Developmental Psychology
2013, Vol. 49, No. 2, 232–242

0012-1649/13/$12.00 DOI: 10.1037/a0028334

The Emergence of Flexible Spatial Strategies in Young Children

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The development of spatial navigation in children depends not only on remembering which landmarks lead to a goal location but also on developing strategies to deal with changes in the environment or imperfections in memory. Using cue combination methods, the authors examined 3- and 4-year-old children's memory for different types of spatial cues and the spatial strategies that they use when those cues are in conflict. Children were taught to search for a toy in 1 of 4 possible hiding locations. Children were then tested on transformations of the array of locations. The transformations dissociated the different types of cues by putting them in conflict with one another. The authors were especially interested in the use of a majority strategy, by which children choose to search in the location indicated by the greatest number of cue types rather than relying on a preferred cue type. Children's memory for spatial cues and their strategies varied both by age and by experimental setup. In Experiment 1, both 3- and 4-year-old children preferred to use the distinct landmarks coincident with the hiding locations over any other types of cues and showed no use of a majority strategy. However, in Experiment 2, when the coincident landmarks were moved adjacent to the hiding locations, both 3- and 4-year-old children preferred to search in the position of the hiding location relative to the array. Furthermore, 4-year-old children in Experiment 2 showed better memory for individual types of cues and the emergence of a majority strategy.

Keywords: spatial cognition, spatial memory, cue combination, landmarks, spatial development

Traditionally, developmental studies of spatial cognition have focused on when children begin to use landmarks (e.g., Acredolo, 1978a; Acredolo & Evans, 1980b; Bremner, 1978; Bremner & Bryant, 1977) and which landmarks children use for navigation (e.g., Foreman, Warry, & Murray, 1990; Laurance, Learmonth, Nadel, & Jacobs, 2003; Learmonth, Nadel, & Newcombe, 2002). However, spatial orientation depends not only on remembering landmarks but also on knowing how to use those landmarks to relocate a previously visited location. Whereas most adults are able to use multiple types of spatial landmarks and spatial landmark strategies (Bell, 2002), young children do not demonstrate mature spatial orientation until around 10 years of age (Laurance et al., 2003; Lehnung et al., 1998; Leplow et al., 2003; Overman, Pate, Moore, & Peuster, 1996). Evidence suggests that it is between the ages of 2 and 5 that children begin to show the emergence of more mature spatial strategies (Foreman et al., 1990). Our goal was to investigate the emergence of spatial strategies during this period of development. To accomplish this, we examined how children use multiple sources of spatial information to make inferences about the location of a hidden object.

At 3 years of age, children are just beginning to reliably encode locations using landmarks that are displaced from the hiding location (DeLoache & Brown, 1983; Laurance et al., 2003). This type of encoding is both allocentric (i.e., in reference to the location's relationship to surrounding landmarks) and noncoincident (i.e., using landmarks that are neither a property of the hiding location nor are they located in the same place as the hiding location). This is in contrast to the types of strategies that younger children use. There are at least two types of strategies younger children may use. One is egocentric encoding, by which a location is encoded in reference to one's own body position. A second is a beaconing strategy using coincident landmarks or features. Using a beaconing strategy, children encode a location using properties of the location itself, such as the color of a box, or using landmarks that are coincident with the hiding location, such as a pillow under which one has hidden a toy.

The development of an allocentric frame of reference and the use of both coincident and noncoincident landmarks are critical for the development of mature spatial strategies. For example, when trying to remember the location of one's parked car, one could encode the location relative to one's body position (e.g., to one's left). However, after one moves, the location in reference to one's body position changes, and this information is no longer useful. Similarly, if one encodes the location using only coincident spatial information (i.e., the features of the location itself, such as the color or model of one's car), one may find it difficult to relocate the vehicle in the presence of other cars that have similar features. Encoding the location in reference to multiple sources of informa-

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This research was supported in part by funding from the University Committee on Research to Lucia F. Jacobs. The views expressed are the authors' and do not necessarily represent those of the University Committee. We thank Alison Gopnik for helpful comments, discussions, and access to university-affiliated preschools and the Institute of Human Development. We also thank Brian Waismeyer and Chris Lucas for helpful comments on the article.

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tion, both coincident and noncoincident, allows one to orient reliably in the world while still keeping track of previously visited locations.

In general, whereas 3-year-old children can use noncoincident landmarks, between the ages of 3 and 5 years, children begin to use landmarks at increasingly further distances from the target location. In one study, children's performance on three different spatial tasks (including an eight-arm radial arm maze, a dry simulation of the water maze, and an open-field task) improved by the age of 5, whereas there were no differences between younger age groups (Overman et al., 1996). Specifically, although many of the older children used noncoincident, distal landmarks to solve the tasks, only a small but significant percentage of the younger children were able to do so. Moreover, in a touch-screen search task in which only noncoincident landmarks were available, 3-year-old and 4-year-old children showed significantly different search patterns in a landmark shift trial. When the landmark closest to the hiding location was shifted, 4-year-old children searched in the original location consistent with all the nonshifted items on the screen. In contrast, 3-year-old children searched in the location closest to the shifted landmark (Sutton, 2006). This suggests that the younger children preferred to use the most proximal landmark over the information provided by all the other available landmarks. Thus, it appears that between the ages of 3 and 4, children are beginning to make greater use of multiple sources of spatial information, including more distal noncoincident landmarks.

However, simply developing an allocentric frame of reference is not sufficient for accurate spatial orientation. The environment is constantly changing both because of our movement within it and because of movement external to ourselves. For example, searching for one's car in a parking lot using only the locations of other nearby parked cars is generally an unreliable strategy, as the other cars may be moved before one returns. Adults solve this problem by using multiple sources of spatial information to remember a location, such as remembering that one parked a green car, near the coffee cart, at the north end of the parking lot. This description includes at least three types of spatial cues, coincident cues (green color of the car), relative position cues (near the coffee cart), and absolute position cues (north end). If one of these cues were to change (e.g., if the coffee cart were to move to a new location), an adult could easily use the remaining cues to relocate the car, whereas a child might have a difficult time if he or she had not developed the use of flexible strategies.

