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The Development of Memory for Location: What Role Do Spatial Prototypes Play?

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Two experiments investigated the role of spatial prototypes in estimates of location. In Experiment 1 ($N = 144$), children and adults learned the locations of 20 objects in an open, square box designed to look like a model house. In two conditions, opaque lines or walls divided the house into four regions, and in the other condition, no boundaries were present. Following learning, the dots marking the locations were removed, and participants attempted to replace the objects. Children and adults overestimated distances between target locations in different regions. Contrary to Huttenlocher, Hedges, and Duncan's hierarchical theory of spatial memory, none of the groups displaced the objects toward the region centers. In Experiment 2 ($N = 96$), boundaries were removed during testing to determine whether children and adults were more likely to displace objects toward region centers when uncertainty about location increased. Again, all age groups overestimated distances between target objects in different regions. In addition, adults and 11-year-olds in the most salient boundary condition displaced objects toward the region centers. Discussion focuses on the implications of these results for understanding how children and adults estimate location.

INTRODUCTION

Memory for location is a fundamental aspect of human functioning. Without the ability to remember locations, children and adults would be unable to carry out even basic tasks, such as getting ready for school or preparing a meal. Many studies have been conducted over the last 25 years aimed at understanding how children and adults code locations (e.g., Acredolo & Boulter, 1984; Allen, 1981; Bushnell, McKenzie, Lawrence, & Connell, 1995; Cohen, Baldwin, & Sherman, 1978; Hirtle & Jonides, 1985; Kosslyn, Pick, & Fariello, 1974; McNamara & Diwadkar, 1997; Newcombe & Liben, 1982; Presson & Hazelrigg, 1984; Rieser & Heiman, 1982; Siegel & Schadler, 1977; Stevens & Coupe, 1978; Uttal & Wellman, 1989). Largely, these studies have focused on the types of information people use to remember locations. For example, several studies have examined how children and adults use landmarks to code location (Holyoak & Mah, 1982; McNamara & Diwadkar, 1997; Sadalla, Burroughs, & Staplin, 1980). Despite a wealth of information about the types of information children and adults rely on to remember previously seen locations, relatively little is known about the processes involved in retrieving such information from memory.

Recently, Huttenlocher, Hedges, and Duncan (1991) outlined a theory called the Category-Adjustment (CA) model to explain how children and adults retrieve spatial information from memory. They propose that retrieval of locations from memory is a hierarchically organized, two-step process involving the use of both metric and categorical (i.e., spatial region) information. When trying to remember the location of a previously seen object, people initially make estimates based on their memory of fine-grained, metric information such as distance and direction from an edge. Because memory for metric information is inexact, however, people adjust these estimates based on categorical information about the location (i.e., region membership). According to the CA model, this categorical information about region membership is represented by a spatial prototype located at the center of the region. Hence, adjustments based on categorical information lead to systematic biases toward the region center.

This theory of spatial coding has been used to explain why children and adults exhibit bias toward region centers (prototype effects) when reproducing previously seen locations (Engebretson & Huttenlocher, 1996; Huttenlocher, Newcombe, & Sandberg, 1994; Laeng, Peters, & McCabe, 1998; Sandberg, Huttenlocher, & Newcombe, 1996). Huttenlocher and colleagues have used a number of different tasks to investigate prototype effects. In the sandbox task, children between the ages of 2 and 10 watched an experimenter hide a toy in a long, narrow sandbox (Huttenlocher et al., 1994). After a short delay in which children were turned away from the sandbox, they were allowed to search for the toy. Analysis of search patterns indicated that all age groups were quite accurate, suggesting that even young children can use metric information to code location. Moreover, the results of these experiments revealed that all age groups exhibited systematic biases toward the region centers. Specifically, 2- and 6-year-olds' searches were biased toward the center of the entire sandbox, and 10-year-olds' searches were biased toward the centers of the two halves of the sandbox. Thus, although the ability to subdivide spaces appears to undergo developmental change, even very young children exhibit prototype effects.

In the circle–dot task, children and adults were shown a sheet of paper with a dot drawn inside a circle (Huttenlocher et al., 1991; Sandberg et al., 1996). This sheet of paper was then removed and participants were asked to reproduce the location of the dot inside an empty circle on a new sheet of paper. Across both sets of studies, responses were clustered around the true locations, indicating that both children (i.e., 5-, 7-, and 9-year-olds) and adults used fine-grained, metric information to estimate location in this task. In addition, measures of response bias revealed that 5- and 7-year-olds used categorical information about radius only to estimate locations, whereas the 9-year-olds and adults used categorical information about both angle and radius to estimate locations. That is, the 9-year-olds and adults placed locations closer to the centers of the circle quadrants than they actually were. This suggests that the ability to combine metric and categorical information pertaining to two dimensions (e.g., angle and radius) may undergo developmental change.

Huttenlocher and colleagues have also used a V task to examine whether children and adults exhibit prototype effects in their estimations of angular information (Engebretson & Huttenlocher, 1996; Sandberg et al., 1996). In the Engebretson and Huttenlocher (1996) study, adults were shown a sheet of paper with a line drawn inside a 90° angle oriented to look like a V. As in the circle–dot task, this sheet of paper was then removed and participants were asked to reproduce the line inside an empty 90° angle on a new sheet of paper. Analyses of responses showed that people's estimates were biased toward the centers of the two halves of the 90° angle. This task has also been extended to examine prototype effects in children's estimations of angles (Sandberg et al., 1996). In this study, 7- and 9-year-olds were shown a line drawn inside a 90° angle oriented to look like an inverted V. This sheet of paper was removed and children were asked to draw the line inside an empty inverted 90° angle on a new sheet of paper. As with adults, children's angle estimates were biased toward the centers of the two halves of the inverted 90° angle. Thus, both children and adults exhibit prototype effects in their estimates of angles.

More recently, Newcombe, Huttenlocher, Sandberg, Lie, and Johnson (1999) have used the CA model of spatial coding to explain asymmetries in spatial judgments. More specifically, they have used this model to explain why people tend to judge nonlandmarks as being closer to landmarks than vice versa. In this task, participants learned several locations on a square map. Some of the locations were designated as landmarks (prototypes) and others were designated as nonlandmarks (nonprototypes). After learning the locations, study participants estimated the distance and the direction between pairs of objects. They saw the location of one member of the pair printed on an otherwise blank map and then marked the spot representing the location of the other member of the pair. As in other studies of this nature (e.g., McNamara & Diwadkar, 1997; Sadalla, Burroughs, & Staplin, 1980), Newcombe and colleagues found that distance estimates were smaller when the landmark (prototype) was fixed than when the nonlandmark (nonprototype) was fixed. Moreover, as predicted by the CA model, these asymmetries were larger when the actual distances involved were larger. Newcombe and colleagues used these findings to contend that the prototype model can account for a range of phenomena involving estimates of location.

