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The Coding of Spatial Location in Young Children

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The present paper is concerned with the representation of spatial location in young children. We report six experiments which indicate that the basic framework for coding location is present early in life. Later development consists of an increasing ability to impose organization on a broad range of bounded spaces. In the first four experiments, we examine whether very young children, like adults, can locate objects in a homogeneous space, estimating by eye the location of those objects within some frame of reference. Results show that children from 16 to 24 months are able to use distance to code the location of an object hidden in a large sandbox. Coding of distance is not dependent on a juxtaposed outside landmark, nor on the child's own position. In the last two experiments, we examine whether young children, like adults, code the location of an object hierarchically—not only as being in a particular location in a bounded space, but also as being within a larger segment of that space. The pattern of bias in responding provides evidence for such two-level coding of location. The age at which children impose subdivisions on a space depends on the nature of that space. The sandbox is subdivided by 10-year-olds, but not by 4- or 6-year-olds. In contrast, a rectangle of similar shape drawn on paper is subdivided even by 4-year-olds. We argue that 16-month-olds in the sandbox studies also use hierarchical coding, treating the whole box as a category, although they do not divide it into subsections.

The present paper is concerned with spatial development in young children. There are, at present, sharply contrasting views of spatial development. One view, originating in the work of Piaget (Piaget & Inhelder, 1948/1967; Piaget, Inhelder, & Szeminska, 1960), holds that spatial competence emerges slowly over childhood, constructed from humble beginnings in simple reflexes. An alternative view holds that the essential features of spatial competence are present at the start (e.g., Landau, Gleitman, & Spelke, 1981). Here, we evaluate these contrasting views

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with respect to one aspect of spatial development. In particular, we examine young children's ability to locate objects in space. To anticipate, the studies indicate that the basic framework for dealing with spatial location is present very early. The critical elements are the use of distance information to code particular locations, the use of larger segments of space to code locations within a region, and the use of both levels of information together to estimate the locations of objects in space. The studies also show that there is later development in the range of spaces which children segment into regions, contributing to the overall accuracy of location coding with age.

DISTANCE CODING

To code the locations of objects in space, it is essential to be able to establish their distance from one or more landmarks, unless the objects happen to be adjacent to or surrounded by those landmarks. That is, distance must be used to locate an object in a plane—either two distances using Cartesian coordinates, or distance and angle using polar coordinates. However, in the Piagetian view, infants and young children can only represent that an object is in a target location when that location is adjacent to or is surrounded by a landmark. The ability to use distance information in coding location is said to emerge only in middle childhood (Piaget, Inhelder, & Szeminska, 1960). This conclusion is based on children's ability to use measurement instruments such as rulers, in judging spatial distances, and on their ability to reproduce arrays using models of a space.

Piaget's evidence that children do not preserve information about distance until they are approximately 6 years old rests on tasks that may mask the underlying ability to code distance. For instance, he found that children report that distances between two points become smaller when an object is interposed between those points. However, more recent evidence (Miller & Baillargeon, 1990) indicates that if preschool children are asked to choose an object to span a particular distance, they are not affected by an interposed object. These investigators argue that 3-year-olds *do* conserve distance when assessed in this way. Similar conclusions regarding early distance judgments have been reached by Bartsch and Wellman (1988), Fabricius and Wellman (1993), and Jansen op de Haar and Fabricius (1993).

In another of Piaget's studies, 4- and 5-year-old children were shown a display village that included an array of objects (Piaget & Inhelder, 1967). They were then shown a model of that display village presented in a different orientation on which the array of objects was to be reconstructed. Children could only place targets correctly if they were contiguous with or surrounded by distinctive landmarks in the display village. This was taken to show that they were unable to use distance in coding location. However, there are reasons why children who *can* code distance might fail to do so in this task. In particular, the model was rotated with respect to the original array. Even adults may have difficulty establishing location when maps or models are oriented differently than the space they represent, especially when the models are located within the same larger space (Newcombe & Huttenlocher, 1992). When models are not rotated, children perform much better (Pufall, 1975).

In assessing early distance coding, it is important to present tasks that only require children to use distance directly (not via models or maps) to locate a desired object. DeLoache and Brown (1983) and Mangan and Nadel (1990) used such tasks with children under 2 years of age. In these studies, a toy was hidden under one of a set of identical covers placed in various locations. When the covers are adjacent to distinctive landmarks, locations can be coded relative to those landmarks (e.g., "the cover near the door"). However, when there are several identical locations and these are not adjacent to landmarks, distinguishing the target location from others may require establishing its distance from one or more landmarks. In the DeLoache and Brown and the Mangan and Nadel studies, children under 2 years of age could only find an object that was adjacent to a distinctive landmark, showing, apparently, that distance was not used. However, a task with several covers under which the target could be located may not be ideal for evaluating the emergence of distance coding since, even if the child can use distance to code the location of a cover relative to landmarks, the necessity of choosing among of a set of alternatives may give rise to difficulties.

Landau, Gleitman, and Spelke (1984) have used a task that required the use of distance information to code location. They studied a blind child at approximately 3 years. They familiarized the child with the relative locations of a set of objects by having her traverse certain paths among pairs of objects. Then they determined whether she could successfully traverse a new path. The child followed a fairly direct route along this new path. In having the child follow a new path, the task required not only distance coding but also an inference about a new distance based on two known distances.

To assess the initial emergence of distance coding, it is desirable to use the simplest possible task, a task in which children's ability to use distance in coding item location can be assessed without requiring a spatial inference. In addition, the task should require locating only a single object and should be suitable for sighted children. Such a task could involve hiding an object from sight in a continuous space; for example, an object could be buried in a sandbox.[1] Finally, the task should require estimation of distance along just one dimension (e.g., a long and narrow sandbox).

In assessing whether young children use distance information to code object location, it is important to realize that estimation of distance by eye will not be exact. Even adults' estimates will be imprecise, and those of young children may be more so. Thus large errors on particular trials will occur, even if an individual is coding distance. The way to answer the question of whether distance is being coded, despite inexactness of measurement, is to obtain several responses at each true location and examine the distribution of those responses. If each response distribution is centered at or near the corresponding true location, with the means of responses at particular locations ordered in the same way as the true locations and with the distances between them roughly preserved. then those locations must have been coded, albeit inexactly on each particular occasion.

To be certain that children are actually using distance information, it is important to make sure that there are not distinctive landmarks close to hidden objects. Also to determine that an item is coded as being a particular distance from an outside landmark rather than from themselves, it is important to have the child move before retrieving an object. These issues are examined in Experiments 1 through 4 below.

HIERARCHICAL CODING

As we have noted, Piaget and Inhelder argue that the representation of location in early childhood is based on contiguity and enclosure. They also argue that, in older children and adults, representation is based on objective measurement of distance (presumably, even when that estimation is done "by eye"). In this view, systematic bias in reporting location in relation to distal landmarks should not occur in adults. That is, Piaget's view leads to the prediction that children will show biases in spatial judgment, but that these will disappear when mature understanding is attained.

There are two studies (Allen, 1981; Kosslyn, Pick, & Fariello, 1974) that have been taken to show that children's estimates of spatial location are more affected by subdivisions of a space than those of adults. Kosslyn et al. (1974) reported that 5-year-olds exaggerated inter-object distances across functional as well as perceptual barriers, while adults showed overestimations only across perceptual barriers. However, Newcombe and Liben (1982) have argued that the results of Kosslyn et al. were due to the fact that subjects were required to use a rank ordering measure

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[1] In fact, this method has been used to study spatial representation in animals (Cheng and Gallistel, 1984).

which made excessive demands on the younger subjects. The evidence for this interpretation was that no developmental interaction was found when subjects were given a task involving distance estimation. Allen (1981) asked subjects to judge the proximity of locations along a walk simulated by a slide sequence. He found that 8-year-olds, unlike adults and 11-year-olds, used only subdivision information; they did not use distance information to code location within subdivisions. However, the task may have been too difficult for 8-year-olds; rather than having to make direct distance estimates, children had to determine distances from a sequence of slides. It should be noted that there are other developmental studies of subdivision effects which show little or no evidence of developmental change (Anooshian & Wilson, 1977; Cohen, Baldwin & Sherman, 1978; Cohen & Weatherford, 1980).

The Piagetian view conflicts with recent results showing that adults exhibit systematic bias in estimating spatial location. The bias, like that in children, consists of a "subdivision effect." Adults' estimates of spatial location are affected by divisions of space into subspaces, whether achieved objectively by physical barriers such as rivers or mountains, or subjectively through division into neighborhoods based on functional grouping, etc. (Hirtle & Jonides, 1985; Maki, 1981; McNamara, 1986; McNamara, Hardy, & Hirtle, 1989; Newcombe & Liben, 1982; Stevens & Coupe, 1978). In fact, even Kosslyn et al. (1974) found that adults misjudged distance across perceptual barriers. In short, adults show bias that could be described as a "neighborhood effect," treating objectively equal distances as unequal; if two items a fixed distance apart are on the same side of some boundary, they are estimated as closer than if they are on opposite sides of that boundary.

