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Modularity and development: the case of spatial reorientation

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Abstract

In a series of experiments, young children who were disoriented in a novel environment reoriented themselves in accord with the large-scale shape of the environment but not in accord with nongeometric properties of the environment such as the color of a wall, the patterning on a box, or the categorical identity of an object. Because children's failure to reorient by nongeometric information cannot be attributed to limits on their ability to detect, remember, or use that information for other purposes, this failure suggests that children's reorientation, at least in relatively novel environments, depends on a mechanism that is informationally encapsulated and task-specific: two hallmarks of modular cognitive processes. Parallel studies with rats suggest that children share this mechanism with at least some adult nonhuman mammals. In contrast, our own studies of human adults, who readily solved our tasks by conjoining nongeometric and geometric information, indicated that the most striking limitations of this mechanism are overcome during human development. These findings support broader proposals concerning the domain specificity of humans' core cognitive abilities, the conservation of cognitive abilities across related species and over the course of human development, and the developmental processes by which core abilities are extended to permit more flexible, uniquely human kinds of problem solving.

What aspects of human cognition depend on mechanisms that emerged long before the human species and are shared by many other mammals, and what aspects are unique to us? Do the distinctive aspects of human thought and knowledge – our apparent flexibility, openness to instruction, and immersion in a complex culture – depend on mechanisms found only in humans, or do they build on mechanisms found in other species?

Where human capacities can be linked to the capacities of other animals, rapid advances in the field of cognitive neuroscience provide unique opportunities for cognitive psychologists. Data from a wealth of psychological and biological

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techniques can be marshalled to shed light on the expression of the capacities in all the organisms who possess them. As these common capacities are better understood, moreover, comparative studies of humans and other species can probe the places where the homology between humans and other animals breaks down, revealing distinctively human modes of thought. Here we report evidence that a basic process for determining one's position in space is common to young children and some nonhuman adult mammals, and that it serves as a building block for human adults' more flexible spatial performance.

While navigating through a known environment, most animals continuously keep track of their position and heading within the environment by means of a variety of orchestrated processes (see, for example, Gallistel, 1990; O'Keefe and Nadel, 1978). If these processes are disrupted and a rat becomes disoriented, it typically re-establishes its position and heading before continuing with goal-directed behavior (Cheng, 1986; Margules and Gallistel, 1988; McNaughton et al., 1995). While complete loss of orientation is difficult to effect in the laboratory (Matthews et al., 1988; Mittelstaedt and Mittelstaedt, 1980), orientation is likely lost to varying degrees during much of behavior (see above references).

When their sense of orientation is intact, mature rats use nongeometric cues such as distinctive odors and surface colors for navigation (e.g., Collett, 1987; McNaughton et al., 1995; Suzuki et al., 1980; Williams et al., 1990). When rats are inertially disoriented, however, considerable evidence suggests that they do not use nongeometric cues to reorient themselves (Biegler and Morris, 1993; Cheng, 1986; Margules and Gallistel, 1988) unless they are extensively trained to do so (Knierim et al., 1995). Because some of these findings provide our point of departure, we describe them in more detail.

Cheng (1986) (also Cheng and Gallistel, 1984) developed a paradigm in which rats searched for food within a closed rectangular environment. The food's location was partly specified by the shape of the environment and fully specified by the brightness of its walls and the patterns and odors at its corners (Fig. 1). After rats were familiarized with the location of a single hidden food source, they were removed from the cage, carried around in a closed box, and returned to the cage to search for the food.

Cheng and Gallistel used the position at which rats searched for the food to assess the information by which rats reoriented themselves, on the following

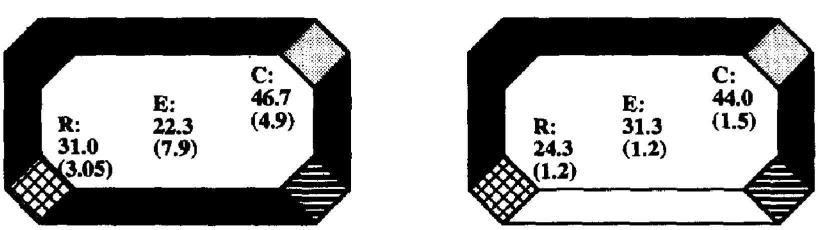

Fig. 1. Testing environments and results for two experiments on reorientation and food search in rats. Search results are collapsed across search locations and across the three subjects in each experiment, with standard errors in parentheses. Nongeometric patterns on corner panels represent both the unique visual pattern and the unique scent on each panel. Redrawn from Cheng (1986).

assumptions (see also Gallistel, 1990; McNaughton et al., 1995). First, when the rat first explores an environment, it combines an allocentric representation of its own position with egocentric representations of food, the surface layout, and other significant locations so as to form a cognitive map of the environment. Second, when the rat is reintroduced into this environment, it searches for food by combining knowledge of the allocentric positions of the food (stored in memory) and of itself (as determined by dead reckoning or from present environmental landmarks) to compute the food's egocentric position. If the rat is disoriented, it must re-establish its own allocentric position before it can find any food source. The disoriented rat's search patterns therefore reflect in part its ability to reorient itself.