Huttenlocher and colleagues have also used this theory of spatial coding to explain subdivision effects, that is, the tendency to exaggerate distances between locations across boundaries. Numerous studies have shown that children and adults overestimate distances between locations in different regions, and underestimate distances between locations in the same region (Acredolo & Boulter, 1984; Allen, 1981; Cohen et al., 1978; Cohen & Weatherford, 1980; Hirtle & Jonides, 1985; Kosslyn et al., 1974; Laeng et al., 1998; Maki, 1982; McNamara, 1986; Newcombe & Liben, 1982). For example, Allen (1981) found that 7- and 10-year-olds, as well as adults, tended to partition routes into regions and used these regions to make distance judgments about locations along the route. In particular, children and adults often judged locations from two adjoining regions as more distant than locations within the same region, even when the locations within the same region were farther apart than were the locations from adjoining regions. Cohen et al. (1978) found that 9- and 10-year-olds and adults familiar with a camp environment overestimated distances separated by barriers and underestimated distances not separated by barriers. Likewise, Kosslyn et al. (1974) found that 5-year-olds and adults overestimated distances between objects separated by opaque barriers. Together, these studies clearly show that both children and adults often think that locations in different regions are farther apart than they actually are.

According to the Huttenlocher et al. (1991) model, people remember locations from different regions as farther apart than they actually are because estimates of location are biased toward region centers. This bias toward the region center necessarily results in underestimation of distances between locations within the same region and overestimation of distances between locations in adjacent regions. This explanation of subdivision effects has not been directly tested, however. Moreover, the tendency to displace locations toward the centers of spatial regions has only been examined in the context of how children and adults remember single locations in undifferentiated spaces (Engebretson & Huttenlocher, 1996; Huttenlocher et al., 1994; Laeng et al., 1998; Sandberg et al., 1996; but see Newcombe et al., 1999, for an exception).

The goal of the present investigation was to further examine the role of spatial prototypes in estimates of location. Two issues were of particular interest. First, when multiple locations exist within a space, do children and adults both displace locations toward the centers of spatial regions and exaggerate distances between locations in adjacent regions? Second, how does boundary salience influence the extent to which children and adults displace locations toward the centers of spatial regions and overestimate distances between locations in adjacent regions? These issues were addressed within the context of a spatial memory task in which 7-, 9-, and 11-year-old children and adults were asked to remember a large number of locations in a small-scale space. The task was divided into a learning phase and a test phase. During the learning phase, children and adults learned the locations of 20 objects marked by yellow dots on a blue floor in an open, square box designed to look like a model house. The house was subdivided into four equal regions by boundaries that varied in terms of salience—either opaque walls or lines on the floor. There was also a control condition in which no boundaries were present. During the test phase, the floor with the yellow dots marking the locations was removed and replaced with a plain, blue floor. Participants then attempted to place all the objects in their correct locations.

Unlike previous investigations of prototype effects (e.g., Engebretson & Huttenlocher, 1996; Huttenlocher et al., 1994; Laeng et al., 1998; Sandberg et al., 1996), the current spatial memory task made it possible to independently assess prototype and subdivision effects. That is, because previous studies have based inferences about the number of subdivisions imposed on a space solely on distortions toward the centers of spatial regions, subdivision of the space could not be assessed independent of bias toward the prototype. For example, systematic search biases toward the center of the entire sandbox or the center of each half of the sandbox are used to determine whether children treat the sandbox as a single region, or as two halves. Hence, it is impossible to test whether bias toward the prototype leads to overestimation of distances between regions. In the spatial memory task used in the present investigation, overestimation of distances between objects in different regions served as a measure of subdivision effects, and distortions toward the centers of spatial regions served as a measure of prototype effects. Although distortions toward the centers of spatial regions would necessarily result in overestimation of distances between objects in different regions, the converse is not necessarily true. That is, overestimation of distances across regions can occur in the absence of bias toward the prototype.

Consistent with other studies (Engebretson & Huttenlocher, 1996; Huttenlocher et al., 1994; Laeng et al., 1998; Sandberg et al., 1996), it was hypothesized that (1) estimates of location would be biased toward the region centers; (2) these spatial prototype effects would be accompanied by subdivision effects, that is, exaggeration of distances across boundaries; and (3) the bias toward the region centers would be stronger in adults and older children. In addition, it was predicted that there would be greater bias toward the region centers when the boundaries dividing the model house into regions were highly salient. More specifically, we reasoned that the presence or absence of physical boundaries within a space might influence the ease with which prototypical locations are represented. When no boundaries exist within a space, children and adults must either treat the space as a single region with a prototype at its center or use mentally imposed boundaries to subdivide the space into different regions with a prototype at the center of each. Thus, representing prototypical locations in multiple regions may be especially difficult for young children. For this reason, undifferentiated spaces such as those used by Huttenlocher and colleagues may present problems for young children. Providing boundaries that divide the space into regions might make it easier for children and adults to represent multiple prototypical locations, particularly if those boundaries are highly salient.

EXPERIMENT 1

Method

Participants

One hundred forty-four 7-, 9-, and 11-year-olds, and adults, participated. There were 36 participants in each age group, comprised of approximately equal numbers of males and females. The mean ages were 7 years, 7 months (*range* = 6,9–7,10); 9,4 (*range* = 8,7–10,5); 11,4 (*range* = 10,9–11,10); and 19,11 (*range* = 17,11–32,9), respectively. Three additional 7- and 9-year-olds who failed to reach criterion during the learning phase were excluded from the experiment. Two additional adults and one 7-year-old were excluded because of experimenter error. Children were recruited from a local public school system, a local private school system, and a child research participant database maintained by the Department of Psychology at the University of Iowa. Most children were from predominantly middle- to upper-middle-class White families. Adults participated to fulfill research credit for an introductory psychology course.

Apparatus and Materials

A 32-inch wide × 32-inch long × 13-inch high model house was used as the experimental space. The model house was an open, square box with white exterior walls. The house had two identical windows evenly spaced on each of its four exterior walls. The floor consisted of a layer of Plexiglas and a layer of plywood separated by a ½ inch space. Removable boards could be inserted between the plywood and the Plexiglas to change the appearance of the floor. Three floors were used in this experiment: (1) a blue carpeted floor with yellow dots, (2) a blue carpeted floor with no dots, and (3) a grid of *x* and *y* coordinates at ½ inch intervals.

The model house could be divided into four identical regions (16 inches × 16 inches) by placing walls or lines inside the house. The white plywood walls were 13 inches tall and 5/16 inches wide. The white lines were ¼ inch tall and 5/16 inches wide. Twenty miniature objects were used during the experiment to help participants code the locations in the house: a pot, bear, birdhouse, pie, iron, paint can, picture, book, purse, flower pot, present, fishbowl, apple, trash can, hat, pail, Lego man, bag of tortilla chips, jar of honey, and a soft drink carton. The average length and width of the objects was .73 inch and .64 inch, respectively.

Each region contained five locations marked by ¾-inch yellow dots (see Figure 1). The dots were arranged to include four target triads. Two members of each triad were in the same region, while one member was in the adjacent region. The "middle" object in each triad was 6 inches from the other two target objects (one in the same region and one in the adjacent region). These triads were designed to determine whether children and adults systematically overestimated distances between objects in adjacent regions. In addition to these target locations, eight nontarget locations were used (two in each region).