It has been argued, notably by Hirtle and Jonides (1985) and by McNamara et al. (1989) that bias in reports of spatial location indicates that people's representations of space are biased. An alternative view has been presented by Huttenlocher, Hedges, and Duncan (1991) who point out that bias in reports of location do not necessarily imply bias in memory for location. Consider the possibility that the location of an item in a bounded space (e.g., a dot in a circle) is represented at two levels of detail; a "fine grain" location (consisting of polar coordinates for the circle) and a category location (consisting of a quadrant of the circle). Consider further that the fine grain coding is inexact since it is done "by eye," but is unbiased, in the sense described above; that is, that the mean of the distribution of people's responses at a given location lies at the true location, showing that the true location was coded. Subjects might combine fine grain and category information in estimating an item's location; that is, category information may be used to adjust an inexact fine grain memory. Using category information in estimation leads to systematic bias towards the category prototype in responding, but nevertheless increases overall accuracy by decreasing the variability of responses. Category information is weighted more highly when fine grain coding is less exact. Thus, bias is greater for points far from landmarks (such as boundaries).

Huttenlocher et al. (1991) showed subjects a circle with a dot in it. Subjects then reproduced the location of the dot in a comparable circle from memory. Their responses showed a consistent pattern of bias, as indicated in Fig. 1. The arrows show that the direction of displacement of dots (bias) was toward the center of mass of each quadrant. The bias can be interpreted by positing that subjects divide the circle into quadrants, imposing on it horizontal and vertical axes. They code both the polar coordinates of the dot (a fine grain location) and the quadrant (category) it appeared in. It was possible to account for all the observed bias by positing that the fine grain coding of location was inexact but unbiased, and that subjects adjusted their inexact memory for the fine grain location of the dot by weighting it with a category prototype lying at the center of mass of the quadrant. Huttenlocher et al. also showed that, even though

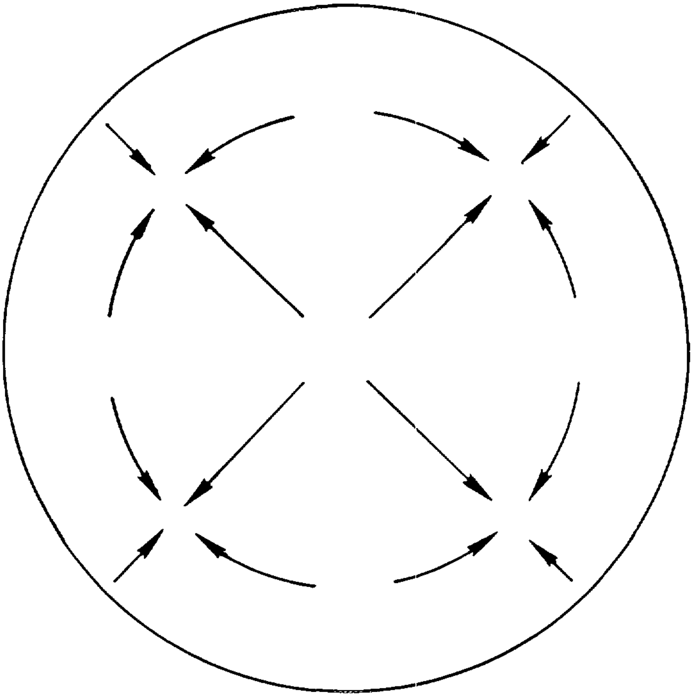

FIG. 1. Schematic representation of bias in reports of location in a circle.

weighting a fine grain value with a prototype resulted in bias in reporting location, it increased overall accuracy compared to what would be expected from use of unadjusted fine grain values.

The existing literature does not provide evidence about the development of hierarchical representation in the coding of spatial location. To explore this issue, it is important to use the simplest of bounded regions. A person will only divide a region into subsections if the shape of that region can be apprehended. Hence the bounded region used should be as simple as possible, perhaps involving only a single dimension, as in the sandbox. The size of the region may be relevant as well, since it may affect the ability to apprehend a shape.

At present, there are alternative possibilities concerning the development of hierarchical organization. First, there may, initially, be no hierarchical coding. One possibility is that young children code neighborhood but not fine grain location, as Piaget argues; in this case, they should show considerable bias due to neighborhood, and that bias should decrease with age. Alternatively, they might code fine grain location but not category (neighborhood) until they reach some particular age; in this case, they will show little bias at early ages, and bias should increase with age. A final possibility is that children might code location hierarchically from the start; in this case, bias would be found at all ages. We examine these alternatives in Experiments 5 and 6 below.

EXPERIMENT 1

The first experiment concerns the emergence of children's use of distance information in coding object location. We presented a hiding task to children under 2 years of age, using a trough-shaped sandbox 5 feet long and filled with sand. The sandbox constituted a homogeneous bounded space in which a small object could be hidden. Children watched a toy being hidden and indicated the location of the toy by pointing to the spot where it was hidden.

Prior to the initiation of this experiment, five adults were tested to determine if sand surface features resulting from the toy burial could be used as clues to the hidden object's location. Subjects first viewed the sandbox and then left the room. A toy was then buried according to the method to be used with the children. The adult subject was then brought back in the room and was asked if he could determine where the toy had been buried. In no case could the subjects determine the burial location from looking at the surface of the sand.

Method

Subjects. Subjects for this experiment were 30 children between 16 and 24 months of age. They were recruited by ads in campus newspapers, signs, or class announcements at the

University of Chicago and Temple University. These invited parents of children between 16 and 24 months of age to participate in a study on the development of memory. Twelve male and 8 female subjects participated in the first variation of the study. The mean age of the subjects was 20 months, 1 day. Subjects for the other variation of the procedure were all from Chicago. Five males and 5 females participated in this experiment. The mean age of the subjects was 19 months, 4 days.

Materials. The sandbox was constructed out of ½-in. plywood. It was 60 in. long, 16 in. wide and 12 in. deep. A false bottom was added 5 in. down from the top. The box was painted red. The sandbox was filled with sterile play sand. A decorative pattern was created along the outside top edge of the box using black and white plastic tape on the side away from the child. White marks were placed every 6 in. along the length of the box and black marks were placed at intermediate points between the white marks. This pattern served as a guide for the experimenter in placing toys and as a scale for scoring the data. A VHS video recorder and tripod stood facing the sandbox and child. The experimental sessions were recorded and the video tapes were used in scoring the data. A set of 12 different small plastic toys were selected from the local toy store. The toys were approximately 2.5 by 1.5 in. Toys included Sesame Street characters, cars, and colorful balls. The sandbox was located in the center of a room with no near landmarks, but with distal landmarks (e.g., doors) visible.

Procedure. The general procedure was explained to the parent. The parent was told that the experimenter would be burying toys in the sandbox, in full view of the child, and that the child's task was, after a brief delay, to indicate where he/she though the toy was buried. The parent was instructed to sit on the floor behind the sandbox and hold the child behind a black line on the floor, 18 inches from the sandbox and equidistant from both ends. The parent was given an eye mask which she lowered before each trial in order to prevent inadvertent parental prompting of the buried toy's location. The parent was told that she could verbally encourage the child to find the toy but not to mention where to look or physically direct the child in any way.

The experimenter, positioned on the opposite side of the sandbox from the child, held up one of the toys and said (for example), "Tommy, look at Grover! I'm going to bury Grover in the sand. You watch!" The experimenter then buried the toy in the sand at one of nine randomly preselected locations. A different random order was used for each child. The experimenter then stood up and moved straight back from the box, out of the field of the video camera. There were two variations of the distraction procedure.

In the first procedure, the experimenter called the child's name to distract attention from the surface of the sand. Once eye contact was made with the experimenter, the child was asked to "find Grover," and the parent was instructed to let the child go. Encouragements such as "Do you know where Grover is?" and "Show Mommy where Grover is hiding" were used until the child indicated a location either by digging or touching a place on the surface of the sand. Then the experimenter would provide assistance in obtaining the toy. If the child became distracted or failed to respond, the toy was dug up by the experimenter and a new trial was started. There were nine trials, with a toy being buried once at each of nine locations. Any unsuccessful trials were repeated at the end. In the second procedure, after the experimenter stepped back from the sandbox, the parent physically turned the child away from the sandbox, gave him a kiss, and turned him back toward the sandbox before allowing him to search for the toy.

Results and Discussion

The data were scored by viewing the videotapes and obtaining a response location for each toy. The length of the sandbox was represented by a 0–10 scale (marking off 6-in. segments), with each whole number representing one of the evenly spaced hiding locations or, in the cases of 0 and 10, the edges of the box (0 represented the end of the box to the child's left at the time of seeking). Increments for scoring responses were ¼ of a unit or 1.5 in. The decorative pattern along the edge of the box served as a "ruler" for making score judgments.

