INFANTS' CODING OF LOCATION IN CONTINUOUS SPACE

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The ability to code location in continuous space is fundamental to spatial behavior. Existing evidence indicates a robust ability for such coding by 12 months, but systematic evidence on earlier origins is lacking. A series of studies investigated 5-month-olds' ability to code the location of an object hidden in a sandbox, using a looking-time paradigm. In Experiment 1, after familiarization with a hiding-and-finding sequence at one location, infants looked longer at an object being disclosed from a location 12 inches (30 cm) away than at an object emerging from the hiding location, showing they were able to code location in continuous space. In Experiment 2, infants reacted with greater looking when objects emerged from locations 8 inches (20 cm) away from the hiding location, showing that location coding was more finely grained than could be inferred based on the first study. In Experiment 3, infants were familiarized with an object shown in hiding-and-finding sequences at two different locations. Infants looked longer at objects emerging 12 inches (30 cm) away from the most recent hiding location than to emergence from the other location, showing that infants could code location even when events had previously occurred at each location. In Experiment 4, after familiarization with two objects with different shapes, colors, and sounding characteristics, shown in hiding-and-finding sequences in two locations, infants reacted to location violations as they had in Experiment 3. However, they did *not* react to object violations, that is, events in which the wrong object emerged from a hiding location. Experiment 5 also found no effect of object violation, even when the infants initially saw the two objects side by side. Spatiotemporal characteristics may play a more central role in early object individuation than they do later, although further study is required.

infant cognition **infant perception** **spatial development** **spatial cognition**

A fundamental aspect of adaptation is remembering the location of objects in the world. One way to accomplish this goal is to code locations of objects in terms of angles and distances from landmarks. Using such a system ensures that the location of objects will

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be known as long as the landmarks are perceptually available and themselves stable. Alternative means of coding the location of objects include using coincident landmarks (but these are not always available), remembering motor movements required to "obtain" an object (but such memories are not useful if one moves), or keeping track of one's movement around the world and using it to update localization information (a useful system, but subject to increasing error as slight estimation errors accumulate). (See Gallistel, 1990, and Newcombe, Huttenlocher, Drummey, & Wiley, 1998 for further discussion.) Thus, coding the location of objects in terms of angles and distances from landmarks constitutes the most powerful and general means of location coding available. In this paper, we consider the origins of this ability, by examining infant reactions to hiding and finding events in a continuous space.

The existing literature on infants' ability to locate objects could be used either to suggest that there is little early ability to code location using distance and angle, or to argue in favor of such early ability. Pessimism about early ability was forcefully voiced by Piaget, who argued that infants entirely lack a notion of extent in early infancy, suggesting that such notions are built up at a sensorimotor level from kinaesthetic experiences with reaching and the mapping of those experiences onto visual and tactile experience (Piaget, 1952, 1954). Support for his claims is often derived from research on infant reaching for hidden objects, and, most famously, from the fact that infants do not succeed on the A-not-B task until towards the end of the first year of life.

It is difficult to draw strong conclusions about infant coding of location from A-not-B studies, however, because A-not-B situations probably index inertial tendencies in the motor system and/or inability to inhibit as much as they do location coding (Diamond, 1985, 1991; Thelen & Smith, 1994). In addition, hiding devices such as cloths or screens are used, so that there is no continuous space. It is not known how such markers might affect location coding. On the one hand, the presence of multiple identical screens could be distracting or confusing to infants. On the other hand, the presence of screens may make location coding easier than in situations involving a continuous expanse, because distinct screens may serve as spatial "place holders" which facilitate infant coding. For instance, Uller, Carey, Huntley-Fenner, and Klatt (1999) found that 8-month-olds have greater difficulty with tasks in which two objects are hidden behind a single screen (similar to a continuous expanse) than in situations in which the objects are hidden behind two separate screens.

Extensive research on the egocentric-to-allocentric transition in infant spatial development might also be used to justify pessimism about early use of distance and angle information to locate objects. Infants frequently seem to locate objects and events in terms of motor movements, failing to take account of their own position changes, and using even coincident external landmarks inconsistently, until the advent of crawling (for one summary, see Acredolo, 1990). If infants fail to use coincident landmarks when they would be advantageous, it seems unlikely that they would use distal landmarks. There are, however, other ways to interpret the existing findings (e.g., Millar, 1994). Infants may be able to use various means of coding location, but yet deal poorly with situations requiring choice among conflicting systems (as occurs when the infant moves). From this point of view, one might argue that there might be an early ability to use distance and angle information, if such coding were not placed in conflict with other systems by moving the baby.

Although the previously considered studies would suggest limits on infants' ability to code distance and angle, several other kinds of study could be taken to suggest the existence of such ability. Unfortunately, however, each of these lines of research can also be argued to have limitations that render the evidence less direct and conclusive than one would like.

First, between 4 and 6 months, infant saccadic eye movements come to be guided by more than a simple retinocentric spatial frame

(Gilmore & Johnson, 1997). By 6 months, infants also use body coordinates (an egocentric frame) in planning saccades, an ability that involves some use of distance information. However, saccadic eye movements to a two-dimensional stimulus occurring over milliseconds seem different in kind from the coding of location of a three-dimensional object over a longer time course, and saccades may be governed by specialized neural systems.

Second, in a series of studies, Baillargeon has investigated coding of the spatial dimensions of an object. These experiments suggest that infants represent the shape and size of objects. For instance, Baillargeon (1987b) found that, after viewing a screen moving through a 180-degree arc to lie flat on a table, and then viewing a block placed in a position where it would impede the motion of the screen, 7-month-old infants looked longer at displays where the screen progressed partway into the space that would be occupied by the box, suggesting that they have encoded its height. In addition, Baillargeon (1987a) showed that even 4.5-month-old (and possibly even 3.5-month-old) infants can encode the height of objects.

However, although these findings are interesting, firm conclusions about coding of object location cannot be drawn from them, because it is not known whether coding the physical dimensions of an object is equivalent to coding the distance between objects. Neuropsychological evidence suggests that coding various attributes of objects is a distinct ability from coding the location of those objects (Ungerleider & Mishkin, 1983). While studies on these "what" and "where" systems have not specifically examined the question of which system codes physical dimensions of objects, there is some evidence from case studies that object dimensions such as height may be coded in a fashion distinct from coding inter-object distance. Patients who can judge the length of a block, and even its aspect ratio, sometimes cannot judge the distance between two objects (see review by Farah, 1990).

A third kind of study, more directly relevant to infant coding of location, has examined infants' reactions in situations in which objects are hidden behind screens. Baillargeon and Graber (1988) and Baillargeon, DeVos, and Graber (1989) found that 8-month-olds, but not 7-month-olds, could remember which of two screens an object had been hidden behind. By contrast, Wilcox, Nadel, and Rosser (1996) found that even 2-month-olds showed evidence of remembering which of two screens an object had been hidden behind, a clear contrast to the failure of 7-month-olds in the Baillargeon studies. However, when a toy was hidden behind one of four screens arranged in a line, Wilcox, Rosser, and Nadel (1994) found that infants as old as 6 months showed evidence of coding location only in certain situations. When objects appeared from behind an end screen, after having been hidden at one of the middle screens or at the opposite end, infants looked longer than in control conditions. But they did not show longer looking times when objects reappeared at a middle screen after having been hidden at one of the ends.

Thus, one problem with screened-location studies is that the findings clearly conflict with each other, showing success in location coding at ages ranging from 2 to 8 months. In addition, and more seriously, the relevance of these studies for understanding coding in continuous space is unclear, due to their use of screens. As argued previously, using such place holders could plausibly either aid or hinder infants in their coding of location.

A final program of research that leads to optimism that young infants encode distance in continuous space is the series of studies by Rachel Clifton and her associates concerning reaching in the dark for sounding objects. These studies have established that, by 6 months, infants use auditory information to guide their reaches, both in terms of radial displacement within reaching space (Perris & Clifton, 1988) and in terms of location within versus out of reaching distance (Clifton, Perris, & Bullinger, 1991). In these studies, however, the object continued to sound as the infant reached, so the data tell us more about auditory localization than about spatial coding in short-term memory. Goubet and Clifton (1998) used a paradigm in which 7-month-old infants had to use sound information to specify location, with a delay between the sound and the reach. While they showed some success at this task, it was more in terms of memory for the hemifield in which the object might be than a representation of exact location within that hemifield. In sum, the existing literature does not allow for a definitive answer to the question of whether infants can code location in continuous space.

Two recent studies concerning the spatial-coding capacities of toddlers have shown clear ability for fine-grained coding of location in continuous space by the second year of life. In a series of studies, Huttenlocher, Newcombe, and Sandberg (1994) investigated the ability of children aged 16 to 24 months to find objects hidden in a long thin rectangular sandbox. Children as young as 16 months were able to remember the location of objects hidden at one of nine locations along the length of the sandbox. The children showed highly significant differentiation among the nine hiding locations (i.e., searches were tightly clustered around the correct locations). Furthermore, this accuracy was as clear at 16 months as at 24 months, with no developmental change found across the 8-month time span. Even earlier coding of extent was observed by Bushnell, McKenzie, Lawrence, and Connell (1995). These investigators observed 12-month-olds searching for objects hidden under one of 58 identical cloth cushions covering the ground of a large circular enclosure. Children searched with impressive accuracy, indicating ability to encode distance and direction. Use of a circular enclosure rather than a long rectangular trough (as in Huttenlocher et al., 1994) meant that two dimensions needed to be used to locate objects (i.e., children had to use either vertical and horizontal axes or angular information combined with a distance from a referent such as the self or the center of the pool). Thus, children are apparently capable of coding extent in a fairly precise way in a two-dimensional situation by 12 months. The ability of children as young as 12 months to code distance and direction would seem to justify at least some degree of optimism concerning the presence of this ability in the first year of life.