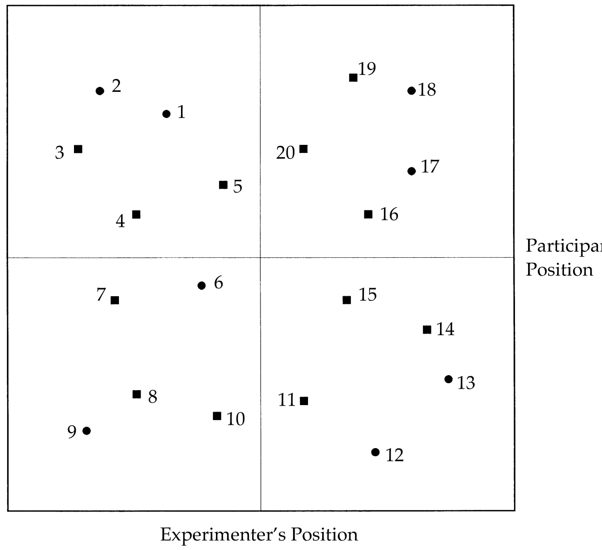

Figure 1 Diagram of target and nontarget locations in Experiment 1. Squares represent triads of target locations (locations 3, 4, and 7; locations 8, 10, and 11; locations 14, 15, and 16; and locations 19, 20, and 5). Circles represent nontarget locations.

Design and Procedure

Participants were individually tested either in the laboratory or at their elementary school. The model house was placed on the floor of the experimental room. At the beginning of the experiment, the experimenter stood directly in front of the house, while participants stood to the right of the experimenter facing an adjacent side of the house (see Figure 1).

Participants were randomly assigned to one of three conditions: walls, lines, or no boundaries. In the first two conditions, the house was divided into four regions by either walls or lines. In the no boundaries condition, no visible boundaries subdivided the house into regions. The experiment was divided into a learning phase and a test phase. During the learning phase, participants learned the locations of 20 objects in the house. At the beginning of the session, the experimenter told participants that she would place 20 objects in the house and that they should try to remember the locations of the objects because they would be asked to replace them later. The object locations corresponded to the 20 yellow dots on the floor of the house (see Figure 1). Participants watched as the experimenter named the objects and placed them in the house one at a time in a random order. The pairings of objects and locations were randomized for each participant.

After the experimenter had placed all 20 objects, she asked participants to turn around while she removed the objects from the house. The experimenter then gave the objects to the participants one at a time and asked them to place them in the house. Thus, the participant's task was to try to place each object in its correct location. Incorrect placements were recorded and corrected by the experimenter. Participants were allowed to move around the outside of the house in order to replace the objects during learning trials. Participants continued with the learning trials until they could correctly replace all 20 objects in a single trial. Objects were presented in a new random order for each learning trial. The mean number of trials to reach the learning criterion for 7-, 9-, and 11-year-olds and adults was 4.7 (SD = 1.8), 4.1 (SD = 1.8), 2.4 (SD = 1.1), and 2.4 (SD = 1.4), respectively.

The test phase began immediately following the learning phase. The experimenter first asked the participants to face away from the model house. She then removed the floor with the yellow dots and inserted the plain blue floor, leaving the walls or lines subdividing the house as before. The experimenter then asked participants to face the house and try to replace the objects in the correct locations. Thus, participants attempted to place the objects in the correct locations without the aid of the yellow dots. Participants were allowed to replace the objects in any order they chose. The experimenter recorded the order in which the objects were placed. After participants replaced all 20 objects, the experimenter thanked them for participating. After participants left the room, the experimenter removed the blue floor and replaced it with the grid of x and y coordinates. The experimenter recorded the x and y coordinates for each object to the nearest ½ inch.

Coding

A placement was considered "correct" if it was in the correct region and in the correct position within the configuration relative to the other objects. Occasionally, participants preserved the overall configuration within a region, but incorrectly paired objects and locations. For example, a participant might correctly preserve the overall shape of the configuration involving Locations 1 through 5, but mistakenly transpose the objects in Locations 3 and 4. One way to deal with this issue is to exclude these locations from further analysis. Another approach is to use the x and y coordinates for these locations, regardless of whether the correct objects were placed in these locations. The second approach was adopted for two reasons. First, although excluding these locations would only result in the loss of a small amount of data, a more selective sample of behavior would be recorded. Second, the primary focus of this investigation was to determine how children and adults represent location per se, not whether they can remember specific pairings of objects and locations. We substituted .56% of the locations for 7-year-olds (4 out of 720), 1.11% of the locations for 9-year-olds (8 out of 720), 1.81% for 11-year-olds (13 out of 720), and .28% for adults (2 out of 720). These substituted locations were used in all analyses. Objects placed in the wrong region or in a completely wrong configuration were omitted from analyses. We omitted 2.5% of locations for 7-year-olds (18 out of 720), 3.1% of locations for 9-year-olds (22 out of 720), .69% for 11-year-olds (5 out of 720), and .14% for adults (1 out of 720).

Intercoder reliability estimates of object placement were calculated on 24 randomly selected participants using exact percent agreement. For each of these participants, two coders judged which object was placed at each of the 20 locations. Coders agreed on 99.8% of the 480 locations coded.

Measures

Overall accuracy score. Participants received a single overall accuracy score representing the distance between the remembered locations and the true locations averaged over all locations.

Between- and within-region distance estimation scores. Each participant received a between-region distance estimation score and a within-region distance estimation score. The between-region score represented the average distance between the four pairs of target locations in *adjacent* regions. Conversely, the within-region score represented the average distance between the four pairs of target locations within the *same* region. These scores were used to assess whether participants systematically overestimated the distance between target locations in different regions and underestimated the distance between target locations in the same region.

Center displacement scores. Center displacement scores were calculated for each participant by subtracting the distance between each remembered location and the center of the region from the distance between the corresponding true location and the center of the region. These differences were averaged across all 20 locations to obtain a single center displacement score for each participant. These scores allowed us to determine whether participants displaced locations toward the prototypic (center) locations in the spatial regions.

Results

Overall Accuracy

Figure 2 shows where participants placed the objects relative to the true locations. In general, it appears that they placed the objects fairly accurately. To investigate possible differences in placement accuracy among the age groups and experimental conditions, participants' mean overall accuracy scores were entered into an Age: (7, 9, or 11 years, or adult) × Boundary Condition (lines, walls, or no boundaries) ANOVA. This yielded significant effects for age, $F(3, 132) = 13.55$, $p < .001$, and boundary condition, $F(2, 132) = 26.42$, $p < .001$. Follow-up tests of the age effect using Fisher Protected Least Significant Difference (PLSD) test ($\alpha = .05$), indicated that adults placed objects more accurately than did 7-, 9-, and 11-year-olds, and that 11-year-olds placed objects more accurately than did 7-year-olds. The mean distance from true locations was 1.97 inches ($SD = .34$) for 7-year-olds; 1.91 inches ($SD = .39$) for 9-year-olds; 1.76 inches ($SD = .39$) for 11-year-olds; and 1.50 inches ($SD = .24$) for adults. Follow-up tests of the boundary condition effect showed that all three conditions differed significantly from one another. Mean distance from the true locations was 2.03 inches ($SD = .47$) in the no boundaries condition; 1.68 inches ($SD = .30$) in the lines condition; and 1.52 inches ($SD = .37$) in the walls condition. Thus, increased boundary salience resulted in increased overall accuracy.