Single hand responses, where the child indicated a specific location in or on the sand with one hand, were assigned the numerical score corresponding to the point of indication. Criteria were assigned for the consistent scoring of locations for single hand responses where the child swept his hand across an area and for various types of two handed responses. A note was made on the child's score sheet of the type of response.

In several instances children made two responses on a given trial. We examined the data using two methods. One analysis involved only the first response made on a given trial. The other analysis used the response which was most accurate. The patterns of error were the same. Therefore, in cases where the child made more than one response to a single actual location, the response closer to the actual location was used in the final analysis. In viewing the videotaped experimental sessions, it was often clear that the child's initial response was unintentional or was recognized as incorrect by the child. No experimenter prompting was ever given in the case of an incorrect response. This further justifies giving the child the benefit of his spontaneous self-corrections by using his most accurate response.

Another observer rescored 15% of the data. The correlation between the two sets of scores was extremely high ($r = .99$). Means and standard deviations were calculated for the responses corresponding to each of the actual locations and are shown in Table 1. If responses were, on average, accurate, the means at each location would fall on the diagonal line in Fig. 2. This figure shows the means of responses at each actual location plotted against actual locations. It can be seen that the means of the responses

TABLE 1

Actual location (in inches)	Mean response location (in inches)	Standard deviations
6	8.53	4.00
12	14.18	3.22
18	20.32	4.84
24	25.55	2.81
30	30.29	4.82
36	33.45	4.63
42	40.46	4.28
48	45.05	5.14
54	50.81	4.04

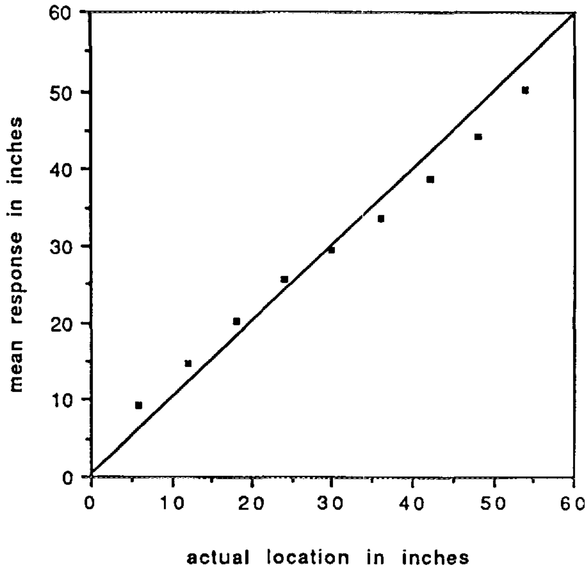

FIG. 2. Mean response locations for Experiment 1: 16- to 24-month-olds—sandbox.

are ordered in the same way as the actual locations and, indeed, lie close to the actual locations.

An ANOVA was performed to examine the effect of the actual location of the hidden object on the magnitude and direction of the subjects' errors. Results were highly significant, $F(8,222) = 8.56$, $p < .0005$. This result substantiates the pattern observed in Fig. 2. That is, responses are systematically related to the hidden object's true location. To examine effects of gender, age and experimental condition (broken visual fixation versus disrupted physical orientation) we computed ANOVAs crossing each of these factors with actual locations. All results except for actual location were insignificant. Additional analysis of the effects of age on the magnitude of error also was performed. A Pearson correlation between error magnitude and age was only .12, showing that there were no age changes across the range studied.

These results do not provide support for the Piagetian view that the ability to use distance information in coding location develops over an extended age period. Estimation of distance by eye is well developed by 16 months of age. Having obtained such clear-cut results, a further question might be raised; one might ask whether there were local landmarks in the room that could have been used to code the locations of objects so that distance did not have to be coded. That is, an object might be coded as directly in front of a door, or at the side of a cabinet. Given the distance of the sandbox from such landmarks, this seems unlikely. However, the strictest test would be to enclose the entire sandbox area in a homogeneous surround. This was the purpose of Experiment 2. If such an experiment further supports the conclusion that distance coding is used in locating objects, a second question arises: whether distance coding is in relation to the child him- or herself (i.e., egocentric) or is in relation to the outside framework (an end of the sandbox). These alternatives could be assessed by having the child move to a new position after the toy is hidden and before searching for it. Egocentric coding, but not coding in relation to the box, would lead to systematic error in the direction to which the child was moved, an issue examined in Experiment 3.

Finally, let us consider bias. As shown in Fig. 2, we found very little bias in subjects' responses. What bias *is* present can be best examined by directionally computing errors; that is, by subtracting the actual location from the subject's response, as shown in Fig. 3a. Positive error indicates a mean response to the right of the actual location while a negative error indicates a mean response to the left of the true location. Note that the subjects' responses, while being quite accurately placed (i.e., near the true locations), are biased toward the center of the sandbox. That is, responses for locations to the left of center are slightly misplaced to the right while the opposite is true for locations right of center. Responses for locations at the center were not biased. Variability of responses at the center was not less than at other locations, but errors were unsystematic.

Bias toward the center is predicted by a model in which inexactly coded locations are weighted with a centrally located prototype. Such bias would be linear if uncertainty at the fine grain level is equal at all locations. However, if uncertainty is reduced close to the ends of the box, then errors will be less there than predicted by a linear model, leading to a better fit for a cubic relation. When polynomial curves were fit to the mean error data (Fig. 3b), the fit of a linear function was excellent (R^2 = .95), but the best fit was obtained by a cubic function (R^2 = .99); the fit of the cubic function was significantly better than the fit of a linear function, $F(2,5) = 9.77$, $p < .05$.[2]

There are several possible explanations for bias toward the center of

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[2] It might be argued that this pattern arises from the fact that there is physically more room in one direction than in the other, for all positions except the middle one. To evaluate this, we also examined bias after discarding, for each hiding location, errors in one direction that exceeded those physically possible in the other direction. That is, for positions 1 and 9 we discarded errors larger than 6 inches, for positions 2 and 8 we discarded errors larger than 12 inches, and so on. Note that this procedure retains large errors in the middle of the box, but discards them increasingly towards the ends, thus providing a very conservative test of our hypotheses. Nevertheless, the results reported here, and later in the paper, were replicated with the data culled in this way.

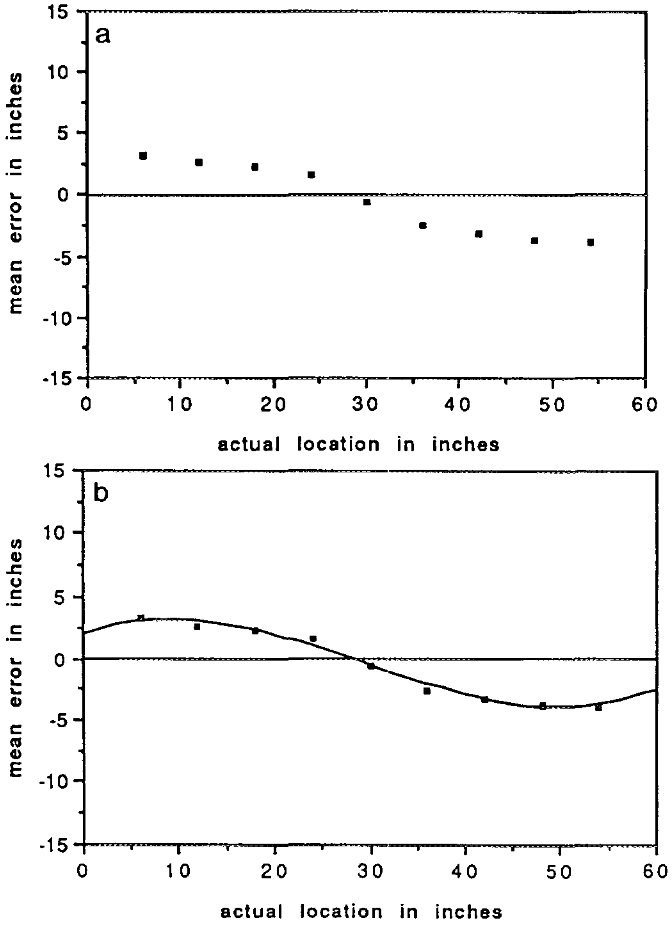

FIG. 3. (a) Mean directed errors for Experiment 1: 16- to 24-month-olds—sandbox. (b) Polynomial curve fit to mean directed errors for Experiment 1: 16- to 24-month-olds—sandbox.

the box. One possibility is that children do not like to walk or reach far from their current position in seeking the hidden toy, thus leading to increasing bias for positions farther from the child. This possibility could be assessed by the same method as noted above to examine the possibility of egocentric coding. That is, if the child is moved toward one end of the box before retrieval, walking or reaching would not be needed at one end, but the demands would be even greater at the other end. Another possible explanation for the observed bias is that children underestimate distances for locations lying farther from the viewing position. That is, as children look outward, positions at a greater distance may seem closer than they are. Of course, if this were equally true in perception both during hiding *and* at retrieval, it would not create bias. However, underestimation might be greater at hiding, when children remained stationary, than at retrieval, when they moved along the box. The possibility of perceptual underestimation could be assessed by having the child off center both while watching the toy being hidden and during retrieval. In this case, underestimation would be less at the nearer end and greater at the more distant end, an issue examined in Experiment 4.