One way to determine the spatial strategies of children is to use methods similar to those used to study classic cue combination in adults. In cue combination studies, Bayesian psychophysical models have been developed to explain optimal integration of multisensory cues in the judgment of object features, such as height and texture (Ernst & Banks, 2002). Considering the problem of spatial search from the Bayesian perspective, the problem is that of determining which location has the highest posterior probability of being the true location one is searching for, given one's previous beliefs about the location and one's memory for the spatial cues associated with the location. To do this, one must also take into account the reliability of the associated landmarks to weight them accordingly, giving those that are more reliable a heavier weight and those that are less reliable a lower weight. Animal studies using these methods have specifically investigated the use of a flexible spatial strategy called the "majority strategy" (Gibbs, Lea, & Jacobs, 2007; Waisman & Jacobs, 2008; Waisman, Lucas, Griffiths, & Jacobs, 2011).

The *majority strategy* can be defined as a Bayesian model of spatial search in which a single cue is never so reliable that it outweighs the combined weight of any other two or more cues. Using the example described above, if one parked a green car, near the coffee cart, at the north end of the parking lot and the coffee cart moved but was still visible, there would now be two types of cues (green car, coincident; north end, absolute position) indicating one location, whereas the coffee cart (relative position cue) would indicate a different location. If a person were using a majority strategy to relocate her or his car, she or he would choose to search for her or his car in the location indicated by both the coincident and absolute position cues rather than by the location indicated by only one type of cue, relative position cues. This would happen regardless of which cue types were in conflict.

To illustrate this point further, if the color of the car happened to change instead of the position of the coffee cart, a person using a majority strategy would attempt to drive away with the car in the location indicated by the coffee cart and the position at the north end of the parking lot, even if it meant driving away in a white car instead of a green one. A person using a majority strategy may believe that the color of a car is relatively stable and therefore that coincident cues should be weighted quite highly. However, they would never weight color more than the combination of two or more other cue types. The majority strategy stands in contrast with other proposed models of spatial decision making. For example, in a hierarchy strategy, participants choose search locations on the basis of their preference for one particular type of cue. Using a hierarchy strategy, if color were the most highly weighted cue, one would always search first for a green car, regardless of where it was located in reference to the relative or absolute position cues.

The use of a majority strategy has been demonstrated in nonhuman animals in two studies on squirrels. Both fox squirrels (*Sciurus niger*) and flying squirrels (*Glaucomys volans*) were able to overcome their preferences and search at a location indicated by two types of landmarks rather than at the location indicated only by the one type of landmark they preferred (Gibbs et al., 2007; Waisman & Jacobs, 2008). To do this, squirrels had to integrate the information from all three landmark types to discover that a majority of the spatial information available to them at the time of search coincided with one particular location. Furthermore, the fox squirrels' pattern of choices was consistent with a Bayesian model of their behavior that corresponds with a majority strategy (Waisman et al., 2011).

To investigate at what age children are able to use a majority strategy when presented with conflicting spatial cue information, we used the same small-scale tabletop task previously developed for spatial studies on squirrels. One concern with a small-scale tabletop task was whether children would use allocentric encoding, and thus use all the available types of cues in such a task. However, previous research had shown that preschool-age children actually found it easier to encode the hidden location of a toy using allocentric encoding than egocentric encoding in a similar small-scale tabletop task (Haun, Call, Janzen, & Levinson, 2006).

We explored children's use of landmarks and landmark strategies in two experiments in which we manipulated three types of spatial cues: absolute position cues, relative position cues, and coincident cues. In Experiment 1, we first determined children's preferred cue type using a hierarchical test in which all types of cues were dissociated from one another. Next we investigated their use of a majority strategy in a majority test that pitted their preferred cue type against two other cue types. To establish whether children at this age were encoding all three types of cues, we also included three single-cue tests, one for each type of cue. In single-cue tests, only one type of cue was available for orientation.

In Experiment 2, we evaluated how children's preferences and spatial strategies changed when only provided with noncoincident cues. We predicted that when only noncoincident cues were available, children would rely less on a coincident cue-based strategy and would be more likely to pay attention to all the available spatial information. This should lead them to rely on more distinctly spatial strategies, and would in turn reveal the use of a majority strategy. Furthermore, we included a second condition in Experiment 2 to verify that children were indeed using an allocentric frame of reference in our task.

Experiment 1

The purpose of this study was to determine which types of landmarks preschool-age children encode when attempting to remember a discrete location and how they use those landmarks when they are in conflict with one another. Children were taught to find a toy in one of four discrete locations. The locations were marked by green plastic boxes set up in a square array on a child-sized table. Each box was distinguished by a unique ceramic figurine attached to the top of it (see Figure 1a). The target location could be encoded using any one or a combination of three types of spatial cues: absolute position cues, relative position cues, and coincident cues. The absolute position of the target location was indicated by its position on the table or in the room. The relative position of the target location was indicated by its position relative to the positions of the other three boxes in the square array on the table. The coincident cues of the target location were composed of the unique features of the ceramic figurine associated with the box, such as the shape, color, and pattern of the ceramic figurine. All ceramic figurines were distinct from one another in shape, color, and pattern. During testing, the locations and the ceramic figurines were shifted to determine which of the three possible cue types children preferred to rely on and whether children would use a majority strategy when the cues were in conflict with one another.

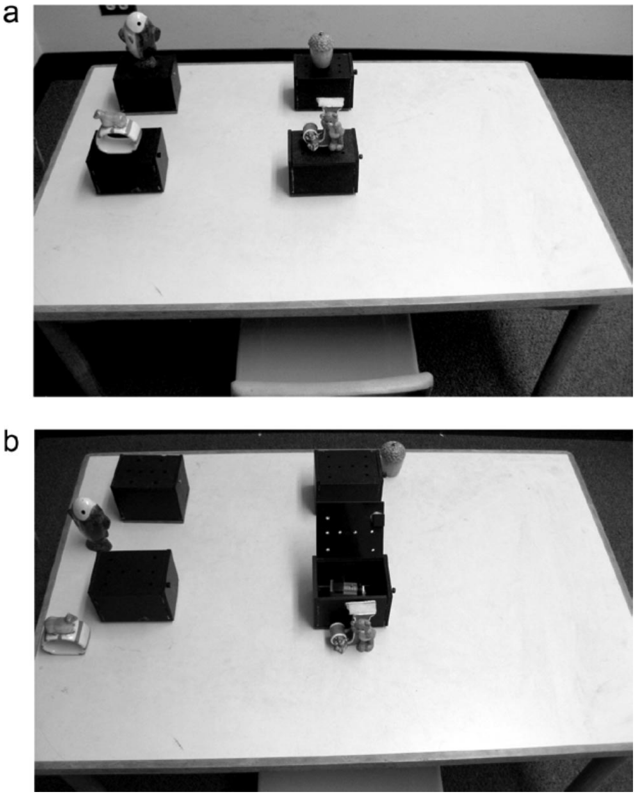

Figure 1. a: Experiment 1 setup with coincident cues on top of the boxes. b: Experiment 2 setup with proximal cues adjacent to the boxes.