Between- and Within-Region Distance Estimates

We examined whether children and adults overestimated distances between target objects in different regions relative to target objects in the same region by entering between- and within-region distance estimation scores into an Age (4) × Boundary Condition (3) × Region (2, between or within) repeated-measures ANOVA with the first two factors as the between-subjects variables and the third factor as the within-subjects variable. This analysis revealed a main effect for region, $F(1, 132) = 32.62$, $p < .001$, and a significant Age × Region interaction, $F(3, 132) = 11.28$, $p < .001$.

Simple effects tests of the Age × Region interaction indicated that 7- and 9-year-olds' estimates of the distances between target locations in the same region and in different regions did not differ significantly (see Figure 3). Eleven-year-olds and adults, however, placed target objects farther apart in different regions than in the same region. These results indicate that 11-year-olds and adults overestimated distances between target locations in adjacent regions relative to distances between target locations in the same region, suggesting that they subdivided the space into regions.

The preceding analyses provided important information about whether participants overestimated distances between objects in different regions relative to distances between objects in the same region, but they did not provide information as to whether participants

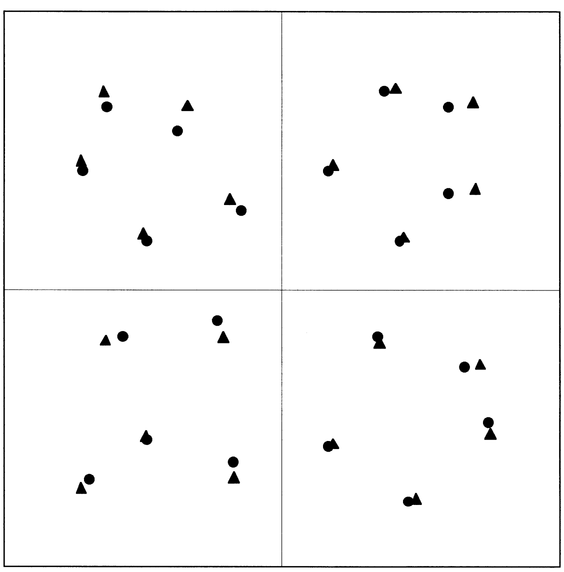

Figure 2 Diagram of true locations (circles) and remembered locations (triangles) averaged across age groups and boundary conditions in Experiment 1.

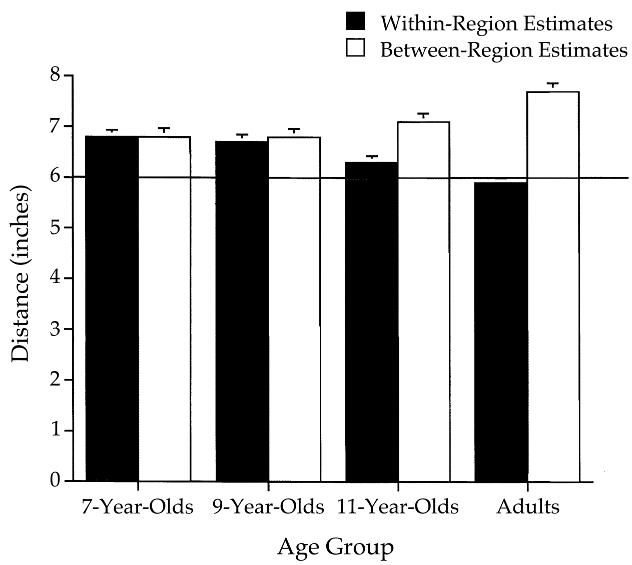

Figure 3 Mean within- and between-region distance estimates by age in Experiment 1. Line represents true distance between locations, 6 inches.

Table 1 Distance between Target Objects Located in the Same or Different Regions for Children and Adults in Each Boundary Condition in Experiment 1

	Distance (inches)	
Age and Condition	Same Region	Different Region
7-year-olds		
Walls	6.9 (.94)**	6.7 (.76)**
Lines	7.0 (.57)***	6.5 (.98)
No boundaries	6.5 (.57)	7.2 (1.2)**
9-year-olds		
Walls	6.7 (.83)*	6.6 (.79)*
Lines	6.8 (1.0)*	6.9 (.58)***
No boundaries	6.7 (.98)*	6.9 (1.4)*
11-year-olds		
Walls	6.0 (.70)	7.0 (.81)**
Lines	6.2 (.79)	7.5 (.91)***
No boundaries	6.7 (.67)**	6.9 (1.3)*
Adults		
Walls	5.9 (.51)	7.5 (.79)***
Lines	5.9 (.65)	7.8 (1.1)***
No boundaries	6.1 (.71)	7.7 (1.1)***

Note: Standard deviations are in parentheses. Asterisks denote results from one-sample *t* tests ($df = 11$) comparing the observed distance with the true distance, 6 inches.
* $p < .05$; ** $p < .01$; *** $p < .001$.

systematically overestimated and underestimated distances relative to the *true* distance between target objects (6 inches). To address this issue, we conducted separate one-sample *t* tests for each age group and condition comparing between- and within-region distance estimates to the actual distance (6 inches). As shown in Table 1, all groups (with the exception of 7-year-olds in the lines condition) overestimated the distances between locations in adjacent regions relative to the actual distances. None of the groups, however, significantly underestimated the distances between locations in the same region relative to the actual distance of 6 inches. In fact, 7- and 9-year-olds in both boundary conditions significantly *overestimated* the distances between locations in the same region, as did 9- and 11-year-olds in the no boundaries condition.

Bias toward the Region Centers

The hypothesis that children and adults overestimate distances between locations in different regions because they are biased toward the region centers was tested by entering center displacement scores into an Age (4) × Boundary Condition (3) ANOVA. This analysis yielded a significant effect for age, $F(3, 132) = 14.03$, $p < .001$. Seven-year-olds ($M = -.63$ inch, $SD = .52$), 9-year-olds ($M = -.46$ inch, $SD = .44$), and 11-year-olds ($M = -.31$ inch, $SD = .44$) placed objects farther from the region centers than did adults ($M = .02$ inch, $SD = .34$). Likewise, 7-year-olds placed objects farther from the centers than did the 11-year-olds.

The previous analyses provided important information about whether displacement toward the region centers was greater in some age groups and boundary conditions than in others. These analyses, however, did not provide information as to whether participants' center displacement scores were greater than the expected score of 0. That is, if participants displaced objects toward the region centers, then the mean difference between the true location–region center distance and the remembered location–region center distance should be greater than 0. To address this issue, separate one-sample *t* tests were conducted for each age group and condition to compare mean center displacement scores with an expected score of 0. Mean center displacement scores for adults did not differ significantly from 0. Mean center displacement scores for 7-, 9-, and 11-year-olds, however, differed significantly from 0. These participants placed the objects significantly *farther* from the centers of the regions than they actually were (see Table 2). Thus, none of the groups exhibited a bias toward the region centers.