Fig. 1 presents the findings from two replications of this experiment, expressed as the percentage of search at each of the two geometrically appropriate locations in the room – the correct location (C) and the rotationally equivalent location (R) – as well as the percentage of search at all other locations, denoted as elsewhere (E). Rats showed high rates of search both at the correct location and at the rotationally equivalent, opposite location, despite the many salient cues – including strong and distinctive odors and large differences in contrast and luminosity – that distinguished these two locations. These findings suggest that rats reoriented by using environmental shape, ignoring the room's varied and salient nongeometric properties.

Although rats in Cheng's experiments did not visit the correct food location significantly more often than the rotationally equivalent opposite location, trends in the data suggest greater search at the correct location. Although these trends might reflect a weak ability to reorient in accord with nongeometric features of the room, they might instead result from a residual sense of orientation from dead reckoning if the disorientation procedure was only partly effective. To distinguish these possibilities, Margules and Gallistel (1988) used a more rigorous disorientation procedure and again tested rats' reorientation in a rectangular environment with distinctive nongeometric cues. When the top of the test box was open, the visible layout beyond the box provided both geometric and nongeometric information that uniquely specified food location, and rats usually located the hidden food directly. When the top of the box was closed and only the shape of the box and nongeometric information within it was available, rats failed to use the nongeometric information and searched the two geometrically appropriate locations with equal frequency.

Biegler and Morris (1993) found results that parallel those of Gallistel and colleagues using a similar procedure. In one experiment, disoriented rats were familiarized with the location of food on the floor of a square arena with three black and one white curtained walls. Despite the constant location of the white curtain, rats failed to locate the food. They evidently could not reorient using this polarizing cue. Another experiment was conducted similarly except that the food was always located in the same position relative to two geometrically and nongeometrically distinctive landmarks on the arena floor, which never moved. Disoriented rats successfully located the food under these circumstances. In a third experiment, the food was always in the same position relative to a landmark, but the positions of each landmark–food pair changed both relative to each other and relative to the larger cage. Disoriented now rats confined their search to locations near the landmarks but did not search the correct location more often than other proximal locations. The experiments suggest a double dissociation between mechanisms for movable object search, for which the rat uses nongeometric landmarks but cannot encode spatial relationships other than proximity, and mechanisms for reorientation in a stable environment, for which the rat encodes both distance and direction but cannot use nongeometric information.

In these behavioral studies, fully disoriented rats made no use of nongeometric information to re-establish their orientation[1]. Rats failed to reorient by nongeometric information even when the shape of the environment did not completely specify their position and heading, and when detectable nongeometric information would have allowed fully successful reorientation. Because rats readily learned to use nongeometric information for solving other tasks that do not involve spatial disorientation (e.g., Suzuki et al., 1980; McNaughton et al., 1995), these findings suggest that the rat's reorientation depends on an encapsulated, task-specific mechanism: a "geometric module" (Cheng, 1986; see Fodor, 1983).

Reliance on geometric information for reorientation is likely to be adaptive in natural settings, where the macroscopic shape of the environment seldom changes but where snowfall and melting, new scent markings on top of old scent trails, displacements of movable objects, and other events frequently change the environment's nongeometric properties. Indeed, a variety of studies with mammals suggest that geometry provides the primary information for reorientation processes (e.g., Tinkelpaugh, 1932). Nevertheless, one set of studies using a variant of Cheng and Gallistel's method with an avian species suggests that the tendency to rely exclusively on environmental geometry may not extend to all vertebrates:

[1] Further studies have focused on the responses of individual hippocampal, subicular, and thalamic neurons that are active when an animal moves through a particular location ("place cells") or faces a given allocentric direction ("head direction cells") (e.g., O'Keefe and Nadel, 1978; O'Keefe and Speakman, 1987; Taube et al., 1990; see McNaughton et al., 1995 for review). When oriented rats are placed in a cylindrical or square environment containing only one distinctive nongeometric feature, the activity of these neurons depends on the location of that feature. Once rats have become familiar with the environment, moreover, the activity of these neurons continues to depend on the nongeometric feature even after disorientation (Knierim et al., 1995): a phenomenon not yet explored in behavioral research. In contrast, the activity of place and head direction cells bears no relation to the location of nongeometric features of the layout in many rats who are disoriented before each encounter with the features, even if the features appear in constant positions (Knierim et al., 1995; McNaughton et al., 1995). Behavioral and electrophysiological studies here converge to suggest that fully disoriented rats, not having had adequate means to learn the position of these nongeometric cues in a larger framework, do not use nongeometric information to reorient themselves.