We used two types of test configurations: cue combination and single-cue tests. There were two cue combination test configurations, the hierarchy and majority tests (see Figure 2), and three single-cue test configurations, one for each type of cue (see Figure 3). Thus, each child participated in five test trials: a hierarchy test, a majority test, and three single-cue tests. The order of the cue combination tests was the same for all children. Each child participated in the hierarchy test first, followed by the majority test. These tests were then followed by the single-cue tests. The order of the single-cue tests was counterbalanced across children.

In the hierarchy test, the positions of the boxes and figurines were moved so that each cue type—coincident, relative, or absolute—indicated a different location (see Figure 2b). The child's choice in the hierarchy test indicated which type of cue she or he preferred to rely on when all three types were in conflict with one another.

In the majority test (see Figure 2c), one location, labeled the preferred cue location, remained consistent with the child's preferred cue type (e.g., location D in Figure 2c), whereas a different location, labeled the majority location, was consistent with the other two cue types (e.g., location A in Figure 2c). The remaining two locations were distractor locations (e.g., locations B and C in Figure 2c). If children continued to search in the location consistent with their preferred cue type, this would suggest that, in contrast with animal studies, children do not use a majority strategy. However, if children chose to search in the majority location over the preferred cue location, this would indicate that they were using a majority spatial strategy. We predicted that children would primarily choose the location consistent with the coincident cues in the hierarchy test (e.g., location D in Figure 2b), but would choose the majority location (e.g., location A in Figure 2c) over their preferred cue location (e.g., location D in Figure 2c) in the majority test.

The three single-cue tests (see Figure 3b–d) evaluated the child's reliance on and memory for each individual type of cue. Thus, for each single-cue test, only one of the four possible locations was consistent with the individual type of cue being evaluated, and all other locations were considered distractors.

Method

Participants. The sample consisted of 25 preschool-age children (M = 48.80 months, SD = 7.81, range = 36.53–59.21 months) recruited at preschools affiliated with the University of California, Berkeley. The sample was primarily middle- to upper-middle class based on previous analysis of the schools, but no

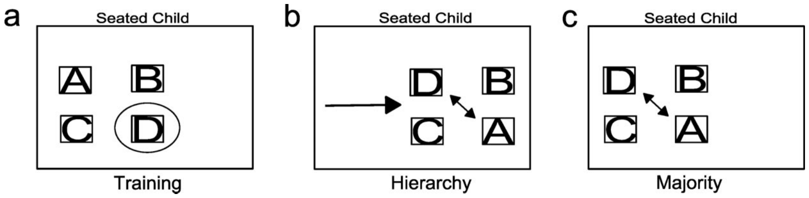

Figure 2. Experiment 1 cue combination tests: The large square indicates the table at which the child was seated across from the experimenter. There were four boxes on the table, indicated by the four smaller boxes in the figure. Each box had a unique figurine placed on top of it, indicated by the letters *A*, *B*, *C*, and *D*. Drawing is not to scale. Children could use three types of spatial cues to remember the trained location: coincident, indicated by the letters *A*, *B*, *C*, and *D*; relative position, the position in the square array of boxes; and absolute position, the position of the target location on the table. a: An example of a training configuration in which D is the target location as indicated by the circle. Following training, there were two cue combination tests: the hierarchy and majority tests. b: In the hierarchy test, the entire configuration was shifted to the opposite side of the table, and the target location was switched with its diagonal opposite, and thus all three cue types were dissociated: D–coincident, A–relative, and C–absolute. c: There were three possible configurations for the majority test. The configuration used was dependent on the child's choice in the hierarchy test. In this example, the child has chosen to use the coincident cues in the hierarchy test. Thus, in this majority test, the target location has been switched with its diagonal opposite. The location marked by *D* is only indicated by coincident cues, whereas the location marked by *A* is indicated by both absolute and relative position cues.

formal demographic data were collected in this study. Twelve participants were girls, and 13 were boys. Eleven participants were 3 years old (M = 41.06 months, SD = 3.27, range = 36.53–46.42), and 14 were 4 years old (M = 54.89 months, SD = 3.71, range = 48.36–59.21). Three additional participants were recruited but were excluded from the final sample because of experimenter error (2) and unwillingness to participate (1). All children were naïve to the experimental procedure. Parents gave written permission prior to testing, and children were asked for verbal consent immediately prior to participation.

Test environment and stimuli. Participants were tested during the school day, in rooms of uniform wall coloring located at the preschools (approximately 3 m × 2 m; room dimensions varied slightly depending on the school). Children sat across from the experimenter at a small rectangular play table (approximately 0.75 m × 0.5 m × 0.4 m; table dimensions varied slightly depending on the school). A single video camera recorded each session, focusing on the child's upper body and torso and the table with the experimental stimuli. A second experimenter sat in a corner of the room taking notes. The setup consisted of four identical green acrylic boxes (10.5 cm × 7 cm × 7 cm) in a square-shaped pattern (range = 30 cm^2–35 cm^2) on the table. One edge of the square array was aligned at the center of the table. One ceramic figurine was attached to the top of each box with Velcro. All figurines were different from one another in both shape and color (see Figure 1a). During the procedure, toy Lego