There is a third possible explanation for bias toward the center of the box. It is that the children treat the set of possible locations in the sandbox as a category with a prototypic central location. Remember that we have argued that if location is coded at two levels of detail, inexactly coded fine grain locations may be weighted with a prototype central to a category. The fact that the data were best fit by a cubic rather than a linear function is consistent with the notion of bias toward a central prototype of a single, bounded category, together with less uncertainty at the ends of the box. That is, if subjects treat the space as a single category and their reports are biased toward a prototype at the center of the box, to an extent depending on degree of uncertainty there should be three points of zero bias; one at the prototype location and one at each end of the box where, presumably, objects could be very accurately located. If the pattern of bias toward the center of the box observed in the present experiment also occurs when the child is displaced toward one end of the box, while watching the toy being hidden as well as during retrieval (Experiment 4), it would support the view that children use categorical as well as distance information in estimating location.

EXPERIMENT 2

The purpose of this study was to make sure children did not use juxtaposition with local landmarks to aid in coding object location in Experiment 1. As noted above, the sandbox was not adjacent to any distinctive landmarks in Experiment 1. Yet the most convincing procedure would be to place the sandbox in a homogeneous field. Thus this study was conducted within a white enclosure.

Method

Subjects. Subjects for this experiment were 20 children between 16 and 24 months of age. They were recruited by ads, signs, and announcements at Temple University, and solicitation based on birth records. Subjects were 9 male and 11 female children. The mean age of the subjects was 21 months, 6 days.

Materials and procedure. The materials and procedure for this experiment were exactly the same as in Experiment 1. The turn-and-give-mother-a-kiss (disrupted physical orientation) procedure was used. The sandbox was surrounded by a circular white enclosure, made by hanging sheets from hooks in the ceiling. The diameter of the circle was 11 feet. People could enter the enclosure by lifting a flap of overlapping sheets; after entry, the sheets fell back to make uniform folds around the circle. The ceiling was composed of uniform squares of white acoustic tile, and the floor was a carpet of uniform coloring.

Results and Discussion

The data were scored and analyzed in the same manner as the data from Experiment 1. Interscorer reliability, again, was .99.

Figure 4 shows a plot of the mean errors for each actual location. The pattern is similar to that found in Experiment 1, with responses being biased toward the center of the box to a larger degree at the ends than near the center. ANOVA's were performed to examine the effects of true location, gender and age on the magnitude and direction of error. Only actual location was a significant predictor of error, $F(8,115) = 3.42$, $p < .001$. A Pearson correlation between age and error magnitude was $-.13$, confirming that there were no significant changes due to age across the range studied. Polynomial curves were fit to the mean error data. The fit of a linear function was $R^2 = .74$, but the best fit was obtained by a cubic function ($R^2 = .95$); the fit of the cubic function was significantly better than the fit of a linear function, $F(2,5) = 9.86$, $p < .05$.

As all features of the room were eliminated by the use of the white enclosure in this study, the observed pattern of bias thus cannot be attributed to coding with respect to distal landmarks in the experimental setting.

EXPERIMENT 3

This study was designed to examine two issues. The first was to deter-

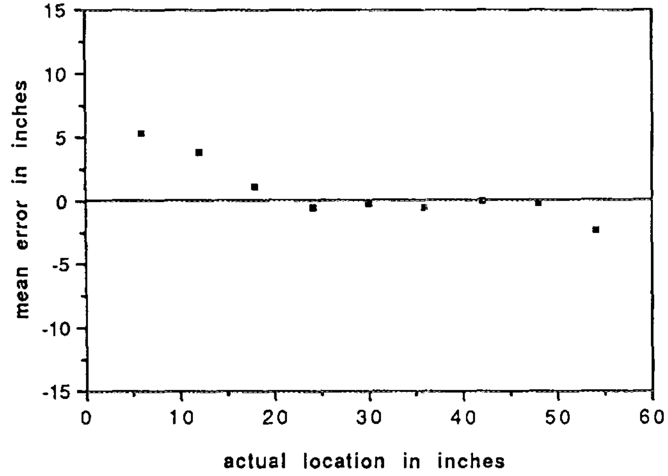

FIG. 4. Mean directed errors for Experiment 2: 16- to 24-month-olds—sandbox.

mine whether the bias observed in Experiments 1 and 2 was due to children's unwillingness to move far to retrieve a toy. The second was to determine if coding was egocentric, or whether children determined distance in an outside framework. In order to explore both issues, we moved children toward one end of the box after they watched the toy being hidden, but before searching for the toy. If the bias was due to children avoiding movement over a great distance, the bias in responding should be systematically shifted in the direction that the child is moved. If the child is coding egocentrically, the region of zero bias should be at the child's own position, not at the center of the box.

Method

Subjects. Subjects for this experiment were 21 children between 16 and 24 months of age. They were recruited by ads, signs, and announcements at Temple University, and solicitation from birth records. The subjects who participated in the study were 15 male and 6 female children. The mean age of the subjects was 20 months, 2 days.

Materials and procedure. The materials and procedure for this study were the same as in the previous work, and it was also conducted in the white enclosure. The major change was that, after the toy was hidden and the child turned and kissed the parent, the child was told (and helped, if necessary) to move laterally before search, to a position 6 in. from the end of the sandbox (i.e., directly in front of the hiding place nearest the end of the box). The parent moved with the child, to encourage movement and to eliminate a central landmark. The children were randomly assigned to move either to the left or to the right throughout the experiment. Twelve subjects were moved to the right and nine subjects were moved to the left.

Results and Discussion

The data were scored and analyzed as in the previous experiments with one modification. The data for subjects in the "move right" and "move left" conditions were examined together by reflecting the scores for the "move right" condition about the center. Position 1 on Fig. 5 (actual location of 6 in.) regardless of condition, corresponds to the position the child *started* his search from, and position 9 (actual location of 54 in.) corresponds to the position most distant from the child. Interscorer reliability was .99.

Figure 5 is a plot of the mean errors for each actual location. The pattern of bias here is again similar to that found in Experiment 1. Responses for locations away from the center of the box are biased toward the center. That is, responses are not made closer to the position of the self at the time of search. This indicates that the pattern observed in Experiment 1 was not due to laziness on the part of the child. For children to have a response biased toward the center for an actual location on the side of the box where they are located (as was observed), they would have to walk *beyond* the actual location to make their responses. The results

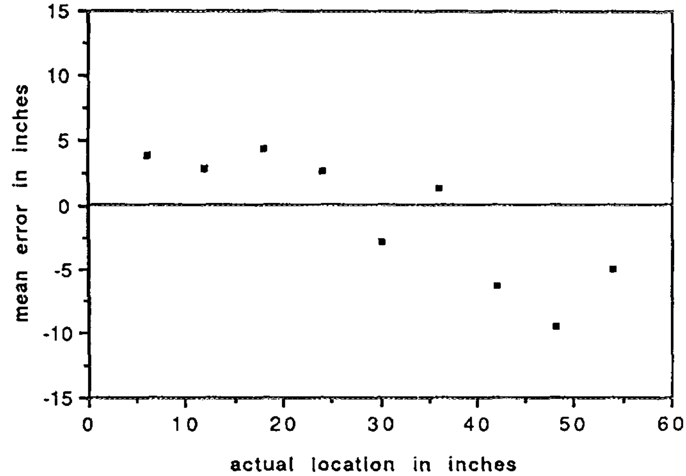

FIG. 5. Mean directed errors for Experiment 3: 16- to 24-month-olds—sandbox.

also show that coding was not egocentric since egocentric coding would lead to bias centered at the child him or herself.

ANOVA's were performed to examine the effects of true location, condition (move left or move right), as well as age and gender, on the magnitude and direction of error. Once again, actual location was a significant predictor of error, $F(8,132) = 4.29$, $p < .0005$. Additionally, we found a significant effect of gender, $F(1,137) = 6.15$, $p < .02$. The mean error was significantly larger for the females. However, since no effect of gender was found in the three other toddler studies, or in Experiments 5 or 6, we did not attempt to interpret this finding. A Pearson correlation between age and error magnitude was $-.18$. A cubic function fit the data ($R^2 = .81$) better than a linear function ($R^2 = .74$), but the difference was not significant, $F(2,5) = .97$.

EXPERIMENT 4

This study was designed to determine whether children's coding of location is substantially changed depending on where they are located at the time a toy is being hidden. Experiment 3 allowed us to establish that the bias observed in Experiments 1 and 2 was not due to either unwillingness to walk or reach, or to the egocentric coding of location. Another possible explanation for the observed bias might be that there is a perceptual effect as children look outward such that more distant positions seem closer that they truly are. By having the child located toward one end of the box both at hiding and at retrieval, it will be possible to determine if this is the explanation for the bias observed in earlier experiments.