One interpretation of the data of Knierim et al. (1995) is that animals reorient by using nongeometric information, but only after they have gained extensive experience with the stability of those cues in the environment (Biegler and Morris, 1993; McNaughton et al., 1995). If this view is correct, then the relevant distinction between reorientation with geometric cues and reorienting with nongeometric cues is that the former is effective after only brief exposure to the stability of those cues within a larger framework, whereas the latter depends on extensive associative learning.

Domesticated chicks use both geometric and nongeometric information to search for food when they are disoriented (Vallortigara et al., 1990).

Given rats' performance, what capacities for spatial reorientation might one expect to find in humans? On one hand, a geometric process for reorientation would seem to be as useful for our human ancestors as for other mammals, considering the distinctiveness and reliability of large-scale geometric information in the natural environment. On the other hand, one might expect humans to reorient more flexibly than rats, given the additional systems by which humans appear to represent space (e.g., Clark, 1973; Hirtle and Jonides, 1985; Levinson, in press; McNamara et al., 1989; Talmy, 1983). Our research tests these possibilities.

EXPERIMENT 1

Our first study investigated the reorientation abilities of adults in two environments similar to those used by Gallistel and colleagues. Adults entered an experimental chamber and witnessed the hiding of an object in one corner of the chamber and then turned slowly many times without vision so as to lose their orientation. In one condition, the chamber was rectangular and contained no distinctive landmarks to break its symmetry. In the second condition, the same chamber contained one bright blue wall. Subjects' abilities to reorient in accord with both the shape and the nongeometric properties of the room was assessed by their search for the hidden object.

1. Method

1.1. Subjects

Participants were eight male and eight female university students ranging in age from 17 to 26 years (mean, 18.8 years). Students were recruited through announcements in department courses and were given extra credit for their participation. Three subjects were omitted from the original sample and replaced because they actively sought (according to their own reports) and found (determined by performance and reports) strategies to maintain their orientation during the disorientation procedure.

1.2. Apparatus

Subjects were tested in a $6.25 \times 4.0 \times 6.25$ ft rectangular chamber, housed within a larger experiment room with no windows or obvious sources of noise. The chamber was entirely composed of white felt fabric stretched onto a concealed wooden frame and a padded floor (Fig. 2). Curtained openings at the center of each of the four walls permitted entry into the room without breaking its symmetry; when not in use, these openings were sealed with velcro. Four indistinguishable 9×48 in. red panels, composed of felt on a concealed wooden

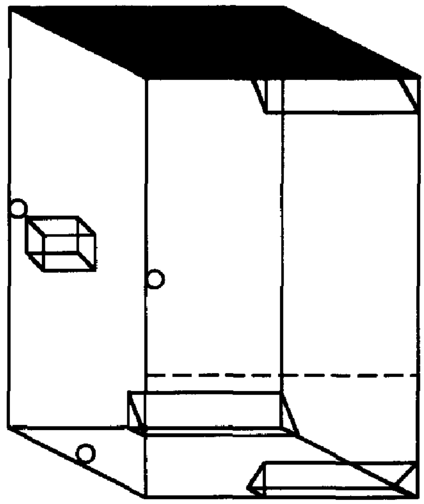

Fig. 2. The chamber for all the present experiments. The box depicts the video camera, small circles depict the lights, and the dotted line depicts the fabric door by which subjects entered the room.

frame with a loose fabric curtain at the bottom, stood in the room's four corners. In the nongeometric landmark condition, a bright blue 4 × 6.25 ft piece of fabric was attached to one of the two shorter walls of the chamber by velcro, such that it covered the wall completely. The room was illuminated from above by four 25 W lights, one in the top center of each wall. A video camera, suspended from the center of the room's ceiling, provided an overhead view of the experiment. A white noise generator was suspended above the center of room, preventing subjects from maintaining their orientation through use of any sound beacon. A ring of keys served as the object for which subjects searched.

1.3. Design

Each subject completed three to four codable trials in the all-white room and three to four codable trials in the room with the blue wall[2]. For a given subject, the object was hidden in a single location throughout the experiment[3]. Across subjects, the order of tasks (all-white room first vs. room with blue wall first), the location of the blue wall (the two short walls provided two possible locations), and the location of the hidden object (four possible corner locations) were orthogonally counterbalanced. Subject sex was distributed evenly across these factors. The facing position of the subject at the end of disorientation varied from trial to trial and was randomly determined with the restriction that approximately equal numbers of trials ended with subjects facing each wall.