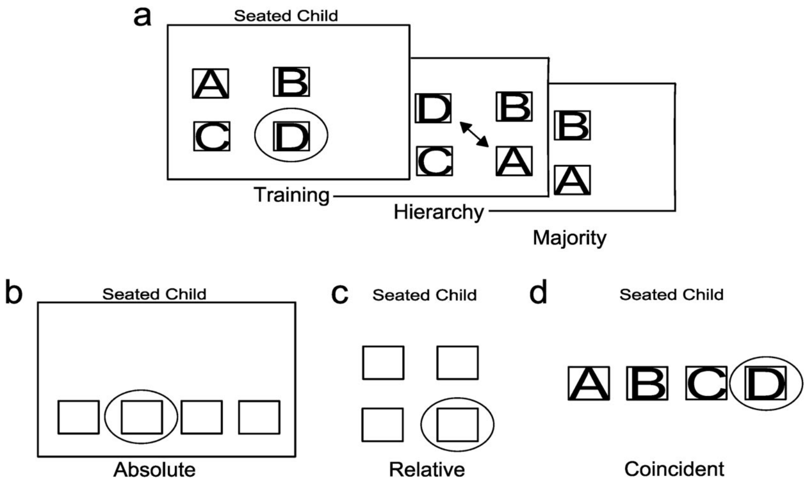

Figure 3. Experiment 1 single-cue tests: Drawing is not to scale. a: An example of a training configuration in which *D* is the target location, as indicated by the circle, followed by the hierarchy and majority tests. Following the hierarchy and majority tests, children participated in three single-cue tests (b–d). The order of the single-cue tests was counterbalanced across participants. In single-cue tests, the boxes were moved such that only one type of cue was available for orientation in each test. The correct location in each test is indicated by the circle.

blocks and other small toys, such as a spinning top, were hidden in the boxes.

Design and procedure. Before entering the room, the experimenter explained to each child that the game would be a hide-and-seek game with Legos. The procedure for each group involved three phases, as described below.

Phase 1: Pretraining. The child sat opposite an experimenter on one of the two long sides of the rectangular play table on which the experimental setup was already in place. The experimenter then explained the rules of the game to the child. The first rule was that a toy would always be hidden in the same place. To demonstrate, the experimenter then placed a toy in one of the boxes, and the child was asked to open the box and retrieve the toy. The location of the hidden toy remained the same for all training and intertraining trials. Trained locations were randomly assigned and counterbalanced across participants. To establish motivation, the child collected toys throughout the experiment to play with.

The second rule was that the other boxes were always locked because they did not have toys inside. To demonstrate, the child was encouraged to try to open the locked boxes to reduce the desire to explore them during the study. The third rule was that sometimes the child would be allowed to open the box to retrieve the toy, "I will say, go ahead, find the toy," whereas at other times, the child would only be allowed to point to the boxes, "I will say, this is a no-touching part, you can point to which box you think the toy would be in." Once the child was familiar with the experimental procedure, the experimenter started the first training trial.

Phase 2: Training. All objects were removed from the table to a location out of sight of the child and then placed back on the table in the same configuration as before. The child was then told, "Find the toy, it's in the same place." This was repeated until the child opened the correct box without first visiting any other boxes on two consecutive trials. At that point, the experimenter started the first test trial.

Phase 3: Testing. There were five different test trials, each with a different configuration (see Figures 2 and 3). Between all test trials, there was at least one training trial in which the child was asked to find the toy in the original training configuration. If the child chose correctly, the experimenter moved on to the next test trial. If the child chose incorrectly, the experimenter repeated training trials until the child chose correctly once. In between trials, the child was encouraged to play with the toys she or he had collected. All children first participated in the two cue combination tests, the hierarchy and the majority tests. To establish children's naïve preferred cue type, the hierarchy test was always presented first before children had any experience with other tests. The majority test was presented second because its configuration was dependent on the child's choice in the hierarchy test. The cue combination tests were followed by the three single-cue tests. The order of the single-cue tests was counterbalanced across participants.

In the hierarchy test (see Figure 2b), the boxes were shifted such that one box remained in the same position relative to the room and the table as the original target location had been (absolute position), a second box was in the same position relative to the three other boxes as the original target location had been (relative position), a third box was located coincident with the same ceramic figurine as the original target location had been (coincident position), and the remaining fourth box was a distractor. The cue associated with the first location the child chose to search in was considered the child's preferred cue type.

The configuration for the majority test (see Figure 2c) was dependent on the child's choice in the hierarchy test. In this test, one location was consistent with the child's preferred cue type (preferred cue location), whereas a different location was consistent with both the other cue types (majority location). The remaining two locations were distractor locations. For example, if the child had chosen the coincident position first in the hierarchy test, then in the majority test, one box would continue to be associated with the correct coincident cue (i.e., with the correct figurine on top of it), whereas another box would be in both the correct absolute position and the correct relative position (see example in Figure 2c).

Finally, children participated in a series of three single-cue tests, one for each cue type. In each single-cue test, only one type of cue was available for orientation (see Figure 3b–d). In the absolute-only test, the four boxes were placed without figurines in a linear array on the tabletop. In this configuration, one box was in the correct absolute position on the table, and there was no longer a square array to orient to, and there were no coincident cues. In the relative-only test, the four boxes without figurines were placed in a square array on the floor of the testing room. In this configuration, one box was in the correct relative position, and there were no coincident cues and no box on the table was in the absolute position. Finally, in the coincident-only test, the four boxes were placed on the floor in a linear array with the figurines on top of the boxes, one on top of each box. In this configuration, one box was coincident with the correct ceramic figurine, and there was no longer a square array to orient to, and there was no box on the table in the absolute position.

During test trials, children were not allowed to touch or interact directly with the boxes, and children received no feedback about their choices because no boxes were opened. Children were asked, "Where do you think the toy would be?" and were reminded to point to their choice. The experimenter removed the first box children pointed to from the configuration and placed it behind herself. Then the child was asked for a second choice, "If the toy was not there, where else would you look?" Because it was determined in pilot work that children would not tolerate making more than two choices during test trials, after the child's second choice, the experimenter removed all the boxes and figurines from the configuration. Gender, age, the target location, and the order of the single-cue tests were counterbalanced across all children.