Investigating infant ability to code location in continuous space also raises the issue of the relation of spatiotemporal characteristics to more static perceptual characteristics, such as color and shape, in specifying what constitutes an object at all. Recently, Xu and Carey (1996) have argued that, almost to the end of the first year of life, objects are defined by their spatiotemporal attributes, rather than by static perceptual attributes such as color and form (see also Bower, 1974; Simon, Hespos, & Rochat, 1995; Spelke, 1990). Infants in the Xu and Carey experiments watched as two objects appeared and disappeared, in alternation, on either side of a screen. When the screen went down to reveal the area behind it, infants' looking times, considered relative to baseline preferences, suggested that the infants had interpreted the original display as the movement of a single object moving from side to side.

Wilcox and Baillargeon (1998) have criticized this conclusion, suggesting that the babies in the Xu and Carey experiments may have had difficulty mapping the oscillating appearance event onto the event in which the screen went down and drawing conclusions based on relating those two events. Wilcox and Baillargeon (1998) in fact reported that infants as young as 7.5 months looked longer at events in which an object (e.g., a ball) went behind a narrow occluder (i.e., not wide enough to hide two objects simultaneously) and then emerged as a different object (e.g., a box), as compared both to situations in which the same object emerged or in which there was an occluder wide enough to hide two objects. They argued that situations of the kind they studied call for event *monitoring* (i.e., watching one ongoing event) rather than event *mapping* (i.e., taking two separate events, seeing them as related, and judging their compatibility) as required in the Xu and Carey work. They suggested that it is only event mapping that poses a challenge for young infants.

OVERVIEW OF THE PRESENT EXPERIMENTS

In this paper, we report evidence bearing on the question of whether infants code location in continuous space. In addition, the last two experiments also bear on the question of the use of spatiotemporal and static perceptual characteristics in defining objects for infants. In five studies, 5-month-old infants observed objects being hidden under the continuous surface of a sandbox. They then saw the objects reappear either from the location in which they were hidden or from a different location. In Experiment 1, the different location was one at which no events had previously occurred. Greater looking to emergence from this location would show coding of distance and/or angle, although such coding might be dependent on the prior absence of events at that location. Experiment 2 was similar to Experiment 1, except that the different location was closer to the hiding location, in order to examine whether coding had more resolution than could be concluded based on Experiment 1. In Experiment 3, the different location was one at which the same object had previously been hidden and discovered on other trials, thus examining infants' ability to code most recent hiding location. In Experiment 4, the different location was one at which an object had previously been hidden and discovered, but not the same object as the one used in the crucial experimental trial. Greater looking in this case would again show coding of the most recent hiding. In addition, Experiment 4 examined infants' reactions to an object emerging from a hiding location where an object of different shape and color had previously been buried. This condition of Experiment 4 bore on the issue of the relation between infants' individuation of objects and infants' ability to code spatial location. The hiding-and-finding sequence constituted a single event (i.e., an event-monitoring situation, in the Wilcox-Baillargeon terminology). Hence, Wilcox and Baillargeon should predict that infants would react with increased looking to the sight of one object being hidden in the sand and a very different looking object emerging from that hiding location. Experiment 5 looked again at reactions to an object of a different appearance emerging from a hiding location.

EXPERIMENT 1

The purpose of this study was to determine whether infants as young as 5 months can code location in continuous space in a very simple situation. An object was hidden in a certain position in a sandbox in full view of the infant and, after a short interval, dug out of that same position. After observing four events of this kind, some infants were shown the object being hidden as usual, but being dug out of a different position, 12 inches (30 cm) away. Finding that infants react to such a demonstration would show evidence of location coding, although it might be fairly primitive in nature. Minimally, such a finding would indicate a basic form of spatial localization, namely discrimination between a location where something had recently been happening and a location at which nothing had ever happened.

Method

Participants

Infants between the ages of five and six months were recruited for this experiment using a commercially available mailing list. Of the 64 infants seen, 47 provided usable data. Fifteen of the 17 unusable subjects were unable to complete the experiment due to fussiness and the other 2 were dropped due to experimenter error. The 47 infants retained in the study had a mean age of 5.44 months (range 5.0–5.99).[1] Infants were randomly assigned to condition (23 in the experimental group and 24 in the control group). There were 13 girls and 10 boys in the experimental group, and 9 girls and 15 boys in the control group.

Apparatus

The infants viewed objects being hidden in a sandbox constructed from 1.9 cm plywood, 91.4 cm × 17.8 cm × 15.2 cm, painted red and containing sterilized white sand 10 cm deep. They sat in an infant seat placed twelve inches in front of the sandbox's long side along a line perpendicular to the midpoint of the long side. White curtains with small patterned observation holes were hung behind the sandbox and along the long sides of the table, obscuring the experimenter and the observer(s) from the subject's view. Two identically decorated plastic eggs, which rattled when shaken, were hidden and then retrieved from the sand. The eggs were 7.6 cm tall, with a 14 cm circumference, painted green, and decorated with shining stars.

Procedure

The experimenter explained the procedure to the parent and then the parent secured the subject in the infant seat and closed the curtains. The experimenter took her place behind the curtains and the sandbox and turned on the audiotape, which cued the timing of events through a headset. Each trial consisted of a 5-second display phase in which the experimenter's hand appeared from behind a white curtain and shook the egg above the hiding position, a 5-second hiding phase in which the experimenter buried the egg in the sand, a 10-second delay with the hand withdrawn and nothing happening, and finally, a 40-second reveal phase in which the hand appeared from behind the curtain, moved immediately to dig out the egg, and held it still above the hiding position in full view of the subject. Once the reveal phase was over, the egg was shaken to signal the beginning of the next trial.

The first four trials were the same for all subjects, consisting of the egg being hidden and revealed in the same place. For half the subjects, this position was in the middle of the box, and for the other half, this position was 30 cm from the middle of the box (equivalent to 45 degrees visual angle), either on the left side (25% of the sample) or the right side (25% of the sample). Babies were randomly assigned to view objects being hidden and revealed either in the middle or at one side or the other of the box. On the fifth trial, control subjects saw the same event as had occurred on the first four trials. Experimental subjects saw the egg hidden in its usual position and then revealed either 30 cm to the left or the right side (if the usual position was the middle) or in the center (if the usual position was to the side). This trick was possible because a duplicate egg had been hidden prior to the testing of each subject. The experimenter moved laterally as needed, so that all hiding and revealing motions were done using the same hand posture.

On-line observation of looking times was used initially (for 53 infants), followed by a change to video recording of the infant, using a camera on a tripod positioned centrally above the sandbox (for 11 infants). All observers and data coders were blind to the condition to which infants had been assigned. This goal was achieved, in the case of on-line observers, by positioning the observers on the sides of the enclosure beyond the sandbox, so that, looking through peepholes in the curtain, they could see the baby but not the experimenter's hands or the events occurring in the sandbox. In the case of video observations (used in all subsequent experiments as well as a portion of this one), the camera was aimed so that only images of the baby were captured; the sandbox, the hand, and the egg could not be seen. On-line observers wore headsets through which they listened to the cuing tape used by the experimenter; after being cued by the command "reveal" on the audio tape, they timed the subjects' looking times, both first look times (from the word "reveal" until the subject perceptibly looked away from the egg) and total looking time during the entire 40-second reveal phase. The videotapes were coded using the same procedure and criteria as on-line coding. Inter-rater reliability for on-line observers was calculated as Pearson $r = .98$, based on seven subjects observed by two coders, and for videotape coders as Pearson $r = .995$, based on four subjects observed by two coders. Percentages of time coders were within 1 second of each other were 80% and 88% respectively.[2] Reliability, in this and subsequent experiments, was high for both first looks and total looks. Agreement on first look times shows that our reliance on observers to judge when an infant had looked away was as acceptable as relying on a specific look-away criterion expressed as number of seconds.

TABLE 1
Mean looking times (with standard deviations in parentheses) as a function of trial and condition in Experiment 1

	Trial				
	1	*2*	*3*	*4*	*5*
First Look Times					
Experimental	11.04 (6.86)	10 (7.40)	10.74 (9.91)	9.22 (7.71)	11.96 (9.01)
Control	10.4 (5.93)	10.83 (8.82)	10.5 (7.71)	10.42 (7.41)	6.04 (2.48)
Total Look Times					
Experimental	24.8 (8.72)	24.3 (6.51)	23.9 (7.42)	21.7 (8.74)	26.1 (6.79)
Control	25.7 (6.37)	25.8 (6.67)	26.2 (7.01)	25.5 (6.38)	23 (7.25)

Results

Preliminary Considerations

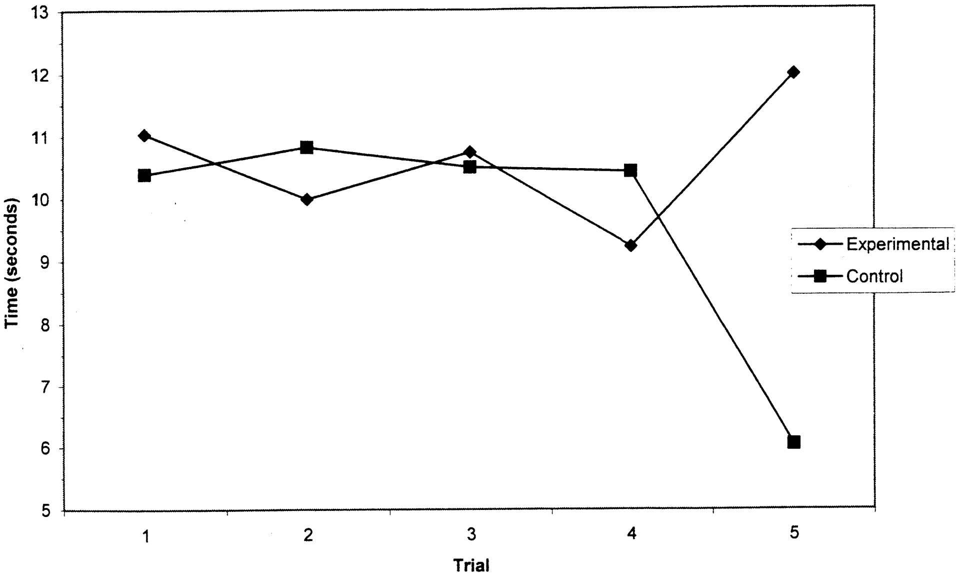
There are three aspects to the analyses of these and subsequent experiments that should be mentioned at the outset. First, the primary analyses involved a search for an interaction of trial (next-to-last and last) and condition (experimental and control), on both first look times and total look times. Ideally, these interactions would reflect a lack of difference between the groups on the next-to-last trial, followed by a divergence on the last trial, where their experiences differed. The divergence might be created by a rise in looking time for the experimental group (due to interest in the event), a fall in looking time for the control group (due to the onset of habituation), or both. Also, in the ideal case, the same pattern would be seen for both the first and total look time measures. Deviations from the ideal in the experiments to be reported in this paper will be noted. Second, in this experiment, as well as the subsequent experiments, there were no significant effects due to sex or due to counterbalanced variables, including whether the initial events were at the middle or at one side of the box. Third, in this experiment, as well as subsequent experiments, the data were examined for outliers, i.e., looking times more than two standard deviations away from the mean. This was considered important because the data are from single trials, not averaged across several trials. However, in Experiment 1, no outliers were found. Means and standard deviations are presented in Table 1; graphs of means only are presented in Figure 1.