If bias continues to be toward the center of the box in this case, it will provide support for the remaining hypothesis. That hypothesis is that the bias is due to hierarchical coding where the set of possible locations in the box as a whole is treated as a category with a prototypic location at the center.

Method

Subjects. Subjects for this experiment were 27 children between 16 and 24 months of age. They were recruited by ads, signs, and announcements at Temple University, and from birth records. Subjects were 16 males and 11 females. The mean age of the subjects was 21 months, 14 days.

Materials and procedure. The materials and procedure for this study were the same as in the previous work, and it was also conducted in the white enclosure. The major change was that the child both viewed the hiding and initiated search from a point 6 in. from the end of the sandbox. The children were randomly assigned to use the point either to the left or the right of the box as one faced it, throughout the experiment. There were 14 children started on the right and 13 children started on the left.

Results and Discussion

The data were scored and analyzed as in Experiment 3. Interscorer reliability was .99.

Figure 6 is a plot of the mean errors for each actual location. The pattern of bias here is similar to that found in the previous experiments. Coding was most accurate near the center of the box and bias increased for positions farther away from the center. These data clearly indicate that the bias observed in earlier experiments is not due to perceptually based underestimation for locations lying at increasing distances from the child's viewing position. The data also provide further evidence that the

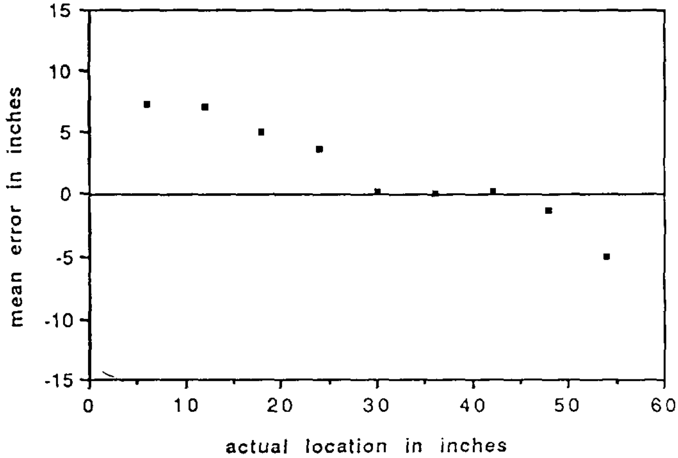

FIG. 6. Mean directed errors for Experiment 4: 16- to 24-month-olds—sandbox.

child's coding of the object's location is not egocentric. Were positions encoded with respect to the *self,* we would expect to find systematic bias toward the location of the child–with larger distances being most greatly underestimated. Were this the case, we would expect to find that the bias would be relative to the location of the child.

Again, ANOVA's were performed to examine the effects of true location and condition (move right or move left), as well as age and gender, on the magnitude of direction of error. Actual location was the only significant predictor of error, $F(8,188) = 6.52, p < .0005$. A Pearson correlation between age and error magnitude was $-.11$. Polynomial curves were fit to the mean error data. A cubic function fit the data ($R^2 = .943$) about the same as a linear function ($R^2 = .941$), and the difference was not significant.

These findings leave us with one remaining hypothesis, namely that the child is treating the space as a bounded category with a central prototypical location. We found bias toward the center of the sandbox in all studies, as indicated by significant linear trends with zero crossings in the middle of the box, regardless of whether the child is moved before retrieving the toy, or is at an end of the box both while the toy is hidden and during retrieval. This fact indicates that the pattern of bias cannot be due to egocentrism, laziness, or perceptual misrepresentation. Further, the fact that the pattern of bias is also well fit in all cases by a cubic function, with a significant increment over a linear fit in Experiments 1 and 2, also suggests that coding is hierarchical, because the pattern is predicted from the fact that the fine grain coding would be expected to be more exact near the ends of the box. However, before drawing a strong conclusion that children under two use hierarchical representation in coding location, one would like to have a better understanding of when they begin to subdivide spaces, using more than one category as has been found with adults. Exploring this issue was the purpose of Experiments 5 and 6.

EXPERIMENT 5

In Experiment 5, we explore coding of location in the sandbox in somewhat older children. Our purpose is to examine the emergence of the subdivision of the sandbox into two halves. In pilot work, we presented adult subjects with the sandbox task and found that they showed a pattern of bias in which objects were misplaced from the center outward and from the edges inward. This is what the Huttenlocher et al. model predicts if subjects code both in terms of a fine grain location and a category consisting of *half* of the rectangle. In this case, a category prototype central to each half is weighted with an inexactly coded fine grain representation in making estimates of location. We found that, for adults, the bias outward near the center of the box was greater than the bias inward near the edge of the box; this is what the model predicts, because distance estimation is most precise at locations near an edge, so category effects should be smaller than locations toward the center of the box.

Method

Subjects. Subjects for this study were University of Chicago Laboratory School students. The proportions of boys and girls in each age group were approximately equal. Three groups of students were used: pre-kindergarten (ages 4–5), first grade (ages 6–7), and fifth grade (ages 10–11). Participation was contingent upon parental approval. There were 29 pre-kindergartners, 30 first graders, and 15 fifth graders in the study.

Materials and procedure. The same rectangular sandbox was used as in earlier experiments. In this study, the white sheet was not used. The stimuli were small black discs measuring approximately ½ in. in diameter. Again, the experimental session was recorded on video tape using a VHS camera mounted on a tripod directly across the room from the subjects and aligned with the center of the sandbox.

Children were tested individually in a quiet room adjacent to the elementary school (the same room in which the 16 to 24 month olds were tested). The child was seated in a revolving chair fixed to the floor at the center of one of the long sides of the sandbox. The experimenter stood at the center of the opposite side of the sandbox. On the experimenter's side of the sandbox, a scale was marked using decorative strips of colored tape. This scale was used by the experimenter as a guide in administering the experiment and as a guide for scoring the video tapes.

Following one of five predetermined and randomly selected placement orders, the experimenter placed one of the black dots on the surface of the sand. As she did this she told the child that she was "going to bury a dot in the sand." The experimenter then used one finger to push the dot straight down into the sand. She then walked around the sandbox (direction was alternated with each trial) to the child, and turned the child 180° (direction of turn also was alternated with each trial). The child remained with his/her back to the sandbox for several seconds. The child was then turned an additional 180° and was asked to use one finger to point to the place where the dot was buried. The child's response was captured on video tape. After the child indicated a location, the experimenter moved around to the opposite side of the sandbox and began the next trial. When all the trials had been completed, the child was allowed to help the experimenter dig up all of the buried dots.

There were 19 trials in all. In order to allow for direct comparison between this study and the study of 16- to 24-month-olds, the stimulus locations for the first nine trials were spaced at 6-in. intervals along the length of the box and presented in a predetermined randomized order. The remaining 10 trials had locations corresponding to points at the midpoints of the first nine trials and were randomized. Thus, there was one trial in each of 19 locations spaced 3 inches apart along the length of the sandbox.

Results and Discussion

The data were scored by recording the location of the child's response from the video tape. 1.5 in. units were used for scoring. These were the units denoted by the tape scale on the side of the sandbox visible to the camera. The videotapes were scored twice to ensure consistency in measurement. The child's responses were then matched up with the actual stimulus display locations for each trial. Errors in responding were computed by subtracting the actual location from the child's response. Analyses from here on were performed by age group. Interscorer reliabilities for each age group were .99 or 1.00.