Scoring. All children's actions during testing were coded in real time both by a second experimenter who remained uninformed of the experimental hypotheses and by the original experimenter from videotape of the session. A child was coded as having made a choice if she or he attempted to raise the lid, pick up, or pointed to any one of the boxes. Intercoder agreement was 100%, Cohen's kappa was equal to one. Because there were four possible hiding locations, chance was 25%. All analyses were run using only each child's first choice for each test. One child was excluded from the majority test analysis due to experimenter error in the setup. All data were analyzed using either two-tailed binomial or Fisher exact tests.

Results and Discussion

Children did exceptionally well in the training trials. Most children reached criterion in two trials (mode = 2 trials, range = 2–3 trials), the minimum number of trials needed to reach criterion, and chose correctly on all intertesting trials (18 of 25 children, binomial test, $p < .001$, OR = 2.57, 95% CI [.51, .88]). Because there were no significant age or gender differences, we pooled the data from all children for analysis. The results are presented in Table 1.

In the hierarchy test, children primarily chose to search in the location indicated by the features of the coincident cue, the individuating ceramic figurine (20 of 25 children, binomial test, $p < .001$, OR = 4, 95% CI [.59, .93]). In the majority test, 19 of 24 children chose the location indicated by their preferred cue type rather than choosing the majority location (binomial test, $p < .0001$, OR = 3.8, 95% CI [.58, .93]). In the single-cue tests, children chose the correct locations above chance in both the relative-only test (binomial test, $p = .037$, OR = .78, 95% CI [.24, .65]) and the coincident-only test (binomial test, $p < .0001$, OR = 5.25, 95% CI [.64, .95]). However, children's responses in the absolute-only test were not significantly different from chance.

In sum, most preschool-age children preferred to use coincident over noncoincident cues and did not appear to make use of more distal noncoincident cues in the surrounding environment. Children's limitations in their use of absolute position cues may underlie their lack of a majority strategy. For the majority location to be a majority, one would have to encode using all three types of spatial cues, including absolute position cues. Otherwise, the majority test is only a test of preference between two cue types, the relative position cues and the coincident cues. Related work has found similar results in which 3-year-old children were more likely to use a beaconing strategy, by which children choose to search in locations based solely on coincident cues, over a relational or place strategy, by which children choose to search in locations based on more distal landmarks (Horn & Myers, 1978; Sutton, 2006).

Table 1
Experiment 1: Percentage (Number) of Children Choosing Locations in Each Type of Test Trial

Cue combination tests

Hierarchy		Majority	
Location	% (number)	Location	% (number)
Absolute	8 (2)	Majority	8.3 (2)
Relative	8 (2)	Preferred cue	79.2 (19)
Coincident	80 (20)	Distractor 1	8.3 (2)
Distractor	4 (1)	Distractor 2	4.2 (1)

Single-cue tests

Absolute		Relative		Coincident	
Location	% (number)	Location	% (number)	Location	% (number)
Absolute	32 (8)	Relative	44 (11)	Coincident	84 (21)
Other	68 (17)	Other	56 (14)	Other	16 (4)

Note. There were four possible locations to choose from in all tests. Choices to any of the three distractor locations in the single-cue tests have been collapsed into "Other" for presentation purposes. For analysis, choices were coded for all four possible positions.

One explanation for the children's poor performance in the absolute-only test is that during the training phase, learning of the coincident cues overshadowed or prevented the learning of the noncoincident cues. In overshadowing, when one cue is learned to predict an event or, in this case, a location, participants are much less likely to learn a second cue in the presence of the first. Both human and nonhuman animals show overshadowing effects in spatial tasks on the basis of relative distance of landmarks to the goal location (Clark's nutcrackers: Goodyear & Kamil, 2004; pigeons and adult humans: Spetch, 1995). Specifically, the closer a landmark is to the goal location, the more likely it will overshadow the learning of other landmarks farther from the goal location. Along these lines, because coincident cues have no distance between them and the goal location, it is very possible that learning based on the coincident cue will overshadow the learning of noncoincident cues.

This explanation is supported by the observation that although children appeared to encode both relative position and coincident cues, they learned the coincident cues better than the relative position cues; children were more likely to choose the correct location in the coincident-only test than in the relative-only test (Fisher's exact test, $p < .01$, OR = .16, 95% CI [.03, .65]). Moreover, children did not choose the correct location in the absolute-only test, despite prior results that indicate preschool-age children can encode the correct location in an absolute position test (Overman et al., 1996).

However, a Bayesian interpretation of the results might focus on perceived reliability. It is possible that children's perceived reliability of the coincident cues is so high that they are weighted more heavily than all other cues. This would also lead children to favor the coincident cues in both cue combination tests and to rely on coincident cues more than relative position cues in single-cue tests. Either way, we can conclude that when coincident cues are present, preschool-age children do not use a majority strategy. In Experiment 2, to determine whether children would be more likely to use a majority strategy in the absence of coincident cues, we moved the ceramic figurines from the top surface of the boxes to locations on the table a short distance from the boxes.

Experiment 2

Children in Experiment 1 appeared to encode coincident cues at the cost of learning other spatial information about the location of hidden toy items. In Experiment 2, we moved the ceramic figurines such that, although they continued to be the most proximal cues to the locations, only noncoincident cues were available for orientation. Pilot work suggested that children were now choosing correctly in the absolute-only test. However, children could have been choosing correctly in the absolute-only test based on either an egocentric or an allocentric frame of reference. For example, a child could choose to search in box in the correct absolute position on the table, either by encoding it allocentrically, as the absolute position, the center of the table, or by encoding it egocentrically, as the location directly in front of them while seated. Although there is evidence that at this age children are much more likely to use an allocentric frame of reference rather than an egocentric one (Haun et al., 2006), a second condition, the rotated condition, was included to confirm which frame of reference the children were using, an egocentric or allocentric one.