First Look Times

Data for trials 4 and 5 were analyzed in a 2×2 ANOVA, with the within-subject factor being trials and the between-subject factor being condition. The main effect for condition was nonsignificant, $F(1,45) = 2.04$, $p = .16$, as was the main effect for trial, $F(1,45) = .34$, $p = .56$. However, the interaction was significant, $F(1,45) = 7.32$, $p < .01$.

The data for trials four and five were compared within each group of subjects using paired t-tests. The control group showed a significant drop from trial four to trial five, $t(23) = 3.1$, $p < .01$. The experimental group showed a nonsignificant increase from trial four to trial five, $t(22) = -1.25$, $p = .22$. Unpaired t-tests showed that the experimental group had significantly longer first looks on trial five than the control group, $t(45) = 3.1$, $p < .005$.

A: First Look



B: Total Look

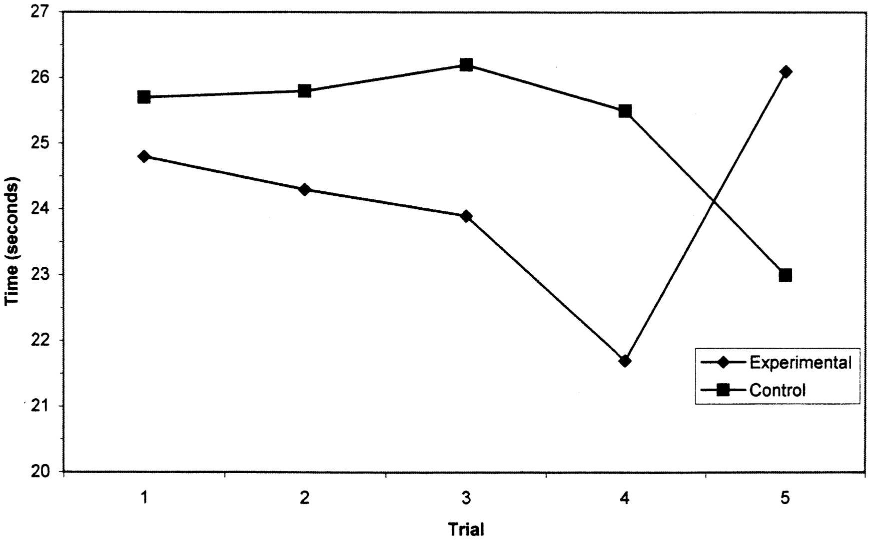


FIGURE 1
First look times (panel A) and total look times (panel B) for experimental and control groups over the trials in Experiment 1.

Total Look Times

Data were again analyzed in a 2 × 2 ANOVA. The main effect of condition was nonsignificant, F (1,45) = 2.15, p = .15, as was the main effect of trial, F (1,45) = .40, p = .53. However, the interaction was significant, F (1,45) = 7.57, $p < .01$.

The experimental group showed a significant rise between trials 4 and 5, t (22) = −2.21, $p < .05$, and the control group showed a significant drop between trials 4 and 5, t (23) = 2.36, $p < .05$. However, the difference in total look time between groups for trial five was not reliable, t (45) = 1.51, p = .14, likely due to the fact that control infants, for unexplained reasons, had quite high looking times on trial 4, while experimental infants had quite low times (see Figure 1B). Thus, this interaction diverged from the ideal form discussed above, although it was still broadly consistent with the hypothesis that the experimental infants noted the difference between the last and the previous events.

Discussion

The data from this study show that 5-month-olds do code at least something concerning the location at which events occur in continuous space. Specifically, they are, at a minimum, able to discriminate between a location where something has recently been happening and a location at which nothing has ever happened. (Whether or not they can do more than this is examined in Experiments 3 and 4.) Finding this kind of basic localization ability is intriguing, because previous experiments using screened locations have found conflicting evidence regarding early localization, of uncertain relevance to coding of location in continuous space.

There might be two questions raised about this conclusion. A first, methodological, question concerns whether infants could have been reacting to a disturbance in the sand evident at the hiding location but nowhere else in the box, rather than having a memory for location. While we made an effort to smooth the sand over after each hiding, the data in this experiment cannot definitively exclude this possibility. Such an artifactual explanation is, however, ruled out by the results of Experiment 3, in which two hiding locations were used. Disturbances in the sand, if any, would be equally evident at the two locations. A second, more conceptual, question concerns whether infants are coding the location of the buried object or the location of the hidden hand. The data are indeterminate on this issue, because the most recent hiding location, in this and subsequent experiments, was also the site of the most recent appearance of the hand. Answering this question is, however, not relevant to our central concern, namely, charting the emergence of the ability to code location using angle or distance. The hand is an "object" as much as the egg is, and it vanishes behind the constant expanse of the curtain just as the egg disappears in the sand.[3]

The evidence of basic localization of the kind found in Experiment 1 is only a first step in characterizing early ability to code object location using angle or distance. Several questions were addressed in subsequent studies. Experiment 2 asked whether infants can only code location given the relatively large distance between hiding and finding locations used in Experiment 1 (associated with a large difference in visual angle). Experiment 3 asked whether infants can remember a location, even when an object has been seen recently at various different locations in the world. That is, to take the simplest case, if an object has been seen at two locations, can young infants still code where the object was most recently hidden? Finally, Experiments 4 and 5 asked whether infants can remember particular objects as having particular locations. That is, are objects, as individuated by color, shape, size, sounding characteristics, or function, considered to have specific spatial locations?

EXPERIMENT 2

One limitation of Experiment 1 is the use of a 30-cm gap between locations. Such a gap is fairly large, twice that of the 15-cm gap between locations studied in prior work with toddlers (Huttenlocher et al., 1994). Because the sandbox used was smaller than that in the toddler work, the gap may have loomed even larger. In particular, objects positioned towards the sides of the box were only 12.5 cm from the end (measured from the inner edge of the wooden box), a position that may have enhanced the distinctiveness of the gap, by allowing for a categorical coding as "at the end" of the box. (Adults reported seeing these locations as describable in this way.) In order to determine whether 5-month-olds are able to code location when one location is not obviously at the "end" of the sandbox, we used a gap of 20 cm. This gap was such that, using the same sandbox as used previously, lateral locations were 22.5 cm from the end of the box, and no longer appeared to adult observers to be "at the end."

Method

Participants

There were 77 infants between the ages of 5 and 6 months recruited for this experiment, using a commercially-available mailing list. Of the 77 infants, 56 provided usable data. Fifteen subjects did not complete the experiment due to fussiness and 6 were dropped due to experimenter error or technical difficulty. The 56 infants retained in the study had a mean age of 5.38 months (range 5.0–5.99). Infants were randomly assigned to condition ($n = 28$ in the experimental group and $n = 28$ in the control group). There were 16 boys and 12 girls in the experimental group and 16 boys and 12 girls in the control group.

TABLE 2
Mean looking times (with standard deviations in parentheses) as a function of trial and condition in Experiment 2

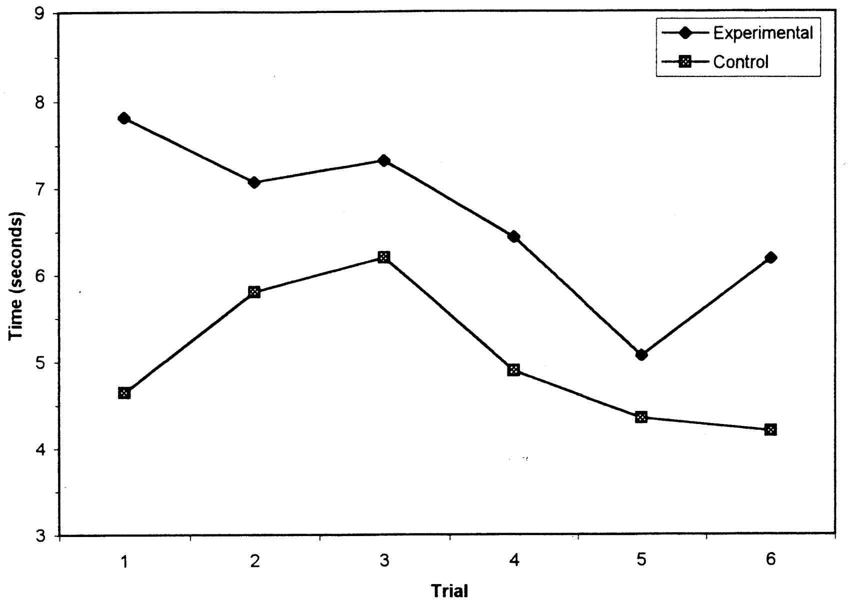
	Trial					
	1	*2*	*3*	*4*	*5*	*6*
First Look Times						
Experimental	7.82	7.07	7.32	6.43	5.07	6.18
	(5.41)	(6.16)	(5.75)	(4.63)	(2.39)	(3.69)
Control	4.65	5.8	6.2	4.9	4.35	4.2
	(3.32)	(7.55)	(7.07)	(3.81)	(1.77)	(2.68)
Total Look Times						
Experimental	19.5	19.8	19.2	19.7	18.3	19.9
	(8.08)	(7.66)	(7.06)	(7.22)	(8.22)	(7.01)
Control	17.1	18	19	18.8	19.5	18.9
	(7.37)	(7.43)	(7.93)	(7.12)	(7.29)	(7.59)