Bias toward the Corners

Given the fact that participants did not displace objects toward the region centers, what then accounts for overestimation of distance across regions? Visual inspection of Figure 2 suggests that participants displaced the objects toward the corners of the model rather than the centers of the regions. To determine whether participants were, in fact, biased toward the corners of the space, a set of additional analyses was conducted. First, we calculated a corner displacement

Table 2 Center Displacement Scores for Children and Adults in Each Boundary Condition in Experiment 1

	Center Displacement Scores (inches)		
Age Group	Walls	Lines	No Boundaries
7-year-olds	−.72 (.53)***	−.63 (.49)**	−.55 (.57)**
9-year-olds	−.37 (.27)***	−.65 (.48)***	−.38 (.50)*
11-year-olds	−.25 (.45)+	−.28 (.30)**	−.41 (.56)*
Adults	.06 (.28)	.04 (.36)	−.05 (.40)

Note: Standard deviations are in parentheses. Positive values reflect displacement toward the region centers. Negative values reflect displacement away from the region centers. Asterisks denote results of one-sample *t* tests ($df = 11$) comparing the observed distance within the expected distance with no displacement, 0 inches.
* $p < .05$; ** $p < .01$; *** $p < .001$; + $p < .10$.

Table 3 Corner Displacement Scores for Children and Adults in Each Boundary Condition in Experiment 1

	Corner Displacement Scores (inches)		
Age Group	Walls	Lines	No Boundaries
7-year-olds	.37 (.42)*	.69 (.68)**	1.7 (1.4)**
9-year-olds	.74 (.90)*	.63 (.70)*	.99 (1.2)*
11-year-olds	.13 (.20)+	.62 (.28)***	.44 (.92)
Adults	.35 (.31)**	.56 (.36)***	.78 (.68)**

Note: Standard deviations are in parentheses. Positive values reflect displacement toward the corners. Asterisks denote results of one-sample t tests ($df = 11$) comparing the observed distance with the expected distance with no displacement, 0 inches.
* $p < .05$; ** $p < .01$; *** $p < .001$; + $p = .052$.

score for each participant by subtracting the distance between each remembered location and the corner of the region from the distance between the true location and the corner of the region. These differences were averaged across all 20 locations to obtain a single corner displacement score. Corner displacement scores were entered into an Age (4) × Boundary Condition (3) ANOVA. This analysis yielded a significant effect for boundary condition, $F(2, 132) = 6.84$, $p < .01$. Follow-up analyses revealed that corner displacement scores were higher in the no boundaries condition ($M = .98$ inch, $SD = 1.17$) than in either the lines ($M = .62$ inch, $SD = .53$) or the walls condition ($M = .40$ inch, $SD = .56$). The difference between the lines condition and the walls condition did not reach statistical significance.

Separate one-sample t tests were also conducted for each group comparing corner displacement scores to the expected score of 0. That is, if participants displaced objects toward the corners, then the mean difference between the true location–corner distance and the remembered location–corner distance should be greater than 0. As shown in Table 3, all groups significantly displaced objects toward the corners with the exception of 11-year-olds in the no boundaries condition. A corner displacement score for each individual location was also calculated and compared each of these scores with the expected score of 0 using one-sample t tests, collapsing across age groups and boundary conditions. These analyses revealed that subjects significantly displaced the individual locations toward the corners, with the exception of three locations: 8, 11, and 14. Thus, participants were biased toward the corners of the model rather than the centers of the regions.

Discussion

Contrary to predictions made by Huttenlocher et al. (1991), none of the age groups placed the objects closer to the region centers than were the actual objects. Instead, both children and adults displaced the objects toward the corners of the regions. As expected, both children and adults exaggerated distances between locations in adjacent regions. We found that adults and 11-year-olds significantly overestimated distances across regions relative to distances within regions, and significantly overestimated the distance between target objects in different regions relative to the true distance of 6 inches. Likewise, 7- and 9-year-olds in all boundary conditions, with the exception of 7-year-olds in the lines condition, overestimated distances between target objects in different regions relative to the true distance. Thus, consistent with other studies (Acredolo & Boulter, 1984; Allen, 1981; Cohen et al., 1978; Cohen & Weatherford, 1980; Hirtle & Jonides, 1985; Kosslyn et al., 1974; Laeng et al., 1998; Maki, 1982; Newcombe & Liben, 1982), there was clear evidence of subdivision effects in all age groups. These findings clearly demonstrate that subdivision effects occurred in the absence of bias toward the region centers.

What accounts for the lack of bias toward the region centers? One possibility is that the corners of the space, rather than the centers of the regions, served as prototypes in this experiment. As highly salient features of the space, the corners may have served as reference points for estimating location. The idea of a prototype at the corner of the region, however, is inconsistent with the previous findings of Huttenlocher and colleagues (1991). Another possibility is that children and adults were relying primarily on metric rather than on categorical information to estimate locations in this task. According to Huttenlocher et al. (1991), the "weight" given to the prototype depends on the precision of the metric information. When metric information is less precise, people give more weight to prototype information. Thus, remembered locations are biased toward the prototype. Conversely, when metric information is more precise, the tendency is to give less weight to the prototype, decreasing the amount of bias toward the prototype. In this experiment, the presence of visible boundaries during the test phase may have increased the precision of metric coding. This increased metric precision may have decreased the weight given to the prototype. As a result, participants did not displace the remembered locations toward the centers of the regions.

To test the hypothesis that increased uncertainty about metric information leads to increased bias toward the region centers, a second experiment was conducted in which we increased uncertainty about metric information by decreasing the available perceptual information for estimating locations during test. The procedures of Experiment 1 were repeated, except that the boundaries were removed prior to the test phase. Thus, participants attempted to remember the locations without the aid of the dots on the floor marking the locations and without the aid of the boundaries subdividing the space. It was hypothesized that if increased uncertainty about metric information leads to greater reliance on categorical information (i.e., prototypes), then both children and adults should displace objects toward the region centers. Additionally, as in the previous experiment, it was hypothesized that both children and adults would overestimate the distances between target objects in different regions.

EXPERIMENT 2

Method

Participants

Ninety-six 7-, 9-, and 11-year-olds, and adults, participated in this second experiment; 24 from each age group, with approximately equal numbers of males and females. The mean ages were 7,7 (*range* = 7,1–8, 2); 9,5 (*range* = 9,1 – 10,0); 11,7 (*range* = 11,1–12,3); and 20,5 (*range* = 18,2–29,11), respectively. Three additional 7-year-olds were tested but excluded because of experimenter error. Children were recruited from a child research participant database maintained by the Department of Psychology at the University of Iowa. Most children were from predominantly middle- to upper-middle-class White families. Adults participated to fulfill research credit for an introductory psychology course.

Apparatus and Materials

The same model house and locations were used as in Experiment 1.

Design and Procedure

Participants were individually tested in the laboratory and were randomly assigned to one of the two conditions, walls or lines. As in Experiment 1, Experiment 2 was divided into a learning phase and a test phase. The procedure for the learning phase was the same as in Experiment 1. The mean number of trials to reach criterion for 7-, 9-, and 11-year-olds, and adults, was 4.9 (SD = 1.8), 5.4 (SD = 1.6), 3.1 (SD = 1.4), and 3.1 (SD = 1.1), respectively. The procedure for the test phase was also the same as in Experiment 1, with the exception that the walls or lines used to subdivide the house were removed along with the dots on the floor marking the locations. Thus, participants attempted to replace the objects in the house with no dots marking the locations and no walls or lines subdividing the space.