Method

Participants. The sample consisted of 49 preschool-age children (*M* = 48.70 months, *SD* = 5.73 months, range = 36.36–59.28 months) recruited at preschools affiliated with the University of California, Berkeley. Children were separated into two age groups, 3-year-olds: 36 months–48 months and 4-year-olds: 48 months–60 months. Children from each age group were randomly assigned to either the constant or the rotated condition. There were 23 participants in the constant condition: 10 three-year-old children (*M* = 42.31 months, *SD* = 3.99 months, range = 36.36–47.47 months), six of whom were girls, and 13 four-year-old children (*M* = 53.10 months, *SD* = 2.48 months, range = 48.89–59.28 months), seven of whom were girls. There were 26 participants in the rotated condition: 12 three-year-old children (*M* = 44.44 months, *SD* = 2.26 months, range = 39.72–46.68 months), six of whom were girls, and 14 four-year-old children (*M* = 52.84 months, *SD* = 3.79 months, range = 48.48–59.31 months), eight of whom were girls.

Participants were tested during the school day in study rooms located at the preschools. The sample was primarily middle- to upper-middle class based on previous analysis of the schools, but no formal demographic data were collected in this study. Three additional participants were recruited but were excluded from the final sample because they did not reach criterion in training (1), there was an experimenter error (1), or they were unwilling to participate (1). All children were naïve to the present procedure. Parents gave written permission prior to testing, and children were asked for verbal consent immediately prior to participation.

Test environment and stimuli. All experimental stimuli and setup were the same as described in Experiment 1, except that the unique ceramic figurines were placed to the sides of the boxes. The figurines were placed between 2 and 6 cm away from each box, depending on the specific figurine (see Figure 1b). The figurines were now labeled as proximal cues, due to their proximity to the hiding locations. The figurines were placed in a nonsquare array pattern to help children distinguish between relative position cues and proximal cues. Each figurine remained closest to one box in all training and testing configurations.

Design and procedure. Children were randomly assigned to one of two conditions: the constant or the rotated condition. In the constant condition, all procedures were identical to those used in Experiment 1, except that the coincident-only test was replaced by a proximal-only test. In the proximal-only test, only the proximal cues were available for orientation: The four boxes were placed on the floor in a linear array, with the figurines in front of the boxes, one in front of each box.

In the rotated condition, children participated in the hierarchy and majority tests, just as they did in the constant condition. However, instead of participating in three single-cue tests, children in the rotated condition first participated in the absolute-only test, followed by a rotation test. Thus, children in the rotated condition only participated in four test trials. In the rotation test, children were presented with the same configuration used in the absolute-only test but were asked to trade places with the experimenter before making a choice.

Children's responses in the rotation test did not reflect their performance in the absolute-only test. Children were coded as using either an egocentric or an allocentric frame of reference based on the match between their response in the original absolute test and their response in the rotation test. If, in the rotation test, a child chose the same location relative to her or his body position that she or he had chosen in the original absolute-only test, the child was coded as using an egocentric frame of reference. If the child instead chose the same location relative to the absolute position cues that she or he had chosen in absolute-only test, the child was coded as using an allocentric frame of reference. For example, a child might choose a location that was located to the right of the correct absolute position in the absolute-only test. The same child might then choose that same location relative to the absolute position cues in the rotation test. From the child's perspective, she or he would now be choosing the box to the left of the absolute position. In a case like this, the child would be coded as using an allocentric frame of reference, even though she or he would not have chosen the correct absolute position in either test. Children who did not choose consistently across both tests were coded as "other." Gender, age, and the target location were counterbalanced across all children in both conditions. As in Experiment 1, the order of the single-cue tests in the constant condition was also counterbalanced.

Scoring. All children's actions in the test phase were coded in real-time both by the second experimenter who remained uninformed of the experimental hypotheses and by the original experimenter from video recording of the session. A child was coded as having made a choice if she or he attempted to raise the lid, pick up, or pointed to any one of the boxes. Intercoder agreement was 100%, and Cohen's kappa was equal to one. Because there were four possible hiding locations, chance was 25%. All analyses were run using only each child's first choices. One child was excluded from the majority test analysis due to experimenter error in the setup. All data were analyzed using either two-tailed binomial or Fisher's exact tests.

Results and Discussion

There were no significant differences between conditions in the tests common to both conditions: the hierarchy, majority, and absolute-only tests. Therefore, the data for those tests were pooled across conditions. For the relative- and proximal-only tests, only children from the constant condition participated and thus were included in the analysis. For the rotation test, only children in the rotated condition participated and thus were included in the analysis for that test. The results are presented in Table 2.

Children excelled at the training for this task as they did in Experiment 1. Most children took the minimum number of trials required to reach criterion and no more (mode = 2, range = 2–7 trials) and chose correctly on all intertesting trials on their first attempt (37 of 49 children, binomial test, $p < .001$, OR = .75, 95% CI [.61, .87]). However, in contrast with the results from Experiment 1, in the hierarchy test, children in Experiment 2 primarily chose to search in the location indicated by relative position cues (33 of 49 children, binomial test, $p < .001$, OR = .67, 95% CI [.52, .80]).

In the majority test, children continued to choose the location indicated by their preferred cue type as in the previous experiment

Table 2
Experiment 2: Percentage (Number) of Children Choosing Locations in Each Type of Test Trial by Condition

Cue combination tests			
Hierarchy		Majority	
Location	% (number)	Location	% (number)
Absolute	18.4 (9)	Majority	33.3 (16)
Relative	67.3 (33)	Preferred	56.2 (27)
Proximal	10.2 (5)	Distractor 1	4.2 (2)
Distractor	4.1 (2)	Distractor 2	6.3 (3)
Single-cue tests			
Absolute			
Location	% (number)		
Absolute	36.7 (18)		
Other	63.3 (31)		
Single-cue tests: Constant condition			
Relative		Proximal	
Location	% (number)	Location	% (number)
Relative	52.2 (12)	Proximal	41.7 (10)
Other	47.8 (11)	Other	58.3 (14)
Single-cue test: Rotated condition			
Rotation			
Location	% (number)		
Allocentric	73.1 (19)		
Egocentric	19.2 (5)		
Other	7.7 (2)		

Note. Cue combination and single-cue test results include children in both conditions except where otherwise noted. There were four possible locations to choose from in all tests. Choices to any of the three distractor locations in the Single-cue tests: Constant condition have been collapsed into "Other" for presentation purposes. Choices to any of the two distractor locations in the Single-cue tests: Rotated condition have also been collapsed into "Other." For analysis, choices were coded for all four possible positions.