Procedure

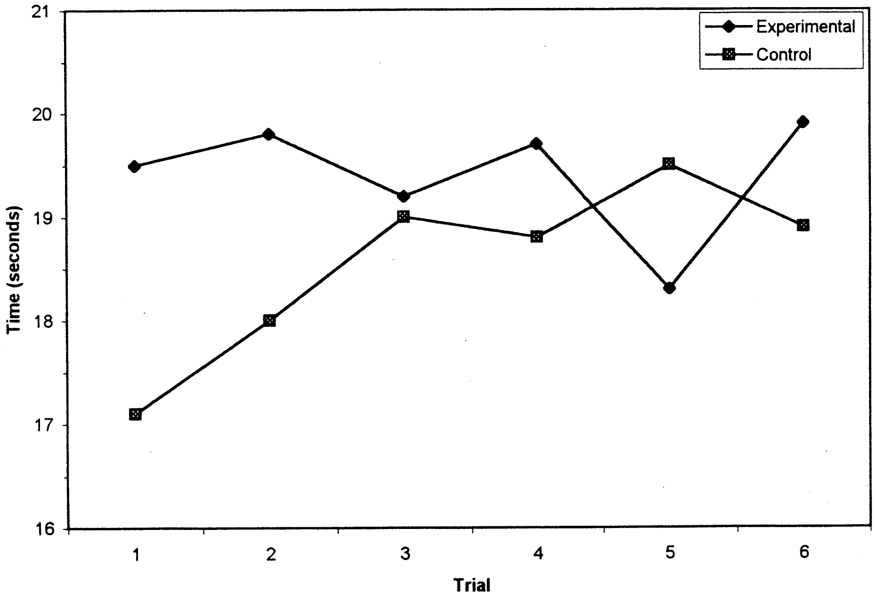
The apparatus and procedure were comparable to that in Experiment 1. The major difference was that the possible hiding locations were in the middle of the box and at points 20 cm either to the left or the right of the middle. The visual angle for the lateral positions was 33 degrees. Infants were randomly assigned to view initial hiding-and-finding events either in the middle (50%) or at one of the ends (25% each). An additional difference from Experiment 1 is that we used five rather than four familiarization trials, so that the crucial trial was the sixth trial. (This difference was inadvertent, but by the time it was discovered a considerable amount of data had already been collected.) Inter-judge reliability, computed on 27 subjects, was $r = .97$, and always above .90. Coders were within 1 second of each other 89% of the time.

Results

Means and standard deviations are presented in Table 2; graphs of means only are presented in Figure 2.



A: First Look



B: Total Look

FIGURE 2
First look times (panel A) and total look times (panel B) for experimental and control groups over the trials in Experiment 2.

First Look Times

Data for trials 5 and 6 were analyzed in a 2 × 2 ANOVA, with the within-subject factor of trials and the between-subject factor of condition. Data from two infants were discarded because looking times for either Trial 5 or Trial 6 were more than 2 standard deviations above the cell mean (one from the experimental group and one from the control group). Main effects for condition and for trial were not significant, F (1,52) = 2.20, $p = .144$ and F (1,52) = .185, $p = .668$ respectively, but the interaction was significant, F (1,52) = 7.43, $p < .01$. There was a significant difference between the experimental and control groups on Trial 6, t (52) = 1.854, $p = .034$, but not on Trial 5. Paired t-tests comparing trials 5 and 6 showed a nonsignificant decrease for the control group, t (26) = .46, $p = .67$, and a trend toward a significant increase for the experimental group, t (26) = −1.86, $p < .07$.

Total Look Times

Data for trials 5 and 6 were analyzed in a 2 × 2 ANOVA. No data needed to be discarded. The main effect for trial was not significant, F (1,54) = .84, $p = .36$, nor was the main effect for condition, F (1,54) = .14, $p = .71$. The interaction was not reliable either, F (1,54) = 2.45, $p = .12$. There were no significant differences between trial 5 and trial 6 for either the control group, t (27) = .45, $p = .66$, or the experimental group, t (27) = −1.79, $p = .085$, and no significant difference between the control and experimental group on trial 6, t (54) = .26, $p = .39$. As with Experiment 1, although to a greater extent, the total look times did not fully confirm the hypotheses. However, in interpreting these results, one should keep in mind that the control group's behavior in terms of total look was, unfortunately, odd, and in particular, that their looking times on trial 5 were higher than one might expect.

Discussion

Although the total look time data were equivocal, the first look time data from this experiment suggest that 5-month-olds can retain the location of an object in a more fine-grained way than demonstrated in Experiment 1. They reacted with longer first looking times when the object emerged from a novel location only 20 cm away from the hiding location, even though both locations would be described categorically by adults as "in" the box rather than "at the end."

It might be argued that one limitation of the finding is that one of the two locations was always at the *exact* middle (i.e., the midpoint), so that infants might have either been categorically distinguishing the midpoint from other points in the box, or using alignment with their own body midline to define one of the positions. Further work should examine performance with two locations in which neither is at the midpoint, to eliminate or substantiate these possibilities. However, note that the first possibility (i.e., an ability to determine the midpoint of the box) would still indicate impressive abilities to code distance, perhaps even more impressive than simple discrimination across a 20-cm gap; coding the midpoint requires considering the entire 91-cm span of the box and dividing it in half. Note also that the second possibility, coding one point in terms of alignment with the body midline, would not be unimpressive either, in that infants would still need to be coding the lateral position as 20 cm (or 33 degrees of visual angle) *off* of the midline. Thus, while coding the object as "away from the center (or not)" is a distinct possibility given our current data, the boundaries of such a category cannot be very wide.

EXPERIMENT 3

The purpose of this experiment was to determine whether infants can code the most recent hiding location of an object that they

TABLE 3
Mean looking times (with standard deviations in parentheses) as a function of trial and condition in Experiment 3

	Trial						
	1	*2*	*3*	*4*	*5*	*6*	*7*
First Look Times							
Experimental	7.79	6.13	6.96	6.29	5.17	4.79	5.5
	(5.42)	(2.39)	(4.49)	(4.35)	(2.31)	(1.57)	(1.96)
Control	6.88	6.96	6.75	7.38	5.63	5.79	4.08
	(4.1)	(5.71)	(4.65)	(6.32)	(3.43)	(3.71)	(2.15)
Total Look Times							
Experimental	17.8	17.6	17.4	16.5	15.9	14.2	16.2
	(5.82)	(5.57)	(5.94)	(7.13)	(7.03)	(4.79)	(5.28)
Control	15.1	17.2	16.4	15.8	15.3	14.1	10.4
	(5.95)	(8.66)	(7.38)	(7.25)	(6.44)	(7.89)	(5.65)

have seen hidden in two locations. Success in such a situation would show that the ability of 5-month-olds to code location in Experiment 1 was more than simply a differentiation between a location where hiding events had occurred and other locations where nothing had happened. It might be argued that coding of the most recent location of an object at this age would be surprising, given that infants of 5 months show A-not-B errors in gaze direction (Hofstadter & Reznick, 1996). However, the deliberate build-up of perseverative tendencies in the A-not-B paradigm may mask the ability of infants to remember an object's most recent location. In this study, the object was hidden alternately in the two locations rather than repeatedly in any one location.

Method

Participants

There were 66 infants between the ages of 5 and 6 months recruited for Experiment 3, 32 female and 34 male. The average age of the 49 usable subjects was 5.59 months, with a range of 5.0 to 6.0. The other 17 subjects had to be terminated from the study due to distress. The experimental group consisted of 25 babies (9 female and 16 male), and the control group consisted of 24 babies (15 female and 9 male).

Procedure

The procedure was comparable to that of Experiment 1, except that, on six initial trials, the decorated egg was alternately hidden in the two locations located 30 cm apart. On the seventh trial, the experimental group saw the object hidden in location A and revealed in location B (or vice versa), whereas the control group saw it hidden and revealed in the same location (either A or B). Interjudge reliability computed on 13 subjects averaged $r = .96$ with none of the pairs of judges falling below .935. Times were within 1 second of each other on 86% of the trials.

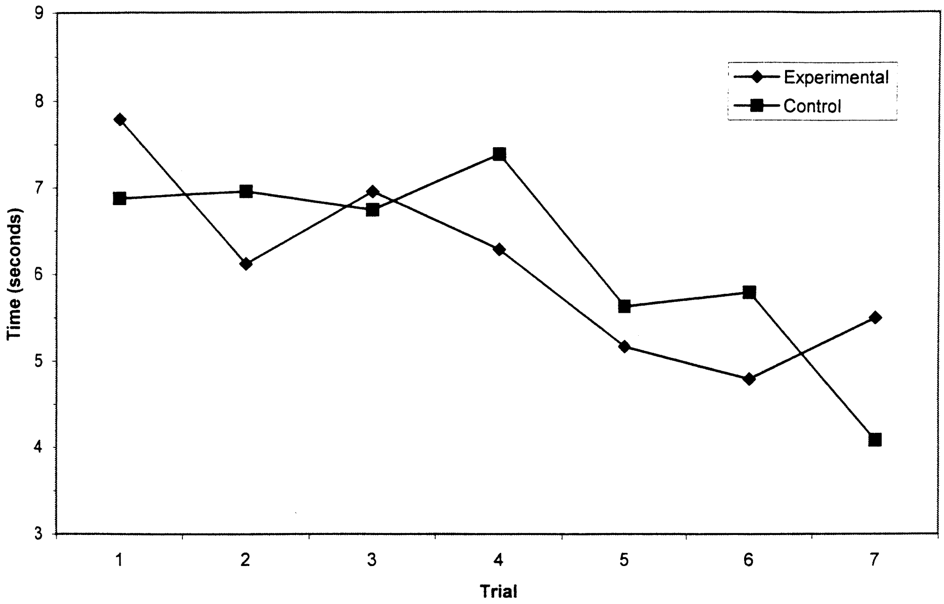
Results

A check for outliers, with looking times more than two standard deviations from the group mean, led to eliminating one infant from the experimental group for both analyses. Means and standard deviations are presented in Table 3; graphs of means only are presented in Figure 3.

