyses

Analyses of constant distance errors to the left, right, and center targets showed a consistent pattern of results that differed substantially from analyses of constant directional error (see Results of Experiment 1). Six-year-olds consistently overshot the targets across delays. The absence of delay-dependent changes in distance error for this age group contrasts sharply with the systematic drift in directional error over delays. Eleven-year-olds' distance responses actually improved as the memory delay increased. This result contrasts with the systematic *increase* in directional error over delays. Moreover, separation-related distance error effects were isolated to a single condition—the 60° condition—while directional errors differed systematically across the 10–80° separations, with much lower constant directional errors to the center target. These differences between constant distance and directional error are consistent with previous studies showing that direction and distance are coded independently (e.g., Ghez et al., 1997; Gordon et al., 1994a, 1994b; Huttenlocher et al., 1991), and have different time-dependent signatures in studies of motor planning (Ghez et al., 1997; Rosenbaum, 1980).

Analyses of variable distance errors to the left, right, and center targets were more comparable to analyses of variable directional error. Both sets of analyses indicated that children's responses became more variable over delays, and that 6-year-olds' responses were more variable than 11-year-olds' responses. There was, however, one important difference across analyses of distance and directional variable errors—variable distance errors to the center target were comparable in magnitude to variable distance errors to the left and right targets. This was not the case with variable directional error, which was consistently smaller for responses to the center target.

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