(27 of 48 children, binomial test, $p < .001$, odds, .56, 95% CI [.41, .71]). However, the qualitative pattern of data from the majority test suggests that children in Experiment 2 were more likely to choose the majority location than children in Experiment 1. In Experiment 1, 19 of 24 children chose the preferred cue location. Of those who did not choose the preferred cue location, only two chose the majority location. In Experiment 2, 27 of 48 children chose the preferred cue location, whereas 16 chose the majority location. This difference in performance between the two experiments showed a slight trend but was not significant (Fisher's exact test, $p = .093$, OR = 2.91, 95% CI [.86, 11.67]).

Nevertheless, further analyses using a subset of the data that excludes children who chose either of the distractor locations in the majority test (Experiment 1, $n = 21$; Experiment 2, $n = 43$) suggest a possible effect to be explored in future studies. Within this subset of the data, children in Experiment 2 were more likely to choose the majority location than children in Experiment 1 (Fisher's exact test, $p = .036$, OR = 5.50, 95% CI [1.08, 54.89]). Furthermore, within Experiment 1, in the majority test, the distribution of the number of children choosing the majority location (two) versus the preferred cue location (19) was significantly different from chance (chance was 50% because we examined a subset of the data that had only two possible choices; binomial test, $p < .001$, OR = .10, 95% CI [.01, .30]). In contrast, the distribution in Experiment 2 was not significantly different from chance, 16 versus 27 children, respectively (binomial test, $p = .13$, OR = .59, 95% CI [.23, .53]). These analyses suggest that children in Experiment 2 were equally likely to choose the majority location as the preferred cue location.

There were also significant age differences in the majority test (see Figure 4). Four-year-olds chose both the majority location and the preferred cue location significantly more than would be expected by chance (majority location: 12 of 27 children, binomial test, $p = .03$, OR = .80, 95% CI [.25, .65]; preferred cue location: 13 of 27 children, binomial test, $p = .01$, OR = .86, 95% CI [.29, .68]). The overall distribution of choices was also significantly different than would be expected by chance (Fisher's exact test, $p = .01$, OR = .92, 95% CI [.21, 4.16]). However, 3-year-olds in the majority test overwhelmingly chose the preferred cue location over all other possible locations (16 of 22 children, binomial test, $p < .001$, OR = 2.67, 95% CI [.50, .89]). Of the six 3-year-olds who did not choose the preferred cue location, only three chose the majority location. The difference between the age groups was significant (Fisher's exact test, $p = .036$, OR = 5.54, 95% CI [1.16, 37.18]). It is possible that 4-year-olds are at a transitional stage at which they use both types of strategies equally.

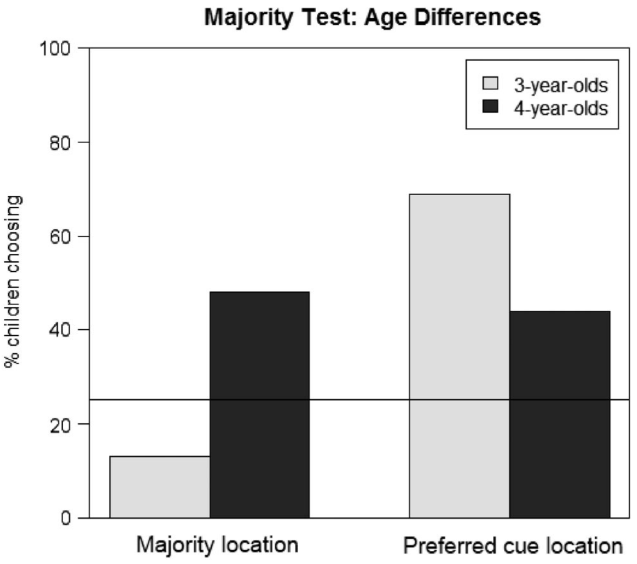

Figure 4. Experiment 2: Age differences between 3- and 4-year old children in the majority test. Younger children were more likely to choose the preferred cue location, whereas older children were equally likely to choose the majority location as the preferred cue location. The percentage of children choosing each location is reported. The remaining children chose one of the two distractor locations. Chance is indicated by the line at 25%.

Moreover, although there were no significant differences between age groups in the single-cue tests, the pattern of data indicates possible age differences in the use of individual types of cues. Our results demonstrate that 4-year-olds were able to orient using only single cues, whereas 3-year-olds were not able to do this. Four-year-olds chose the correct location above chance in all single-cue tests (binomial test; absolute only, $p = .046$, OR = .75, 95% CI [.24, .63]; relative only, $p = .024$, OR = 1.16, 95% CI [.25, .81]; proximal only, $p = .024$, OR = 1.16, 95% CI [.25, .81]). Three-year-olds did not choose the correct location above chance in any of the single-cue tests. Future research is needed to explore these age differences with more sensitive tests.

The only significant sex difference occurred in the absolute-only test. Boys were significantly more likely to choose the correct absolute position (11 of 22 children, binomial test, $p = .01$, OR = 1.0, 95% CI [.28, .72]), whereas girls showed no preference for any position (Fisher's exact test, $p = .06$, OR = .56, 95% CI [.15, 2.0]). Both boys and girls chose the location consistent with relative position cues as their preferred cue type in the hierarchy test trial, and the preferred cue location in the majority test. Many prior studies in spatial tasks have found no significant sex differences in young children (e.g., Lehnung et al., 1998; Overman et al., 1996). The work that has found sex differences prior to puberty has varied considerably depending on the specifics of the task. Girls were found to have an advantage in an outdoor radial arm maze task (Mandolesi, Petrosini, Menghini, Addona, & Vicari, 2009), whereas boys were found to perform more accurately and faster both when learning a novel route based on landmarks and when learning to search for a hidden object between two landmarks (Beilstein & Wilson, 2000; Spetch & Parent, 2006). Although future work is needed to clarify in which situations sex differences apply to young children, our work suggests that sex differences in the use of distal landmarks may be found in children prior to puberty.