Mean responses for each actual location for each age group were computed along with the standard deviations about those mean responses. A positive response error indicates a mean response location that was to the right of the actual location. A negative response error indicates a mean response location that was to the left of the actual location. The plot of bias for the fifth graders is shown in Fig. 7a. The observed pattern of bias indicates that the sandbox has been subdivided at the center into two categories, and that locations within each half of the box are biased to-

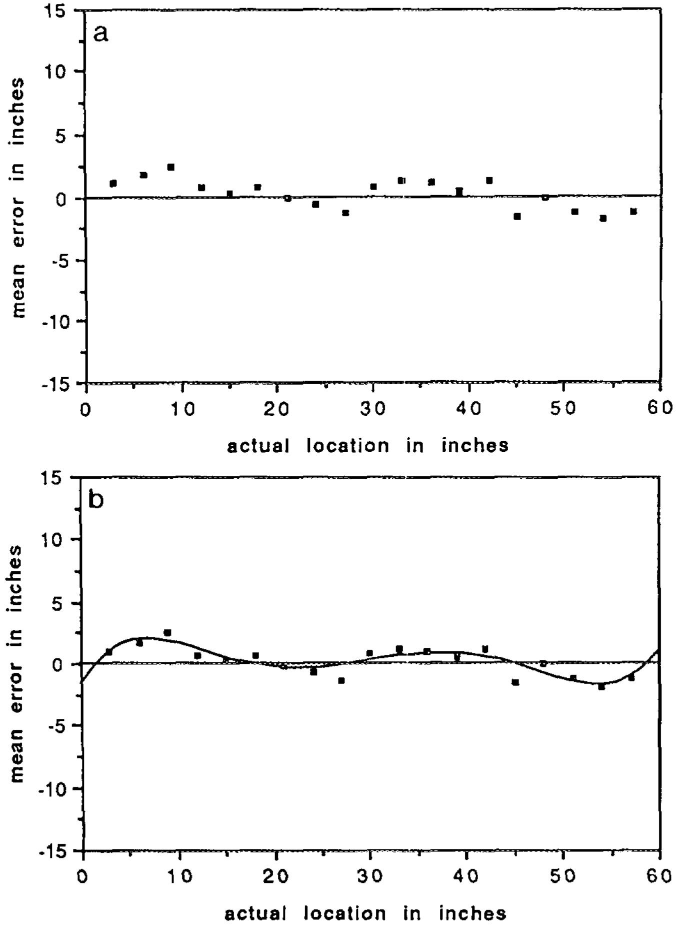

FIG. 7. (a) Mean directed errors for fifth graders—sandbox. (b) Polynomial curve fit to mean directed errors for fifth graders—sandbox.

ward a prototype for that particular category. Polynomial curves were fit to the mean error data (Fig. 7b). The best fit was obtained by a quintic function ($R^2 = .72$). This is consistent with division of the space into two categories. If subjects are dividing the space in half and utilizing two prototypes (one for each half), we would expect to find five points of zero bias: one at each prototype, one at the center where there is a categorical split, and one at each end of the box. The fit of the quintic function was significantly better than the fit of a cubic function (for which $R^2 = .50$), $F(2,13) = 5.05$, $p < .05$.

In contrast to fifth graders, plots of mean error by actual location for the pre-kindergarten and first grade children are similar in pattern to those of the 16- to 24-month-old subjects. Figures 8a and 8b show the bias data for the pre-kindergarten and first grade children respectively. The actual locations are displayed along the horizontal axis, and bias (the mean response at each true location minus the true location) along the vertical axis. If the means of responses were at exactly the true location, the points would fall at zero. Although the true locations were fairly faithfully preserved, responses near the edges of the sandbox were slightly misplaced toward the center of the box. Comparing the figures for these two age groups, it does not seem that there is any change in size of bias across age.

A 19 (actual location) × 2 (grade) ANOVA was performed and the results indicated that actual location is the main predictor of magnitude and direction of error, $F(18,1061) = 12.07$, $p < .0005$. The results also indicated that the first grade subjects were not significantly more accurate than the pre-kindergarten subjects, $F(1,1061) = .73$, $p < .39$. Polynomial curves were fit to the mean error data. For the pre-kindergarten group, a cubic function fit the data ($R^2 = .87$) better than a linear function ($R^2 = .85$), but the difference was not significant. For the first grade group, the cubic function ($R^2 = .90$) fit significantly better than the linear function (for which $R^2 = .80$), $F(2,15) = 7.5$, $p < .01$. Fitting a quintic function to the data did not improve the curve fit.

We did not formally compare the amount of bias toward the center of the box in 4- and 6-year-olds to that in 16- to 24-month-olds in Experiment 1, because different methods were used in this young group. However, it is interesting to note that mean absolute errors for the 16- to 24-month-olds, 4-year-olds, and 6-year-olds were 2.6″, 4.1″, and 3.4″, respectively. The fact that bias was of a similar magnitude in 16- to 24-month-old children and in 4- and 6-year-olds suggests that there are no age differences in the size of bias effects.

EXPERIMENT 6

We have seen that the sandbox is not divided into two subsections until

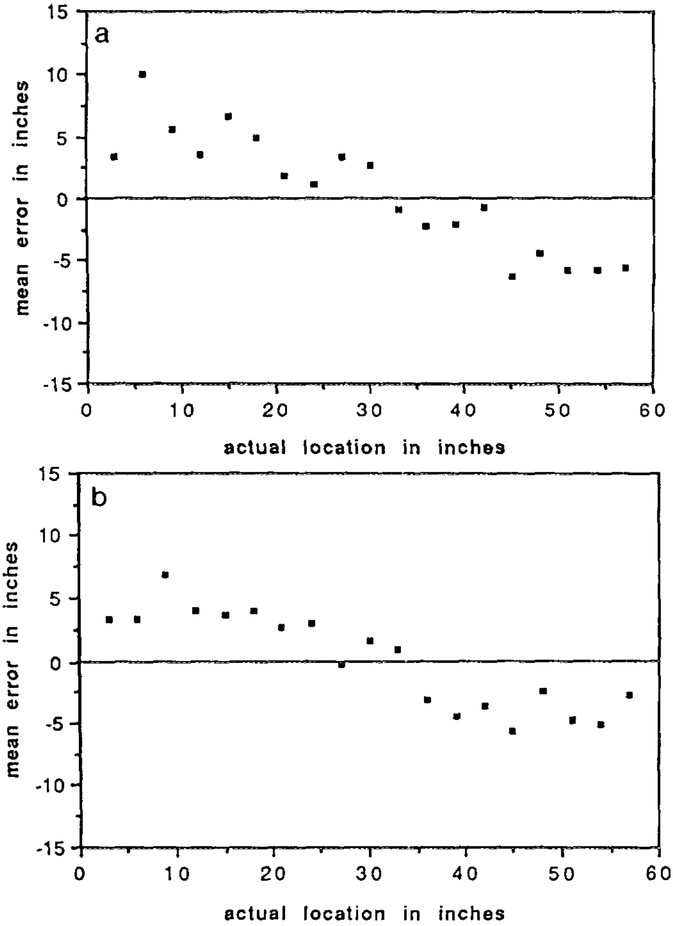

FIG. 8. (a) Mean directed errors for pre-kindergartners—sandbox. (b) Mean directed errors for first graders—sandbox.

after age 6, possibly not until age 10. Nevertheless, we have suggested the possibility that the toddlers in Exp. 1–4 coded location at two levels of detail, with categorical coding being simply "in the box" rather than in a subsection. However, our evidence for the claim that even very young children code location hierarchically would be far stronger if we could show that children impose an organization involving subdivisions of a space into smaller categories (e.g., halves) at an earlier age than 10 years, at least in some circumstances. Hence, the purpose of this next study was to determine if we could find evidence that subdivision of a bounded space occurs in younger children. We thought that this might be possible if we were to use a simple rectangular shape smaller than the sandbox. Therefore, in this study, we used a bounded form consisting of a rectangle 20 centimeters long proportioned like the sandbox drawn on a sheet of paper. We made up a booklet in which there was a page on which a rectangle with a dot was presented, then a blank page, and then a response page with an empty rectangle. Subjects placed a dot in the position in which they just had seen it. We showed dots in 15 locations across the box, 1 at each location, randomly ordered.

We first tested adults and found that they divided this one-dimensional space in half, showing a pattern of bias like that shown by fifth graders and adults for the sandbox. That is, there was displacement from the center and edges of the rectangle, as we would expect if subjects code a fine grain location and a category consisting of the half of the rectangle, and a category prototype central to each half is used in estimation. The bias outward near the center was greater than the bias inward near the edge, as we expected because distance estimation is less precise at locations far from an edge. Since there is evidence that the rectangle is subdivided by adults, we used this figure to test children in various age groups.

Method

Subjects. The subjects for these experiments were children from the University of Chicago Laboratory Schools. Three groups of children were used: Pre-kindergarten (ages 4–5), first grade (ages 6–7), and fifth grade (ages 10–11). Participation in the study was contingent upon parental approval. There were 30 pre-kindergartners, 30 first graders, and 30 fifth graders in this study. Some of these children had participated in Experiment 5 a few months prior to this portion of the study.

Materials. The stimuli for these experiments consisted of fifteen 1-mm dots evenly distributed horizontally in a rectangular frame which measured 20 cm by 4 cm. Each stimulus display page contained the rectangular frame and one of the 15 stimulus dots. Response pages contained only an empty rectangular frame identical to the display frame. Display and response pages were interleaved with sheets of light blue card stock. Each of the 15 dots was presented once in each test booklet. Five different random orders for the display of the stimuli were used. Holes were punched along the top side of the pages and the booklets were held together with binding rings. Subjects responded using a sharpened No. 2 lead pencil.

Procedure. Subjects were tested individually. The testing was performed in a quiet area either in or just outside the child's classroom at a desk or table appropriate for the child's height. The subject was seated next to the experimenter. Right/left orientation with respect to the experimenter was varied across subjects.