After participants replaced all 20 objects, the experimenter thanked them and the participants left the room. The experimenter then removed the blue floor and replaced it with the grid of x and y coordinates. The experimenter recorded these coordinates for each object to the nearest ½ inch.

Coding and Measures

A placement was coded as "correct" if it was in the correct region and in the correct position within the configuration relative to the other object locations. Occasionally, participants preserved the overall configuration within a region, but incorrectly paired objects and locations. The x and y coordinates were used for these locations, regardless of whether the correct objects were placed in the locations. We used substituted objects for 5% of the locations for 7-year-olds (24 out of 480), 2.5% for 9-year-olds (12 out of 480), 0% for 11-year-olds (0 out of 480), and .83% for adults (4 out of 480). These substituted locations were used in all other analyses. Objects placed in the wrong quadrant or in a completely wrong configuration were omitted from all analyses. We omitted 3.33% of locations for 7-year-olds (16 out of 480), 4.2% for 9-year-olds (20 out of 480), .63% for 11-year-olds (3 out of 480), and .63% for adults (3 out of 480).

Intercoder reliabilities for object placements were calculated on 16 randomly selected participants using exact percent agreement. For each of these participants, two coders judged which object was placed at each of the 20 locations. Coders agreed on 99.7% of the 320 locations coded.

All scores were calculated in the same manner as in Experiment 1. Each participant received an overall accuracy score, a between-region distance estimation score, a within-region distance estimation score, a center displacement score, and a corner displacement score.

Results

Overall Accuracy

Figure 4 shows where participants in each age group and boundary condition placed the objects relative to the true locations. As in the previous experiment, children and adults placed the objects fairly accurately. The issue of whether participants in the various age groups and boundary conditions differed with respect to how accurately they remembered the

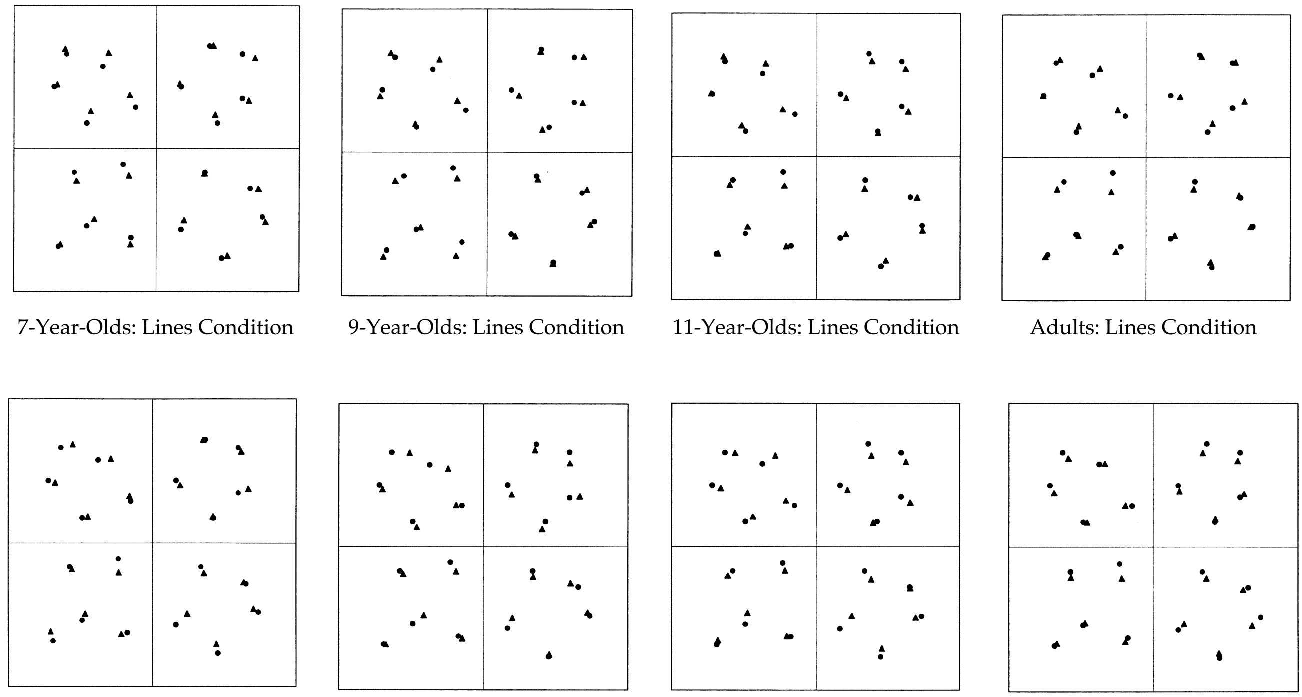

Figure 4 Diagram of true locations (circles) and mean remembered locations (triangles) for each age group and boundary condition in Experiment 2.

object locations was addressed by entering subjects' mean accuracy scores into an Age (7, 9, or 11 years, or adult) × Boundary Condition (walls or lines) ANOVA. This analysis yielded a significant effect for age, $F(3, 88) = 8.97, p < .001$. Adults placed the objects more accurately than did either the 7-, 9-, or 11-year-olds; and 11-year-olds placed the objects more accurately than did the 7-year-olds. The mean distance from the true locations was 2.0 inches ($SD = .34$), 1.9 inches ($SD = .39$), 1.8 inches ($SD = .39$), and 1.5 inches ($SD = .24$) for 7-, 9-, and 11-year-olds, and adults, respectively.

We also compared accuracy scores in Experiment 1 and Experiment 2 to determine whether removing the boundaries at the testing phase increased metric uncertainty. Accuracy scores were entered into an Age (4) × Boundary Condition (2) × Experiment (2, Experiment 1 or 2) ANOVA. (Participants in the no-boundaries condition from Experiment 1 were not included in this analysis.) This analysis yielded a significant effect for experiment, $F(1, 176) = 15.91, p < .001$, indicating that participants placed the objects more accurately in Experiment 1 than in Experiment 2. The mean distance from the true locations was 1.6 inches ($SD = .34$) in Experiment 1 and 1.8 inches ($SD = .38$) in Experiment 2. There was also a significant Boundary Condition × Experiment interaction, $F = 6.23, p < .05$. Simple effects tests revealed a significant effect of experiment for the walls condition, $F(1, 94) = 14.45, p < .001$, but not for the lines condition, $F(1, 94) = 1.05$, *ns*. As shown in Figure 5, the mean distance from the true locations was much higher in Experiment 2 than in Experiment 1 in the walls condition. This suggests that children and adults in the walls condition were more uncertain about metric information in Experiment 2 than in Experiment 1.