First Look Times

The data were analyzed in a 2×2 ANOVA for trials 6 and 7 by condition. The main effect for condition was nonsignificant, F (1,46) =

A: First Look



B: Total Look

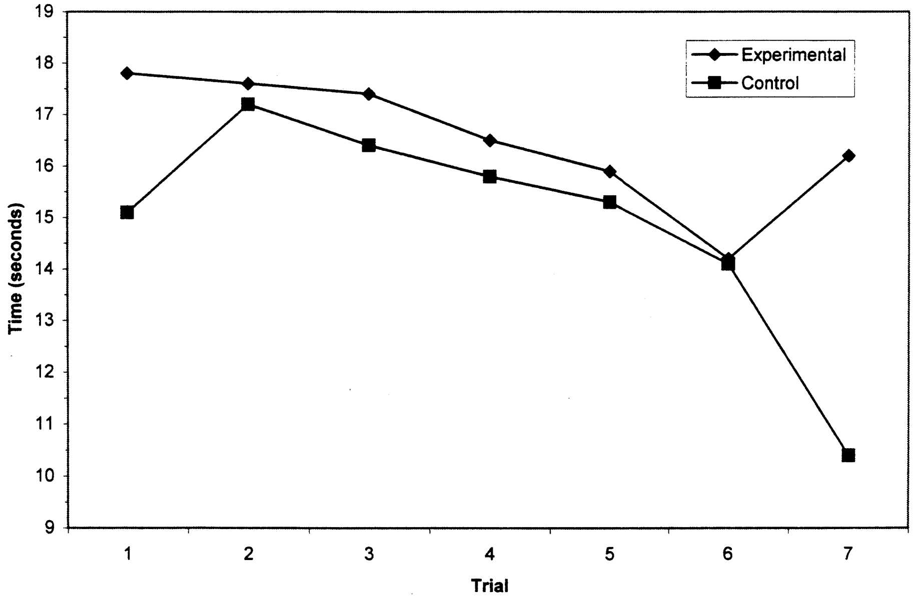


FIGURE 3
First look times (panel A) and total look times (panel B) for experimental and control groups over the trials in Experiment 3.

.10, $p = .76$, as was the main effect for trial, F $(1,46) = 2.32$, $p = .13$, but the interaction was significant, F $(1,46) = 13.55$, $p < .001$.

Paired *t*-tests for trials 6 and 7 showed a significant drop for the control group from trial 6 to trial 7, t $(23) = 3.72$, $p < .001$. The experimental group showed a significant increase from trial 6 to trial 7, t $(23) = -1.87$, $p = .037$. The experimental group had significantly longer first looks on trial 7 than the control group, t $(46) = -2.30$, $p = .013$.

Total Look Times

Data were analyzed in a 2 × 2 ANOVA. The main effect for condition was close to significant, F $(1,46) = 3.99$, $p = .052$; the main effect for trial was not significant, F $(1,46) = 1.77$, $p = .19$. The interaction was significant, F $(1,46) = 15.22$, $p < .001$.

The experimental group showed a significant increase in looking times between trial 6 and trial 7, t $(23) = -1.81$, $p = .04$. The control group showed a significant decrease in looking times between trial 6 and trial 7, t $(23) = 3.72$, $p < .001$. The difference in total look time between groups for trial 7 was significant, t $(46) = -3.72$, $p < .001$.

Discussion

The 5-month-old babies in Experiment 3 showed an impressive ability to remember the most recent location of an object that they had just seen hidden six times, three times in one location and three times in another. The data from this experiment also eliminated a potential artifactual explanation for the results from the first two experiments, namely that babies expected objects to appear where subtle disturbances in the sand marked the hiding location. In this study, two locations were used, so that use of any disturbances in the sand remaining despite smoothing would not allow the infants to react to objects emerging from a location different from the most recent hiding location.

At first glance, the ability shown by infants in Experiment 3 may seem contradictory to Hofstadter and Reznick's observation of A-not-B errors in 5-month-olds' gaze behavior (Hofstadter & Reznick, 1996). However, there is a contradiction only if one assumes that behavior in an A-not-B paradigm is directly informative about memory for spatial location. More recent accounts of the A-not-B error stress its multidimensionality. Specifically, in A-not-B tasks, infants experience the hiding and revealing of an object at A, at least once and sometimes many times. There is then a switch to location B, at which point the error may occur. In the present Experiment 3, the infants saw a sequence of hiding and revealing in which both locations were used equally often. It is likely that this familiarization broke up tendencies to perseveration, teaching the infants, in effect, that the object could be hidden in more than one location and that finding it would require tracking the current location. Such an analysis is consistent with discussions of A-not-B errors as involving perseverative responding (Diamond, 1985; Thelen & Smith, 1994).

One question that might be raised about the data from Experiment 3 concerns the importance of the fact that the hidings at the two locations occurred in alternation. That is, did the familiarization trials set up an expectation that one should look first in one direction then in the other in order to see the object? Such expectations have been shown to develop fairly rapidly in 3-month-olds (Haith, Hazan, & Goodman, 1988). However, the work by Haith et al. is of uncertain relevance to the present situation. First, these experiments used sequences of stimuli for which rhythmicity might be much more salient than in our situation. Specifically, stimuli appeared for 700 msec, with 1100 msec intervals between stimuli; by contrast, event cycles in the present experiments took one minute (60,000 msec) each. Second, although expectations in the babies studied by Haith et al. developed more quickly than one might have expected, they were not instantaneously evident. Infants required 5 or 6 stimuli on each side before showing expectations. Of course, though, the ultimate test of the importance of alternation to our findings is empirical. In future work, irregular series of events in familiarization trials should be used as well as regular ones.

EXPERIMENT 4

The purpose of this study was to determine whether infants of 5 months show evidence of coding objects, distinguished on the basis of static perceptual characteristics, as having particular locations. Such an ability is what is generally meant when one speaks of having a memory for the location of an object. That is, location is considered an attribute of an object, individuated on the basis of nonspatial attributes as well. For example, one's hat is considered an entity with a variety of particular attributes (e.g., a black beret bought in France five years ago, with a small moth-hole at its edge), one of whose attributes is its current location (e.g., on the coat hook in the vestibule). However, there have been proposals that, for infants, spatial location, taken alone, defines what an object is (Bower, 1974; Simon et al., 1995; Spelke, 1990; Xu & Carey, 1996). If true, this hypothesis implies a very different function for location coding in the lives of infants as contrasted with those of adults.

To address the goal of determining whether location is the definitional attribute of an object for 5-month-olds, or simply one of several attributes of differentiated objects, Experiment 4 used familiarization trials in which infants were shown one object hidden at one location in a sandbox and a second object hidden at a second location, in alternation. One experimental group then saw one of the objects hidden in its usual location, but dug out of the location previously used only to hide the other object. Reacting to this event, which can be called a "location violation," would show either that the infants coded the habitual location of each object, or coded the location where some object (its characteristics not further specified) was most recently hidden.

A second experimental group, having seen an object hidden at its usual location, saw the object usually hidden at the other location dug out of the "wrong" location. If this group, which can be called an "object-violation" group, were to show reactions in looking time as well as the location-violation group, one could conclude that infants coded the particular locations of particular objects. On the other hand, if the location-violation group showed reactions but the object-violation group did not, one could reach two conclusions: first, that infants code the most recent of two hiding locations, even when events have been occurring at both, and second, that infants do *not* code particular objects as having particular locations.

Method

Participants

There were 110 infants recruited for Experiment 4, 94 of whom provided usable data and 16 of whom could not complete the experiment due to fussiness. The average age of the 94 usable subjects was 5.46 months (range 5.0–5.99). There were 32 subjects (12 female, 20 male) in the location-violation group, 26 subjects (12 female, 14 male) in the object-violation group, and 34 subjects in the control group (15 female, 19 male).

Materials

The basic apparatus was the same as that used in previous experiments. Two objects were used in hiding events. One object was a clear box filled with colorful beads that moved and sounded when shaken; the box was 3.8 cm by 6.4 cm by 1.3 cm in size. The other object was a pink and purple plastic mesh ball, 3.8 cm in diameter, containing a bell.

Procedure

The basic procedure for this experiment was similar to previous experiments. There were seven trials. On the first six trials, the two different objects were hidden alternately in two locations 30 cm apart, either the middle and the right side or the middle and the left side. That is, on trials 1 through 6, the experimenter alternately hid and revealed object A at location A and object B at location B, for a total of three hide-and-reveal events for each object at each location. On trial 7, for the location-violation group, object A was hidden in location A (as usual) but revealed in location B (having previously been hidden there). On trial 7, for the object-violation group, object A was hidden in location A (as usual) but object B was dug out of location A (having previously been hidden there). For the control group, the object was revealed as usual in the same location in which it was hidden. Assignment of the subjects to group was randomized. Whether the initial and final trials were at the middle or at the side was counterbalanced across subjects, as was the pairing of objects and locations.

Validity Check

In order to assess whether 5-month-old infants could distinguish the two objects used in this study, 16 other infants were observed in a preferential looking paradigm (9 males, 7 females, mean age 5.2 months, range 5.0–5.9). (Two additional subjects did not provide usable data due to fussiness.) These infants saw one of the two toys used in the main experiment for four trials, with each trial consisting of displaying the object as in the main experiment, shaking and sounding it, then removing it behind the white curtain surrounding the apparatus for 10 seconds, and then showing it again for 40 seconds. Infants were randomly assigned to familiarization with either the mesh toy or the clear box containing beads. On the fifth trial, after seeing the target object displayed as usual, the infants saw two toys, one familiar and one novel, reappear from behind the white curtain. The toys were held equidistant from the infant's midline, one on the left and one on the right. Left-right position of the familiarized toy was counterbalanced.