The child was told that he was going to be given a memory test. It was explained that the experimenter would show him a shape with a dot in it and that he should try very hard to remember exactly where in the shape the dot was located. At this point the experimenter revealed the first display page and allowed the child to look at it for approximately 2 s. As the experimenter turned the display page she explained that now she was going to take the dot away and show the child an empty shape. At this point the experimenter turned the blank blue page to reveal a response page. The child was told to use the pencil to draw the dot exactly where he remembered it.

After children completed the first response, they were asked if they understood the test. All of the children tested understood the demands of the task. The experimenter then revealed the second display page while instructing the child to look. The page was turned again after approximately 2 s, the blank filler page was turned, and the child was instructed to draw the dot. Verbal instructions were repeated for each trial with the youngest age groups along with occasional verbal praise and encouragement. Continual verbal input was not required for the older groups and instructions were only repeated if the child deviated from the experimental procedure. Subjects of all ages were able to complete their booklets within 5 min.

Results and Discussion

Responses were scored by measuring the distance of the child's response, in millimeters, from the left edge of the rectangular frame. Occasionally a large dot was drawn (especially in the younger groups); in such cases, measurement was made from the left edge of the frame to the center of the child's dot. Scoring was done by a person who had not been involved in the administration of the experiment. Reliability of coding was checked by remeasurement of 15% of the data by a second scorer. The interscorer reliability was 1.0 for each age group.

Error in responding was computed by subtracting the actual location of the display from the subject's response. Standard deviations about the mean response error at each location were then computed. Responses that were more than three standard deviations from the mean were dropped from the analysis. In the first grade data set, there were six responses which were clearly "mirror image" responses. That is, three responses at the location of the fourth dot from the left edge and three at the location of the fourth dot in from the right edge had very large errors; in fact, these responses were located within the range that was given for a true location in the "mirror image" position at the other end of the box. It is as if the subjects were encoding the dot's distance from the center (or end) correctly but made right/left confusion errors in responding. These six responses were dropped from the data set. No such responses occurred for fifth graders. The problem of mirror image responses was sufficiently great in the preschool data that we used an alternative method for examining data, as indicated below.

Plots of mean error by actual stimulus location are shown in Fig. 9a and 9b for the first grade and fifth grade subjects. These figures, in which true locations (on the horizontal axes) are subtracted from the mean responses for each true location (on the vertical axis), reveal clearly similar patterns of response. Evidence of subdivision is found in the bias outward from the center and inward from the edges. A 15 (actual location) × 2 (grade) ANOVA was performed and the results indicated that the fifth grade subjects were significantly more accurate than the first graders, $F(1,846) = 7.03$, $p < .008$. Actual location was significantly related to magnitude

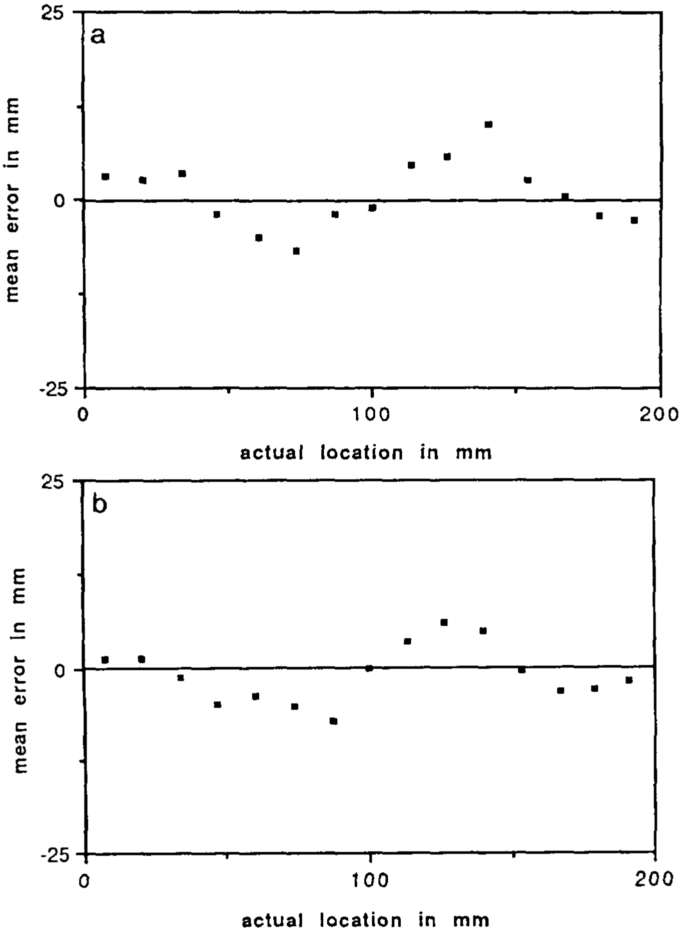

FIG. 9. (a) Mean directed errors for first graders—paper and pencil. (b) Mean directed errors for fifth graders—paper and pencil.

and direction of error, $F(14,846) = 2.42$, $p < .002$. Polynomial curves were fit to the mean error data. For the first and fifth graders, the best fit was obtained by a quintic function, ($R^2 = .90$ and .86, respectively). The fit of the quintic function was significantly better than the fit of a cubic function, $F(2,9) = 14.82$, $p < .01$ for the first grade and $F(2,9) = 11.94$, $p < .01$ for the fifth grade.

Finally, we examine the data from the 4-year-olds. A problem arose in examining whether the 4-year-olds subdivided the box because a sizable number of the children made some mirror image errors. That is, they seemed to be putting their dot approximately the correct distance from the edge (and center), but in the *wrong half* of the rectangle. A tendency to place the dot in the mirror image position is a separate issue from that of subdivision and the use of two levels in estimation of location. The question of subdivision of the space can be examined by folding the response distribution at the middle; that is, the actual locations can be treated as locations at particular distances from the center (or edge) along the horizontal. This places together two actual locations, one on each side of the center, that are equally distant from the two edges. Along the vertical, the mean of responses is collapsed across these pairs of locations that are equally distant from the edges. We analyzed the data in this way for first graders, who are known to subdivide the space, so it could be compared to parallel data for 4-year-olds.

Figures 10a and 10b show the locations, as described above, plotted against mean responses for 6-year-olds and for 4-year-olds; the patterns of response are parallel. A positive error means misplacement away from the center and a negative error means misplacement away from an edge. Polynomial curves were fit to the collapsed mean error data. Consistent with the notion of each half of the box being one category, a better fit was obtained by a cubic function than by a linear function. For the pre-kindergarten group, a cubic function fit the data ($R^2 = .962$) better than a linear function ($R^2 = .960$), but the difference was not significant. For the first grade group, the cubic function ($R^2 = .97$) fit significantly better than the linear function ($R^2 = .85$), $F(2,4) = 6.94, p < .05$. Clearly, even 4-year-olds organize the rectangle into two halves and use category information in estimation as do adults.

OVERALL DISCUSSION

Our studies show that by 16 months, at the latest, children use distance information in estimating the location of an object in space. They also use information about the location of the item in a larger segment of space, combining distance information with the prototype for a spatial category to estimate location. Thus our results indicate that the basic mechanisms for locating objects in space are available at an early age (and are possibly innately available; see discussion below). The findings also indicate that there are later developmental changes involving the ways in which bounded spaces are sub-categorized into component regions.

The Use of Distance Information

We have examined distance coding in a task involving continuous space. We found in Experiment 1, that by 16 months, children code the location of a hidden object in a 5-foot-long homogeneous sandbox. In Experiment 2, we showed that children did not need external landmarks to code location using distance by enclosing the sandbox (including the child) in a white surround. In Experiment 3, we established that coding

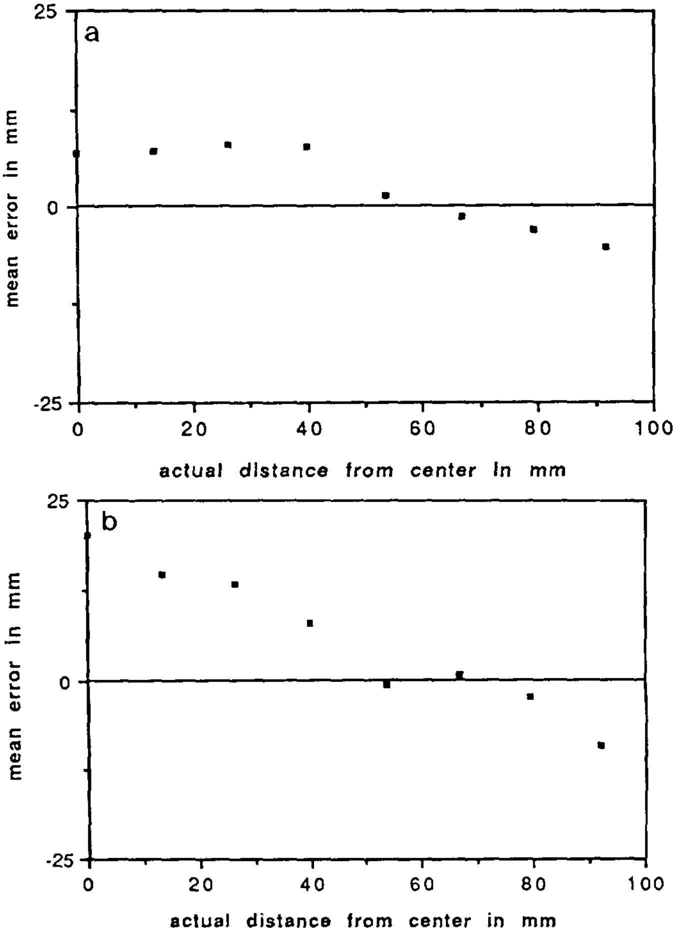

FIG. 10. (a) Mean errors shown in distance from center for first graders—paper and pencil. (b) Mean errors shown in distance from center for pre-kindergartners—paper and pencil.

was relative to the outside frame of the sandbox, not the child him- or herself. Further evidence for this was found in Experiment 4, where subjects' accuracy was greatest at the center of the box, not at their own position. (The implications of Experiment 4 for hierarchical coding are discussed below.) Within the age range 16 to 24 months, studied in these experiments, there were no differences in accuracy between older and younger subjects. Thus, encoding location using distance is robustly present by 16 months.