Between- and Within-Region Distance Estimates

To determine whether participants overestimated distances across regions relative to distances within regions, between-region and within-region distance estimation scores were entered into an Age (4) × Boundary Condition (2) × Region (2) repeated-measures ANOVA with the first two factors as the between-subjects factors and the third as the within-subjects factor. This analysis yielded a significant effect for boundary condition, $F(1, 88) = 10.85, p < .01$, indicating that overall distances were shorter in the walls condition ($M = 6.5$ inches, $SD = 1.4$) than in the lines condition ($M = 6.8$ inches, $SD = 1.4$). More important, there was a significant effect for region, $F(1, 88) = 75.66, p < .001$. Distances between target objects in dif-

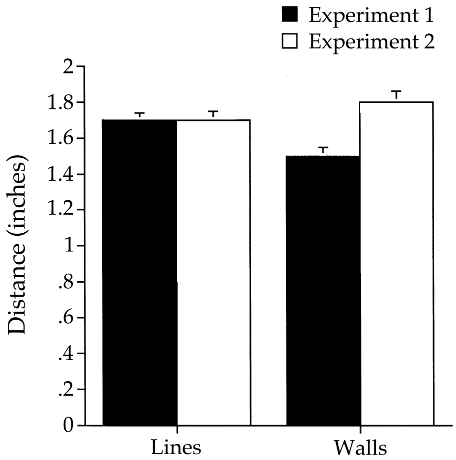

Figure 5 Mean distance from true locations by boundary condition and experiment.

ferent regions (M = 7.5 inches, SD = 1.3) were much larger than were distances between target objects within the same region (M = 5.8 inches, SD = .93). Thus, participants overestimated distances across regions relative to distances within regions.

Separate one-sample t tests also were conducted for each age group and condition comparing observed distances with the actual distance of 6 inches. As shown in Table 4, children and adults in all boundary conditions significantly overestimated distances between target objects in different regions relative to the true distance of 6 inches. Moreover, 11-year-olds and adults in the walls condition and adults in the lines condition systematically underestimated distances between target objects in the same region (see Table 4). Thus, all groups overestimated distances between targets in different regions, but only the oldest children and the adults in the most salient boundary condition underestimated distances between targets in the same region.

Table 4 Distance between Target Objects Located in the Same or Different Regions for Children and Adults in Each Boundary Condition in Experiment 2

	Distance (inches)	
Age and Condition	Same Region	Different Region
7-year-olds		
Walls	5.6 (.66)	7.4 (1.6)*
Lines	6.4 (1.3)	7.4 (1.6)**
9-year-olds		
Walls	6.0 (1.2)	6.7 (1.0)*
Lines	6.0 (.84)	7.4 (1.4)**
11-year-olds		
Walls	5.3 (.81)*	8.0 (1.2)***
Lines	5.9 (.80)	7.6 (.85)***
Adults		
Walls	5.3 (.67)**	7.3 (1.3)**
Lines	5.5 (.64)*	8.0 (.86)***

Note: Standard deviations are in parentheses. Asterisks denote results of one-sample t tests (df = 11) comparing the observed distance and the true distance, 6 inches.
$^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

Bias toward the Region Centers

Two sets of analyses were carried out to test whether estimates of location were biased toward the centers of spatial regions. First, center displacement scores were entered into an Age (4) × Boundary Condition (2) ANOVA. This analysis yielded no significant effects. Separate one-sample t tests were conducted for each age group and condition, comparing center displacement scores to the expected score of 0. As shown in Table 5, these analyses revealed that 11-year-olds and adults in the walls condition significantly displaced objects toward the center of the regions. Thus, only the 11-year-olds and the adults in the most salient boundary condition exhibited the prototype effect hypothesized to underlie distortions in estimates of location.

Bias toward the Corners

As in Experiment 1, a series of analyses were conducted to determine whether participants were biased toward the corners of the model. Corner displacement scores were entered into an Age (4) × Boundary Condition (2) ANOVA. This analysis yielded a significant effect for boundary condition, $F(1, 88) = 9.21$, $p < .01$. Corner displacement scores were significantly higher in the lines condition (M = .66 inch, SD = .99) than in

Table 5 Center Displacement Scores for Children and Adults in Each Boundary Condition in Experiment 2

	Center Displacement Scores (inches)	
Age Group	Walls	Lines
7-year-olds	.14 (.50)	.17 (.51)
9-year-olds	.18 (.52)	−.17 (.74)
11-year-olds	.34 (.46)*	.08 (.38)
Adults	.40 (.50)*	.17 (.35)

Note: Standard deviations are in parentheses. Positive values represent displacement toward the region centers. Negative values represent displacement away from the region centers. Asterisks denote results of one-sample t tests (df = 11) comparing the observed distance with the expected distance with no displacement, 0 inches.
$^{*}p < .05$.

Table 6 Corner Displacement Scores for Children and Adults in Each Boundary Condition in Experiment 2

	Corner Displacement Scores (inches)	
Age Group	Walls	Lines
7-year-olds	−.09 (.68)	1.27 (1.2)**
9-year-olds	.21 (1.3)	.69 (1.3)+
11-year-olds	.07 (.68)	.27 (.36)*
Adults	.11 (.98)	.41 (.44)**

Note: Standard deviations are in parentheses. Positive values represent displacement toward the corners. Negative values represent displacement away from the corners. Asterisks denote results of one-sample *t* tests ($df = 11$) comparing the observed distance with the expected distance with no displacement, 0 inches.
* $p < .05$; ** $p < .01$; + $p < .10$.

the walls condition ($M = .08$ inch, $SD = .92$). Separate one-sample *t* tests were also conducted for each group comparing corner displacement scores with the expected score of 0. As shown in Table 6, all age groups in the lines condition significantly displaced the objects toward the corners; however, none of the age groups in the walls condition displaced the objects toward the corners. Thus, it appears that participants were more likely to displace the objects toward the corners in the less salient boundary condition.

Discussion

The results of this experiment revealed some evidence of bias toward the centers of spatial regions. Both 11-year-olds and adults in the walls condition significantly displaced objects toward the centers of regions. In the lines condition, however, both children and adults significantly displaced the objects toward the corners of the model. Again, all age groups subdivided the space into regions. Even though the true distance between target objects was the same, both children and adults placed target objects further apart in different regions than in the same region. In addition, both children and adults significantly overestimated distances between target objects in different regions relative to the actual distance of 6 inches.

These findings lend some support to the idea that categorical information receives greater weight as uncertainty about metric information increases. In fact, analyses of accuracy scores for participants in both the lines and walls conditions revealed that children and adults placed the objects more accurately in Experiment 1 than in Experiment 2. This was particularly true for participants in the walls condition. In other words, when the walls were visually available during testing, both children and adults placed the objects more accurately than when the walls were absent. Thus, it appears that participants in the walls condition were more uncertain about metric information in Experiment 2 than in Experiment 1. This may help to explain why the older children and adults in the walls condition exhibited bias toward the region centers in Experiment 2 but not in Experiment 1.

GENERAL DISCUSSION

The results of this investigation clearly show that with the exception of the 11-year-olds and adults in the walls condition in Experiment 2, children and adults did not displace objects toward the region centers. Nonetheless, children and adults in both experiments exaggerated distances across boundaries. With the exception of the younger children in Experiment 1, children and adults in all boundary conditions overestimated distances between locations in different regions relative to distances between locations in the same region. Likewise, both children and adults overestimated the distance between locations in different regions relative to the true distance between those locations. These findings are consistent with other studies showing that children and adults overestimate distances between locations in different regions (Acredolo & Boulter, 1984; Allen, 1981; Cohen et al., 1978; Cohen & Weatherford, 1980; Hirtle & Jonides, 1985; Kosslyn et al., 1974; Laeng et al., 1998; Maki, 1982; Newcombe & Liben, 1982).