Interjudge reliability was $r = .98$, calculated on 5 subjects. Coders were within 1 second of each other on 91% of the trials.

Results

The data for the location-violation and for the object-violation groups were examined separately, each in relation to the common control group. An examination for outliers eliminated one infant from the control group. Means and standard deviations are shown in Table 4; a graph of means only is in Figures 4 and 5.

First Look Times for Location-Violation vs. Control

A 2 × 2 ANOVA was conducted on the data shown in Figure 4A. The main effect for condition was nonsignificant, F (1,64) = .18, $p = .67$, as was the main effect for trial, F (1,64) = 2.9, $p = .09$. The interaction was at the margin of significance, F (1,64) = 3.69, $p = .06$.

Paired *t*-tests for trials 6 and 7 showed a nonsignificant change for the control group from trial 6 to trial 7, t (33) = −.38, $p = .35$, but a significant increase for the experimental group, t (31) = −1.86, $p = .036$. Unpaired *t*-tests for the trial 7 data showed that the experimental group had marginally reliable longer first looks on trial 7, t (64) = −1.51, $p = .068$.

Total Looking Times for Location-Violation vs. Control

Again a 2 × 2 ANOVA was conducted on the data (shown in Figure 4B). There was a nonsignificant main effect for condition, F (1,64) = .07, $p = .80$, a significant main effect for trial, F (1,64) = 7.3, $p < .01$, and a significant interaction, F (1,64) = 5.17, $p = .026$.

The experimental group showed a significant increase in looking times between trial 6 and trial 7, t (31) = −2.78, $p = .004$. The control group showed a nonsignificant change in looking times between trials 6 and 7, t

TABLE 4
Mean looking times (with standard deviations in parentheses) as a function of trial and condition in Experiment 4

	Trial						
	1	*2*	*3*	*4*	*5*	*6*	*7*
First Look Times							
Location Violation	7.27	6.84	8.5	7.47	5.75	5.5	7.03
	(4.33)	(3.68)	(6.27)	(4.66)	(3.33)	(2.76)	(5.09)
Object Violation	6.41	6.85	7.07	5.67	6.37	5.52	6.19
	(4.22)	(3.75)	(4.5)	(3.23)	(5.29)	(2.57)	(3.14)
Control	6.17	6.11	7.40	7.20	5.63	4.91	5.66
	(3.47)	(3.38)	(6.01)	(4.54)	(2.66)	(1.89)	(3.60)
Total Look Times							
Location Violation	16.8	16.9	17.7	17.0	15.5	15.3	18.4
	(7.16)	(7.04)	(8.70)	(6.75)	(6.88)	(5.65)	(7.20)
Object Violation	17.8	19.1	20.9	17.9	18.3	16.7	16.8
	(8.03)	(7.21)	(7.01)	(6.78)	(6.72)	(6.86)	(7.60)
Control	15.9	16.9	18.4	16.9	16.5	15.5	15.7
	(7.94)	(7.01)	(7.59)	(7.73)	(6.57)	(6.39)	(7.54)

(33) = $-.033$, $p = .49$. The difference in total look time between the experimental and the control group for trial 7 was nonsignificant, t (64) = -1.11, $p = .136$.

First Look Times for Object-Violation vs. Control

A 2 × 2 ANOVA on the data shown in Figure 5A revealed the main effect for condition to be nonsignificant, F (1,58) = .88, $p = .35$, as was the main effect for trial, F (1,58) = .24, $p = .62$. The interaction was also not significant, F (1,58) = .15, $p = .69$. Paired t-tests for trials 6 and 7 showed a nonsignificant change from trial 6 to trial 7 for both groups, t (33) = $-.38$, $p = .35$, for the control group and t (25) = -1.05, $p = .15$ for the experimental group. There was no difference between the experimental group and the control group on trial 7, t (58) = $-.85$, $p = .19$.

Total Looking Times for Object-Violation vs. Control

The 2 × 2 ANOVA on the data shown in Figure 5B yielded a nonsignificant main effect for condition, F (1,58) = .41, $p = .52$, and a nonsignificant main effect for trial, F (1,58) = .02, $p = .88$. The interaction was not significant, F (1,58) = .05, $p = .82$. The experimental group showed a nonsignificant change in looking times between trials 6 and 7, t (25) = $-.50$, $p = .31$, as did the control group, t (33) = $-.03$, $p = .49$. The difference in total look time between groups for trial 7 was nonsignificant, t (58) = $-.87$, $p = .19$.

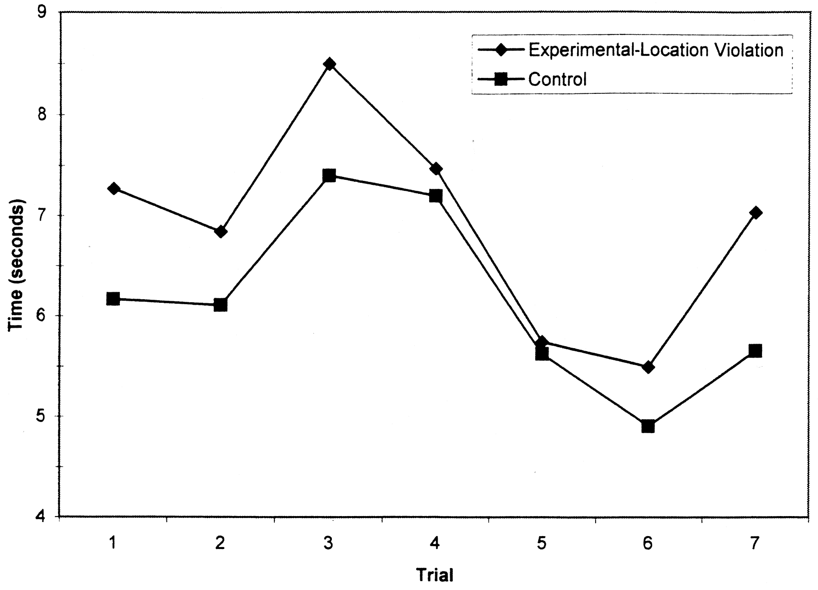
Object-Violation vs. Location-Violation

The two experimental groups did not differ significantly from each other, on either first looking time or total looking time measures.

Validity Check

The results for the object-violation group would be uninteresting if infants were simply incapable of distinguishing between the two objects used in the study. The data from the infants in the preferential-looking paradigm showed, however, that infants of this age differentiated between the two toys, preferring to

A: First Look



B: Total Look

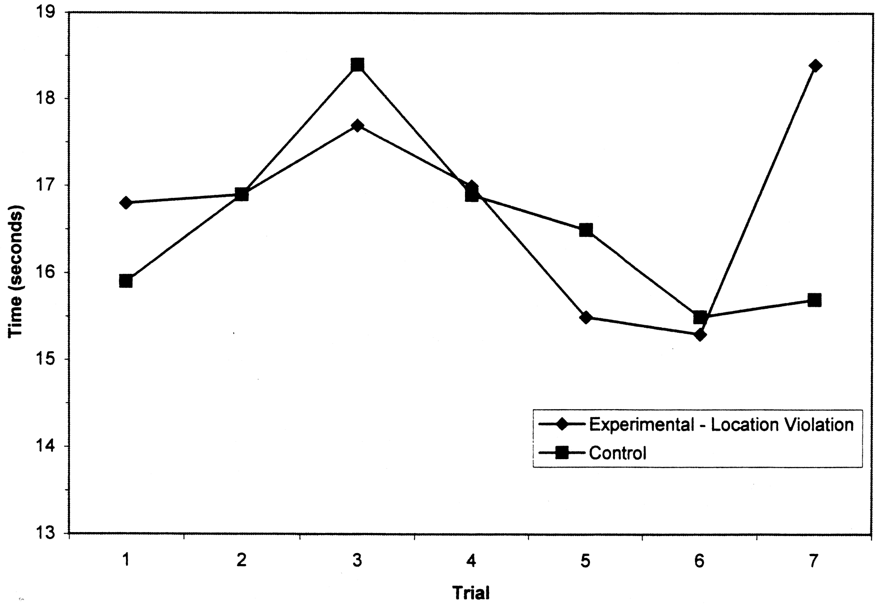
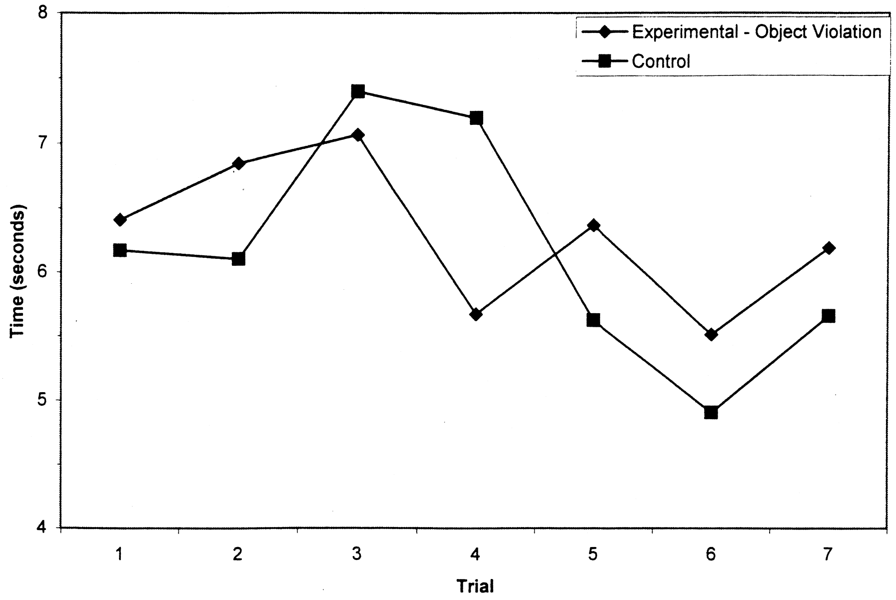
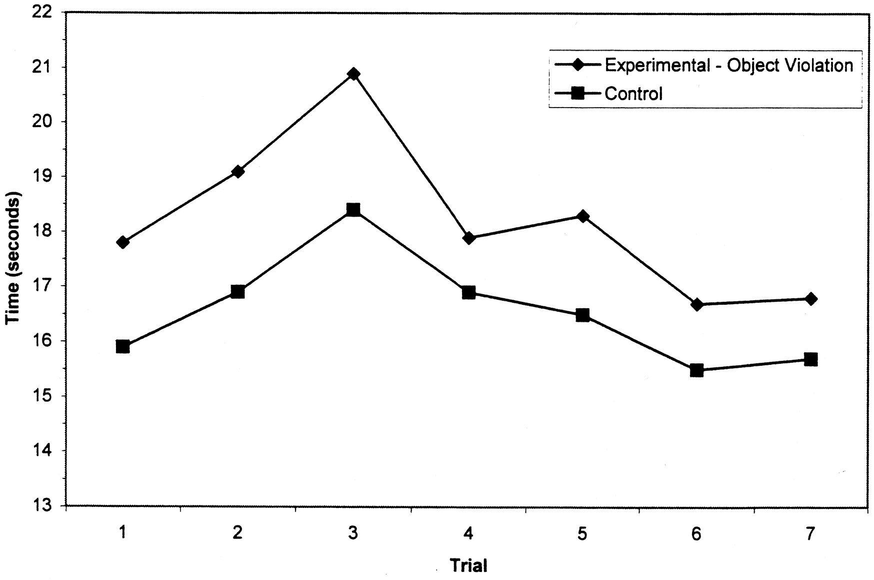