These findings leave open the possibility that children even younger may use distance in coding location. It may be that infants search for a hidden object using distance information to represent its location just as soon as they search for hidden objects at all, at approximately 8 months, or that they code location using distance even before they initiate manual search. Infant studies have not directly examined the issue of whether distance information is used in location coding, but certain studies (cf. Baillargeon, 1991) suggest that infants are sensitive both to extent and to location. In one set of studies, Baillargeon (1986) habituated infants under 6 months of age to a screen that rotated through 180° (starting and ending in a "lying down" position). In the first study, infants were shown two displays with a box behind the screen. In one, the screen rotated as before, 180° (past the point where it would have been stopped by the object). In the other case, the screen stopped at the box. Infants looked longer at the screen that continued past the point where the box would have stopped it (the full 180° rotation to which they had been habituated). In a further study (Baillargeon, 1987), the screen descended only part of the way past where the box would have stopped it. Nevertheless, infants looked longer when the screen went past the point where it should have stopped. This finding indicates that infants were sensitive to the vertical extent of the object (the distance from one end to the other).

In another study (Baillargeon, 1986), infants between 6 and 9 months of age were habituated to a vehicle that moved along a track. Then they were shown two displays. In one case, a moving object passed along a path that had an object that would stop the passage of the other object. In the other case, there was no obstructing object. Infants looked longer at the impossible situation. This study shows that infants are sensitive to information about location, at least to whether an object is "on" or "off" a demarcated area such as the track. The fact that infants' expectations involve extent and location as shown in these studies suggests that infants also may be able to use distance information to code the location of an object in a continuous space as in our sandbox.

Piaget (1937/1971) argued that sensorimotor experiences of reaching or locomotion and their coordination with each other and with visual input are critical to the emergence of an idea of extent on the level of practical action. If infant studies were to show definitively that distance coding occurs by just a few months of age, it would suggest that the notion of distance does not appear first in action as Piaget believed. However, the issue goes beyond the empirical question of when sensitivity to distance can first be demonstrated. To posit that the notion of extent is first evident in reaching or locomotion does not in fact provide an account of its origin. It would seem that the basic notion of extent is assumed to be present, presumably from the outset, but is embodied first in action, rather than in perception.

Piaget (1937/1971) drew a distinction between practical and conceptual space (see also Liben, 1981) and it might be argued that our data bear on the former rather than the latter. While the distinction between practical and conceptual space is not yet as clear as we would like it to be, we would not disagree. The child's explicit realization that the use of measurement tools is important in making distance judgments in situations with conflicting cues may well develop over the preschool years (although it appears earlier than Piaget claimed; see Bartsch & Wellman, 1988; Fabricius & Wellman, 1993; Miller & Baillargeon, 1990). Our data simply show that the fundamental ability to estimate distance "by eye" and to use that information to locate objects is present by 16 months at the latest.

The Use of Hierarchical Coding

We observed some bias in location coding in the sandbox experiments with our 16- to 24-month-old subjects. The bias seems to be due to hierarchical coding of location, in terms of specific location and location in a larger space, even in these very young subjects. That is, the observed pattern of bias suggests that children organize the entire sandbox as a category, generating a mean or middle location and weighting their uncertain memory for particular locations with this central value. This interpretation was supported by further experiments which eliminated alternative explanations. To find hierarchical organization of a space at such an early age, with location coded both at a fine grain level and at a category level (where the category is a bounded form of a particular shape) might seem even more surprising than to find distance coding. In fact, however, a wide variety of animal species have been shown to possess "cognitive map(s)" that preserve "the (Euclidean) shape of the environment" (Gallistel, 1990, p. 220).

In work with adults, Huttenlocher et al. (1991) showed that the use of hierarchical coding in estimating location improves the accuracy of estimates on average. Thus, while use of an adjustment process in the estimation of location produces bias in single judgments, it nevertheless is a "rational" process in the sense that it contributes to the overall accuracy of performance. The use of hierarchical coding and adjustment is not the result of a deliberate strategy. In fact, adults are not aware of using these processes. Given the fact that adults do not use category information in estimation as a conscious strategy, it seems possible that the use of such information is based on an "intuitive statistics" acquired from the accumulation of judgment experiences on the basis of its advantage for overall accuracy. The present data, showing the availability of such adjustment processes by age 16 months, indicate that the amount of experience required is not enormous.

Hierarchical coding involving the overall shape of perceptually bounded spaces is, however, different in an important way from hierarchical coding in which a bounded form is divided into subsections, each with its own center. Such subdivision requires not only apprehension of form but also the imposition of subjective organization. As noted in the introduction, subdivision of a space can increase the overall accuracy of location coding. In Experiment 5 we found that, for the sandbox, subdivision into subjective spaces did not occur until quite late in development. In addition, Hollister (Sandberg) and Huttenlocher (S.R.C.D. 1993) have shown that a circle presented on paper is not organized into quadrants until age 10. However, Experiment 6 in this paper demonstrates that children as young as 4 years do subdivide a simple bounded form. Whether children younger than 4 years impose organization on any bounded form is not known.

Thus, what seems to develop more gradually than the fundamental process of hierarchical coding is the use of subjective categories in such coding and the kind of spaces on which subjective categories can be imposed. Subdivision seems to emerge initially where location is coded along only one dimension, or where the scale of the bounded space is small, as in the rectangle, used in Experiment 6. Possibly it is experience with the advantages of hierarchical coding using subdivision in simple situations which leads the child, over time, to subdivide spaces in less obvious situations. Such a change may underlie age related increases in accuracy for tasks such as pointing to the location of home from the grocery store (e.g., Anooshian & Nelson, 1987; Cousins, Siegel, & Maxwell, 1983). Thus, it is possible that development of a differentiated and broadly applied hierarchical system does indeed reflect an ''intuitive statistics'' which emerges through experience with this increased accuracy of judgment, even though the basic system does not originate in this way.

In addition to developmental change in the organization of space, change also occurs in the ability to reason about space. The young child's success at distance estimation is susceptible to disruption by task demands. As noted in the introduction, Piaget used distance estimation tasks where differently oriented spaces were used by the experimenter and the child. Here, children resorted to the use of juxtaposition in location coding. Also, children's distance estimates tend to be disrupted when interspersed objects are introduced which require that they ignore perceptually distorting factors. In other words, some past assessments of the use of distance information in young children may have been affected by requiring higher level spatial reasoning skills which do not develop as early as distance coding itself.

Finally, it should be noted that category effects in the reconstruction of particular events are a widespread cognitive phenomenon. That is, when people make estimates of inexactly remembered stimuli, they are likely to report them as being more like typical (central) values in a category than is actually the case; e.g., remembering the color of a blue sweater as a more typical blue (cf. Bartlett, 1932; Brewer & Nakamura, 1984). Huttenlocher and Hedges (1992) have pointed out that such phenomena, like the spatial category effects reported in the present study, may be the result of multilevel coding and adjustment processes that improve the overall accuracy of estimates of stimuli when memory is inexact (but unbiased). Even toddlers form categories of objects, properties, and so on. The question arises of whether young children show multilevel coding and adjustment toward central values as soon as they acquire such inductively based categories of objects, properties, etc.

CONCLUSIONS

We have found evidence that, by 16 months, children code location by combining distance information with information regarding a spatial category. These components of location coding may be present from the start, although further work with infants would be required to assess this possibility more decisively. However, development occurs in the type of categories imposed in coding, as well as in distance estimation in cases involving conflicting cues. Our data support a view of spatial development in which the starting point is far less humble than that proposed by Piaget (Piaget & Inhelder, 1948/1967), but in which there is greater developmental change than has been suggested in nativist accounts (e.g., Landau, Gleitman & Spelke, 1981).

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