One key issue raised by these results is how to explain subdivision effects in the absence of prototye effects. That is, if children and adults did not displace objects toward the region centers, what then accounts for the overestimation of distance across regions? At a descriptive level, it appears that participants displaced the objects toward the corners of the model rather than the centers of the regions (see Figures 2 and 4). A visual inspection of Figure 2 indicates that participants in Experiment 1 displaced virtually all the objects toward the corners of the model. With the exception of the participants in the walls condition in Experiment 2, this general pattern appears to characterize all groups. Displacing the objects toward the corners of the model necessarily resulted in greater distances between objects in different regions. Hence, overestimation of distance across regions was the result of bias toward the corners of the model rather than bias toward the centers of the regions.

What implications do these findings have for the model of spatial coding proposed by Huttenlocher et al. (1991)? First, it is important to point out that there are several differences between the task used here and the tasks used in previous studies by Huttenlocher and colleagues. Most important perhaps is the fact that the present study involved memory for multiple locations whereas previous research has involved memory for single locations (for an exception, see Newcombe et al., 1999). In addition, most other studies requiring subjects to coordinate two dimensions (e.g., angle and radius), have used a circular space rather than a square one (Huttenlocher et al., 1991; Sandberg et al., 1996; for an exception, see Newcombe et al., 1999). Despite these differences, it seems clear that spatial prototypes (if they exist) are not always at the center of a geometrically defined region. One possibility is that the corners of the model served as prototypical locations in the present study (see Newcombe & Huttenlocher, 2000). Clearly, the corners were a salient feature of the space. In fact, analyses of bias toward the corners of the model revealed that participants in all conditions, with the exception of the walls condition in Experiment 2, displaced the objects toward the corners. This answer, however, is unsatisfying for two reasons. First, one usually thinks of the prototype as being at the center of the category (i.e., region) rather than at the edge of the category. Second, it is difficult to explain why the prototype would be at the corners of the model for some of the groups and at the centers of the regions for others—that is, the 11-year-olds and adults in the walls condition in Experiment 2.

The results of this investigation suggest that a more general framework is needed for understanding how children and adults estimate location. In broad terms, we propose that estimates of location are the result of a retrieval process involving the integration of perceptually available and remembered sources of information about location. This retrieval process is ordinarily weighted toward perceptually available information. That is, children and adults prefer to use stable, perceptually available frames of reference to estimate location. When perceptual information is unstable, however, children and adults are forced to rely more on remembered frames of reference. The two key elements of this framework are specifying (1) what perceptual information and what remembered information are used for estimating location, and (2) how perceptual and remembered information are weighted to arrive at estimates of location. Note that this framework is broader than, but not necessarily incompatible with, the one outlined by Huttenlocher et al. (1991) and by Newcombe and Huttenlocher (2000).

How does this framework apply to the results of the present investigation? In Experiment 1, children and adults in all boundary conditions were biased toward the outside corners of the model. Given that all the perceptual information except for the dots on the floor marking the object locations remained stable across the learning and testing phases of Experiment 1, children and adults relied more heavily on perceptual than remembered information for estimating the object locations. Furthermore, it appears that the outside corners of the model served as an important source of perceptual information for estimating location. As highly distinctive features of the space, the corners may have served as landmarks. Previous studies have shown that even infants and toddlers use the corners of a space to code location (Hermer & Spelke, 1996; Keating, McKenzie, & Day, 1986). Moreover, studies with older children and adults (Acredolo, 1977; Allen, Siegel, & Rosinski, 1978; McNamara & Diwadkar, 1997; Newcombe et al., 1999; Sadalla, 1988; Sadalla et al., 1980; Siegel, Herman, Allen, & Karasic, 1979) have revealed systematic biases in memory for distance relative to a landmark. For example, studies by McNamara and Diwadkar (1997) and Sadalla et al. (1980) showed that the remembered distance from a nonreference point to a reference point was smaller than the remembered distance from a reference point to a non-reference point. Thus, it appears that estimates of location are biased toward landmarks. This may explain why participants displaced objects toward the corners of the model in the present investigation.

Given that the corners were perceptually available in both experiments, why did 11-year-olds and adults in the walls condition in Experiment 2 displace the objects toward the region centers? In Experiment 2, it is important to note that much of the perceptual information that was available during the learning phase was absent during the test. Although the corners of the house were perceptually available during both the learning and test phases, the dots on the floor marking the object locations and the boundaries subdividing the space were available during the learning phase but not during the test phase. Hence, participants in Experiment 2 were forced to rely much more on remembered information. This may have shifted the relative weighting toward a greater reliance on remembered information rather than perceptually available information. One important source of remembered information may have been the configuration of the objects themselves. The configurations may have been especially salient in this task given that participants had several opportunities to view the entire array of objects during the learning phase. Reliance on this information, however, appears to be a function of both boundary salience and age. In terms of boundary salience, highly visible boundaries such as opaque walls may have served to highlight the groupings of objects. In terms of age, older children and adults may have been more adept at remembering configural information (Uttal, 1994). This may explain why only the 11-year-olds and adults in the walls condition showed bias toward the region centers. The idea of a shift in how children and adults in Experiment 2 weighted the perceptually available information based on the corners of the model and the remembered information about the configurations is further supported by the finding that 7- and 9-year-olds in the walls condition did not exhibit displacement toward either the corners or the region centers. For these two younger age groups, it appears that the pull toward the corners may have been offset by a pull toward the configuration centers.

One additional question is why would the older children and adults underestimate distances between the locations within configurations? There are at least two possibilities. One is that estimates of location were biased toward a prototype at the geometric mean of the configuration. (In the present investigation, it was not possible to distinguish between prototypes at the centers of regions and prototypes at the centers of configurations because our configurations were almost perfectly centered on the centers of the regions.) This idea is similar to Rosch's original notion of a prototype as a summary representation of all members of a category (Rosch, 1973, 1975a, 1975b). One advantage of this conceptualization of a spatial prototype is that the location of the prototype can be specified by the locations that actually exist within the space rather than by a predefined location (e.g., the center) within a geometrically defined space. Note that in many cases, the location of the prototype would be close to the center of a region if the locations within the region are distributed relatively evenly. Another possibility is that the older children and adults underestimated distances between locations within configurations because these locations are highly associated in memory. This idea is consistent with spatial priming studies showing that locations within a region "prime" each other more readily than locations in other regions (Hirtle & Jonides, 1985; McNamara, 1986; McNamara, Hardy, & Hirtle, 1989). One implication of this idea is that increasing the strength of the associations between locations in a configuration should result in stronger biases toward the center of the configuration. Further research is necessary, however, to determine which of these two explanations best accounts for underestimation of distance between locations.

In conclusion, the framework outlined here provides a starting point for thinking about how children and adults integrate perceptually available and remembered information in their estimates of location. Two important features of this framework are (1) specifying what information is available for estimating location, and (2) specifying how perceptually available and remembered information are weighted when estimating location. Future investigations that manipulate the salience and stability of perceptual and remembered information are necessary to further understand the cognitive processes underlying the development of location memory.

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