FIGURE 4
First look times (panel A) and total look times (panel B) for location-violation and control groups over the trials in Experiment 4.



A: First Look



B: Total Look

FIGURE 5
First look times (panel A) and total look times (panel B) for object-violation and control groups over the trials in Experiment 4.

look at the familiar toy rather than the novel one, t (15) $= 2.75$, $p < .05$.[4,5]

Discussion

The data from the location-violation group in Experiment 4 largely confirm the findings of Experiment 3, although some of the findings were at the margin of reliability. Taken together, though, the data from the two experiments suggest that 5-month-old infants can code the most recent hiding location of an object (or, possibly, the most recent place at which the hand disappeared behind the curtain). On the other hand, there was no indication from the object-violation group in this experiment that, at 5 months, infants react with increased looking when an object emerges from a location at which a different object had just been hidden.

This combination of findings suggests the possibility that, at 5 months, infants do not remember location as an attribute of objects individuated by static perceptual characteristics (as when one says the black beret is on the coat hook). Rather, they may consider an object as defined by its location. That is, an "object" is whatever is found where something recently disappeared (either object-in-the-sand or hand-behind-the-curtain). Such a conclusion would be supportive of the results of Xu and Carey (1996) and Simon et al. (1995). While Wilcox and Baillargeon (1998) criticized this conclusion, suggesting that it was due to difficulty with relating or mapping two events, the paradigm used in Experiment 4 allowed for a test of the Xu and Carey hypothesis in which there was no need for infants to map events onto one another and see their relation. If infants can use static perceptual attributes as well as spatiotemporal characteristics to individuate objects, then they should react with increased looking time to the sight of a perceptually different object being dug out of the sand at a location at which they have just seen a different object buried—they need only monitor the event, to use the Wilcox and Baillargeon terminology. However, using the same familiarization events as seen by the location-violation group, infants in the object-violation group did not react to a change in static perceptual attributes when the location remained constant. That is, even in monitoring a single event in progress, they showed the same kind of error observed by Xu and Carey.

It is important to note that this conclusion clearly does not entail the claim that infants do not individuate objects using attributes such as shape, size, color, or sounding characteristics. Recent research suggests that, by 4 months, infants can use simple featural information to perform object segregation tasks (Needham, 1997), although shape and size may be used earlier than color information (Wilcox, 1999). However, while infants can use certain perceptual attributes in the absence of conflicting spatiotemporal attributes, they may prefer to rely on spatiotemporal trajectory in situations where these kinds of cues conflict, leading to erroneous expectations about how many such objects there are (in the Xu and Carey experiment) or about the objects' location (in the present experiment). Perhaps their bias to use spatiotemporal attributes arises due to the fact that some important "objects" in infants' environments, namely people, actually do change their characteristics as they change clothes, adjust their hairstyles, and so on.

However, using the data from Experiment 4 to argue for infants' reliance on spatiotemporal characteristics as defining objects involves dependence on a null effect. Therefore, to evaluate the argument further, Experiment 5 explored a situation in which infants might be more likely to have a basis for reacting to the different-looking object.

EXPERIMENT 5

It might be argued that infants would be more likely to react to the different-looking object if they had been given an initial opportunity to see the two objects side by side. They

TABLE 5
Mean looking times (with standard deviations in parentheses) as a function of trial and condition in Experiment 5

	Trial						
	1	*2*	*3*	*4*	*5*	*6*	*7*
First look times							
Experimental	5.76	4.62	7.06	4.32	4.43	3.71	3.76
	(4.88)	(3.08)	(5.47)	(3.54)	(2.31)	(1.94)	(2.75)
Control	6.45	6.09	6.82	4.86	5.03	4.76	3.80
	(4.00)	(3.48)	(4.94)	(3.07)	(1.76)	(1.70)	(1.73)
Total look times							
Experimental	17.4	19.2	18.5	16.7	16.1	14.6	12.8
	(7.92)	(6.30)	(5.90)	(6.80)	(4.87)	(6.56)	(5.77)
Control	22.6	21.5	21.2	17.8	19.0	18.2	15.3
	(5.34)	(8.00)	(6.51)	(7.62)	(6.84)	(7.84)	(5.80)

would then, perhaps, realize that there were two objects, and compare them so as to encode their different characteristics comparatively and contrastively. Therefore, we replicated the location-violation conditions of Experiment 4 with the addition of an initial period of familiarization with the two objects side by side.

Method

Participants

There were 48 infants recruited for Experiment 5, 40 of whom provided usable data. Of the other eight infants, six became fussy and experimenter error occurred with the other two. The average age was 5.4 months (range 5.0–5.9). There were 20 subjects in each group (11 female and 9 male in the experimental group and 12 female and 8 male in the control group).

Materials and Procedure

These were exactly as in the location-violation conditions of Experiment 4, except for the addition of a two-object familiarization phase before the main procedure. All infants began by seeing the two objects side by side for one minute. During the first five seconds, one object was shaken to attract attention, and during the second five seconds, the other object was shaken. The two objects were then held still for the remaining 50 seconds. After a 5-second delay, the experiment proper began. Inter-judge reliability for looking times averaged .99, with no values below .95.

Results

Two outliers needed to be omitted, one from the experimental group and one from the control group. (Three babies whose data just exceeded the limits for outliers were retained, but analyses with these data omitted produced parallel results.) Means and standard deviations are shown in Table 5. Analysis of variance of first look times showed no significant main effects of condition or trial, and, most important, no interaction, F (1, 36) = 1.88, p = .179. Analysis of variance of total look times showed no effect of condition, a close-to-significant effect of trial, F (1, 36) = 3.88, p = .057, with the last trial producing shorter looking times than the next-to-last trial, but, most important, no interaction, F (1, 36) = .18.

Discussion

This experiment replicates the finding of Experiment 4, that infants of 5 months do not react with increased looking when a different-appearing object emerges from a location where something has recently been hidden. This lack of effect occurred even when the infants had been given an opportunity to compare and contrast the two objects. Thus, the data strengthen the case that spatiotemporal characteristics are heavily weighted by young infants as determining what counts as an object in the world.

Still, further experiments are necessary to determine the conditions under which infants do and do not show a reliance on spatiotemporal information in object individuation. For instance, in our work, if infants attended to the location of the hand, the fact that, in the object-violation condition, it appeared at the same location as that at which it disappeared may have supported a focus on spatiotemporal information. An experiment in which objects emerged and disappeared into the sand without a hand in evidence (using a hidden mechanical device) could evaluate this possibility. Infants might also do better if the two objects were even more obviously discriminable, or if they were given more time to learn the characteristics of the objects. The fact that infants in the validity check of Experiment 4 showed a familiarity preference rather than a novelty preference is consistent with the argument that it may simply take some time for infants at this age to encode the appearance of objects.

In addition, our experiments only involved 5-month-olds, so it is not known at what point in development infants would begin to show reactions to different objects being removed from a certain location in the sandbox. It may be that this ability would emerge considerably earlier than the 10 months at which Xu and Carey began to see mature behavior in their paradigm. In fact, Wilcox and Baillargeon found success in an event-monitoring situation (the condition they argue is the easier one) only at 7.5 months. Thus, it may be that reliance on spatiotemporal attributes for object individuation is a graded phenomenon, seen more and more robustly as the first year of life progresses. The fact that the object-violation and location-violation groups in Experiment 4 were not significantly different from each other, although location-violations differed from the control group and object-violations did not, also supports the idea of a graded phenomenon.

GENERAL DISCUSSION

The experiments reported in this paper show both strengths and possible limitations in the way infants code the locations of objects. We begin by reviewing the strengths, proceeding next to the possible limitations. We then take up the questions remaining unsettled by the present research, and the implications of these studies for understanding the development of hierarchical coding of spatial location. Hierarchical-coding models of spatial estimation posit a process in which fine-grained estimates of spatial location are adjusted by categorical memories of location to the extent that there is uncertainty about the former (cf. Huttenlocher, Hedges, & Duncan, 1991). Huttenlocher et al. (1991) presented evidence for this model of spatial estimation in adults, and showed that hierarchical combination is an adaptive process, resulting in reduced variability of spatial estimates.

Coding Location in Continuous Space

A surprising strength in the infant repertoire is the ability to code location in continuous space. Prior studies often considered most germane to the issue of infant location coding (Baillargeon & Graber, 1988; Baillargeon et al., 1989; Wilcox et al., 1994, 1996) had shown conflicting results, and were, in any case, ambiguous with respect to the issue of coding in continuous space, due to their use of screens that defined discrete possible locations. The present data show clearly that, by 5 months, infants have considerable ability to fix locations in continuous space, at least for short periods of time.