The results of the rotated condition confirmed that children used an allocentric frame of reference. Of the 26 children who participated in the rotation test, 19 children chose the same location relative to absolute position cues that they had chosen previously in the absolute-only test (chance was 33% because there were only three possible outcomes, binomial test, $p < .001$, OR = 2.71, 95% CI [.52, .88]). Five children chose egocentrically, choosing the same location relative to their own body position (e.g., nearest on the right). The remaining two children chose at random. There were no age or sex differences in the rotated condition.

General Discussion

Our goal in these studies was to determine whether children would use a flexible spatial strategy such as the majority strategy found in squirrels. We found evidence of the emergence of the majority spatial strategy in 4-year-old children. Slightly over half (56%) the 4-year-olds in Experiment 2 chose to search in the location indicated by a majority of the cue types in the majority test. In contrast, 3-year-old children and 44% of 4-year-old children continued to search for the toy in the location consistent with their preferred cue type, not the majority location. However, 4-year-olds only showed evidence of a majority strategy in the absence of coincident cues. When coincident cues were present, preschool-age children, regardless of age, primarily relied on the coincident cues to find a hidden object. Children at both ages continued to rely on this preference even when a majority of other cue types indicated a position different from that of the coincident cues. In the absence of coincident cues, children preferred to rely on relative position cues over proximal cues, even when the proximal cues were only placed a few centimeters from the hiding locations.

Examining these results from a Bayesian perspective, children's perceived reliability of the ceramic figurines appeared to vary according to the distance that the figurines were from the hiding locations. This could be due to the increased variability introduced in the change from coincident cues to proximal cues. In Experiment 1, when the figurines were coincident with the hiding locations, they were always located on top of the boxes. In Experiment 2, the position of the proximal cues changed relative to the boxes to ensure that each figurine was only ever associated with one box. In a Bayesian model, the introduction of variability would result in a loss of reliability. Consistent with this prediction, children relied on the figurines less in Experiment 2, when the figurines were proximal to the locations, than they did in Experiment 1, when the figurines were coincident with the locations (Fisher's exact test, $p < .01$, OR = .14, 95% CI [.03, .60]). We are presently examining these data using a Bayesian model of children's choices to explore this question further.

The above results are consistent with previous research indicating that by the age of 5, children appear to be able to integrate multiple frames of reference in a spatial task (Nardini, Burgess, Breckenridge, & Atkinson, 2006). This would suggest that even very young children are able to integrate information from multiple sources when making decisions. However, the integration of multiple sources of information appears to be highly task dependent. Recent studies have found that preschool-age children do not show integration of multiple sources within some modalities, such as the integration of two visual cues or between two different modalities, such as visual and self-motion cues (Nardini, Bedford, & Mareschal, 2010; Nardini, Jones, Bedford, & Braddick, 2008). For example, in a replication of the classic Ernst and Banks (2002) cue combination study, children did not integrate visual and haptic information until 8 years of age (Gori, Del Viva, Sandini, & Burr, 2008). The authors suggested that such cross-modal integration may be delayed in development due to children's need to make error corrections in one modality using cues from other modalities. Taken altogether, it appears that although young children may have difficulty integrating multiple sources of information, they may be able to do so earlier in the spatial domain than in other cue combination tasks.

Although 4-year-olds in Experiment 2 did show evidence of using a majority strategy, it is possible that the size of our search space might have caused younger children to be less likely to use a majority strategy. Previous studies have demonstrated that the size of the defined search space has a strong effect on search strategies. Younger children tested in large-scale, natural spaces have shown both broader landmark use and the use of broader spatial strategies (DeLoache & Brown, 1983; Gouteux, Vauclair, & Thinus-Blanc, 2001; Uttal, Sandstrom, & Newcombe, 2006). For example, 30-month-old children performed better in a large-scale spatial task in their home than in a small-scale spatial task (DeLoache & Brown, 1983). Furthermore, in the same large-scale task, 4-year-olds were able to use relational search strategies, such as a center search strategy, by which children are able to learn that a hiding location is always in the middle between two landmarks (Uttal et al., 2006). Such strategies are typically difficult for young children in smaller scale tasks. Following this line of reasoning, it is possible that children may be capable of integrated spatial strategies at younger ages when tested in a larger scale search space.

One way the size of a search space may affect spatial cognition is in the amount of locomotion required to explore the space. Although maturation may play a role in the development of spatial cognition, studies have demonstrated that the experience of self-locomotion, especially in infancy, is a much better predictor of spatial abilities than age alone (Clearfield, 2004). Infants who have transitioned to locomoting (i.e., crawling or walking) begin to prefer allocentric over egocentric frames of reference. Moreover, giving prelocomotor infants self-locomotion experience in a walker improves their performance on spatial tasks so that there are no differences between the group with walker experience and a group of age-matched crawling infants (Kermoian & Campos, 1988). These results indicate that experience in the world can aid and even induce changes in spatial cognition. Similarly, although 3- and 4-year-old children do not differ considerably in their locomoting abilities, they may have differences in the amount of space that they have explored in their natural environment.

Another factor that may play a role in how children explore space is their field of attention. One theory of the development of spatial cognition predicts that as infants gradually expand their attentional fields, they will move from using more proximal to more distal landmarks (Pick, Yonas, & Rieser, 1979). There are a number of attentional shifts occurring at transition between 3 and 4 years. These shifts include changes in false-belief understanding and other psychological shifts that may have an effect on how children perceive both psychological and physical phenomena. It is possible that these attentional shifts contribute to older children's increased ability to integrate multiple sources of spatial information. Our results are consistent with this interpretation in that older children showed better performance than younger children on all single-cue tests, suggesting that they had better memory for those cues. This effect did not appear to be an issue of memory alone, however, because the younger children were still able to remember the hiding location on all intertest training trials. Our findings suggest the need for further work exploring the relationship between the development of flexible spatial strategies and critical attentional shifts in other domains.

In conclusion, our results show that by the age of 4, children have begun to use flexible, integrated strategies such as the majority strategy to solve spatial problems. We have also shown that children's use of landmarks may change drastically depending on the availability of different types of cues, such as the coincident cues used in our methods. Furthermore, we have demonstrated the importance of integrating human and nonhuman animal studies to explore children's development of mature spatial cognition.

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Received May 27, 2011
Revision received March 14, 2012
Accepted March 23, 2012 ■