The reactivity of 5-month-olds in the present experiments to unexpected movements in continuous space give some reason to question Piaget's claim that the notion of extent arises from the coordination of sensorimotor schemes, notably vision and grasping (Piaget, 1952, 1954). Infants of 5 months typically are just beginning to achieve effective grasp abilities. It might be argued, in defense of the sensorimotor coordination hypothesis, either that coordination of early grasp attempts is sufficient to support the abilities shown here, or that coordination of vision or grasping with other sensory systems is sufficient. This may be. However, it should also be noted that doubts about the role of sensorimotor coordination in the formation of a notion of extent are not based only on empirical data. While coordination among sensory systems is required of any organism (and has been extensively studied for adults in studies of adaptation to prisms), coordination is not a process that can logically be considered as plausibly *leading to* a notion of extent. If a notion of extent were not present in at least one of the sensory systems being coordinated, coordination would simply give rise to unordered one-to-one mappings of states across systems.

Suppose, for instance, that perception of body position were the leading sensory system in a process of sensorimotor coordination. Unless infants' kinaesthetic experiences were ordered along some continuum, mappings of motoric experiences to other sensory experiences would be nothing more than unordered paired associates. Establishing an ordering for kinaesthetic experiences presumes the availability of some idea of extent. Such an idea could be based on temporal order (e.g., I do this, and then this, and then this) or on muscle sensation (e.g., a little bit of extension, a little more, a little more than that). Whatever the specific ordering principle, some such principle must exist, in at least one sensory system, for a general notion of extent to emerge at all.

There has recently been considerable discussion of the representational status of the capacities attributed to infants on the basis of looking time experiments. It has been common to claim that infants have certain kinds of world knowledge if they react with longer looking times to "impossible" physical situations, but there are also perceptual interpretations of the data (e.g., Bogartz, Shinskey, & Speaker, 1997; Haith & Benson, 1998). We have been careful in this paper to talk about infant coding of location, not infant representation. The data certainly do not compel the interpretation that infants experience states such as expectations, beliefs, surprise, or puzzlement, or that they could use their codings to think about the world (all of which are often taken to be implied by use of the word "representation"). In addition, there are several other limitations to the current data set, discussed below. The term "coding" is intended as a more neutral term than "representation," simply indicating the registration of a certain kind of information at some time somewhere in the nervous system.

We consider the looking-time data noteworthy, nonetheless. Minimally, the data indicate what infants of this age are capable of registering as input regarding spatial locations in the world. Further research will be needed to determine if perceptual processes alone are sufficient to account for effects of the kind in this paper, as claimed by Bogartz et al. (1997). Such perceptual processes might be visual ones, or they might, instead or in addition, be kinaesthetic body-centered codings based on the orientation of the head, neck, or body while looking at an object. If such perceptual hypotheses are correct, how the registration of such information ultimately results in the development of representational abilities will be a fascinating research challenge.

Individuating Objects

Experiments 4 and 5 in this article suggest the possibility that infants' competence in coding location is juxtaposed with what, from an adult point of view, is an odd limitation. While infants certainly are able to perceive the color and shape of objects in the world, and the sounds those objects make, they may not use color, shape, or sound information to individuate objects (see also Xu and Carey, 1996). Rather, at first, infants may act as if individuated objects can be defined simply as bounded entities that exist along a traceable spatiotemporal track, with color, shape, or sound changes being irrelevant. (This concentration on spatiotemporal properties as defining objects is, perhaps ironically, a profoundly Piagetian notion.) Further work is needed to delineate the boundary conditions of such a generalization and to determine if infants' early object individuation is qualitatively different from that developing later, or whether early object individuation is simply more vulnerable to processing constraints than it will be later.

Unsettled Questions

There are several aspects of the ability shown in these studies that remain unclear and that will need to be examined in future work. First, the useful life of infant location coding is not known. The hiding interval was only 10 seconds, longer than is often used in A-not-B tasks, but still not very long. The length of the delay between hiding of an object and infant search is known to markedly affect infant behavior in the A-not-B situation. Furthermore, 10 seconds is within the span during which information may be maintained by firing of parietal neurons (Gnadt & Andersen, 1988; cf. Haith & Benson, 1998 for discussion of this general issue). The duration of infant spatial coding deserves further study, especially as it bears on whether the spatial information acquired by infants can be considered to have any important representational status.

Second, the experiments did not determine whether the referent used to code location was the frame of the box or the self (or both). The fact that one of the positions in these experiments was always directly in front of the infants suggests the potential use of self-reference, and an egocentric-to-allocentric shift in infant spatial development has been the focus of much previous research (see Acredolo, 1990 and Millar, 1994 for somewhat different summaries of this literature). Experiments in which the box and/or the infant seat were moved laterally would be required to examine this issue.

Third, coding the distance of a target object from distal landmarks is fundamental to what has been called place learning. Recent evidence indicates that place learning in an object search task is not evidenced by children until about the age of 21 months (Mangan, Franklin, Tignor, Bolling, & Nadel, 1994; Newcombe et al., 1998). Exactly why infants can code location in continuous space in the situations studied in this paper, and yet not show place learning in searching for objects, will require further study. There are many possibilities, not mutually exclusive. One possibility concerns the fact that distance could be coded in the present studies with reference to the sandbox, i.e., an enclosing space with a specified geometric shape. Studies conducted with animals (see Gallistel, 1990) and with children (Hermer & Spelke, 1994, 1996) suggest that coding with respect to geometric shape may be a privileged kind of spatial coding, distinct from coding inter-object distance in an "open field." A second possibility is that infant coding is initially only in terms of distance and angle from the self, rather than in terms of object-to-object codings. The fact that Bushnell et al. (1995) found that 12-month-olds searching for a hidden object in a circular enclosure were more successful when there were no landmarks than when landmarks distant from the object were available is consistent with this argument. A third possibility is that searching for objects requires spatial codings with a longer duration than infant codings have, or "stronger" representations (cf. Munakata, McClelland, Johnson, & Siegler, 1997).

Implications for Origins of Hierarchical Coding

Prior work with toddlers has shown that, by 16 months, children not only have fine-grained coding of extent but also code location categorically and show hierarchical combination of these two sources of information, as described by Huttenlocher, Hedges, and Duncan (1991) in their model of spatial coding. Children as young as 16 months show fine-grained coding in their high degrees of accuracy in searching for an object hidden in a five-foot-long sandbox. They also show evidence of categorical coding of the location (i.e., as "in a sandbox") and of combination of this information with fine-grained coding, in that there are biases in their error patterns towards the center of the box. This pattern indicates the use of a prototypic location in a category (i.e., the center of the box) in adjusting fine-grained estimates of location (Huttenlocher et al., 1994). Fine-grained estimates are corrected by categorical estimates, to an extent proportional to uncertainty about the former, resulting both in bias and in an overall increase in accuracy (Huttenlocher et al., 1991). While there is further development in hierarchical coding after the age of 2 years (Sandberg, Huttenlocher, & Newcombe, 1996), the basic elements of hierarchical coding seem to be present by 16 months.

This conclusion invites the question of how early hierarchical coding arises in development. This paper shows that fine-grained coding may exist by 5 months. There is also evidence that infants can code at least certain categorical spatial relations early in development. Quinn (1994) showed that 3-month-olds treat a distribution of points in space as constituting a region, as long as the points were all graphically the same (e.g., dots), although they do not form categorical groupings when the objects shown in habituation differ from each other (Quinn, Cummins, Kase, Martin, & Weissman, 1996). By 6 months, infants succeed even in the latter case (Quinn et al., 1996). Thus, categorical coding of the sort likely required to support hierarchical combination is evident somewhere between 3 and 6 months and fine-grained coding is present by 5 months. It will be interesting to determine if hierarchical combination is evident as soon as the components are available, or if it takes some further time to develop.

SUMMARY

The experiments in this paper suggest that, by 5 months, infants are able to code location in continuous space, at least in certain situations. Indeed, the ability to track spatiotemporal characteristics of objects may represent infants' primary means of defining objects, with other aspects of objects, such as size, shape, and color, treated as less important or even, possibly, irrelevant. There is a need to further explore many aspects of infant location coding ability, including its duration, the extent of its dependence on a constant infant position, and its possible dependence on an available geometric shape with respect to which to code location. In addition, one would like to know more about both the earlier ontogeny of location coding, before 5 months, and its later course, between 5 and 16 months. In particular, it will be important to ascertain when coding of extent is incorporated into a system of hierarchical coding in which fine-grained coding, when uncertain, is corrected by categorical information. These experiments begin the exploration of the starting states for spatial development by delineating certain early-appearing abilities hitherto not known to exist.

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NOTES

1. In this paper, we follow the convention of referring to infants between their 5- and 6-month birthdays as "5-month-olds," even though their average age hovers around 5.5 months.
2. We coded times correct to the nearest second, and thus, the percentages agreement within a second actually represent exact agreement between coders.
3. From a different perspective, though, namely, the issue of object individuation raised by the Xu and Carey (1996) findings, the question is crucial. If infants code the spatial location of a particular individuated buried object, not just the most recent appearance of the hand, then they should react with longer looking if a perceptibly different object appears at that hiding location. Experiment 4 began the exploration of this question.
4. One might wonder why the preference was not for the novel object. However, preferences for the familiar are often seen in infants who have been familiarized rather than habituated (Hunter, Ross, & Ames, 1982). Note that preferences either for familiarity or novelty of objects do not affect results in the main experiment, because the two objects are shown equally often during familiarization.
5. One might argue that the validity check in this experiment is "unfair" because infants in the validity check *did* see the two objects side by side. We agree, to an extent. The problem is that other possible validity checks are equally unfair. For example, habituation to one object followed by dishabituation to the other would involve showing infants one object repeatedly, something that did not happen in the experiment itself. The important issue of the role of discriminability will need further experimentation, involving parametric variation of stimulus attributes.

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