[2] In some cases, subjects were run in only three trials per condition because of time limitations, and in other cases four trials were run but one was uncodable by a blind observer because of occlusion on the video record.

[3] Because preliminary experiments revealed that changes in the object's hiding location across trials produced extensive proactive interference for young children, hiding location was held constant over a session for all experiments, unless otherwise noted.

1.4. Procedure

Before the experiment, the experimenter told subjects that they would see an object being hidden, undergo a disorientation procedure, and be asked to find the object. They were instructed to allow themselves to become disoriented rather than to attempt to maintain their orientation. A subject entered the chamber with the experimenter, who asked the subject to "look around at the room" and then hid the object behind one corner panel. The subject was then instructed to begin rotating slowly with eyes closed. The subject was made to turn at least 10 full rotations, changing direction on cue from the experimenter, who was walking around the subject at varying speeds so as not to serve as a landmark herself. The subject was asked to stop by the experimenter, who continued walking around slowly so as not to cue the subject to any possible location. When the subject was facing in the predetermined direction, he was instructed to open his eyes and to search for the object.

A subject searched as many corners as necessary until the object was retrieved. Then the experimenter took the object and hid it again in the same corner to begin the next trial. After completing the trials in the first condition, the subject was escorted from the room, and the blue cloth was attached to or removed from a wall. Then the subject and experimenter re-entered the room, the subject was asked to inspect the room again, and the second set of search trials began.

1.5. Coding and analyses

All searches for the object were coded from the video record by two assistants unaware of the purpose of the experiments or the findings with rats and blind to the position of the object at least on the first trial. Coders considered a subject to have searched for the object whenever he was judged first to touch a corner panel after disorientation, regardless of whether the object was retrieved at that corner. To make this judgment, one experimenter cued the videotape to the point immediately after the hiding of the object, and the other experimenter judged the direction in which the subject faced at the end of disorientation and the location of each of the subject's searches for the object. This procedure ensured that the coder of subject search was blind to the hidden object's location on the first search trial.

The principal analyses focused on the location of the subject's first search on each search trial. Search location was coded along two dimensions (see Fig. 3a): It was coded as "geometrically appropriate" if the subject searched either at the correct corner (C) or at its rotational equivalent (R) and as "geometrically inappropriate" otherwise (corners N and F), and it was coded as "proximal" if the subject searched either at C or at the corner nearest to C (N) and as "distant" otherwise (R and F). (In the condition with the blue wall, corners C and N both corresponded in color to the correct corner – either both were entirely white or both were half white and half blue — and so the proximal/distant distinction corresponded to a distinction between search at nongeometrically appropriate vs. inappropriate corners.) For each subject's first search trial, search at geometrically

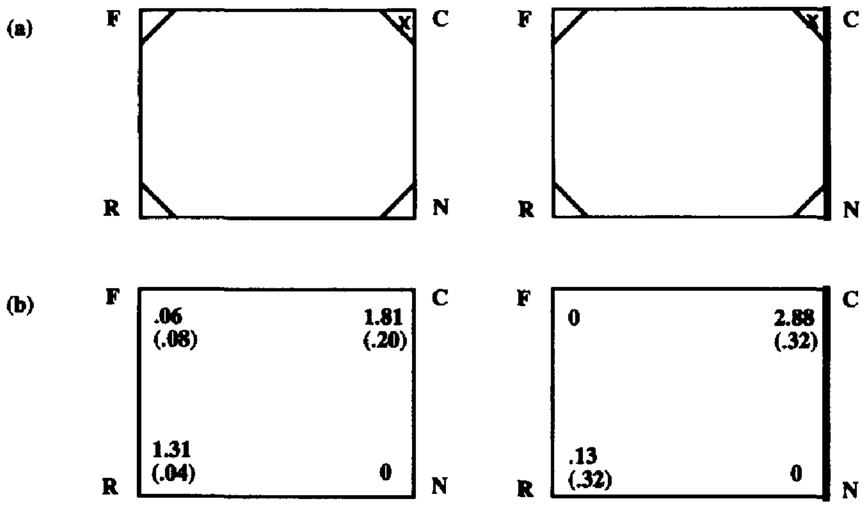

Fig. 3. Overhead view of testing environments (a) and search patterns (b) for adults in Experiment 1. The search patterns are summed over all trials and collapsed across hiding locations in the all-white condition (left) and the condition with the blue wall (right). Standard errors are in parentheses.

appropriate versus inappropriate corners and at proximal versus distant corners was analyzed with binomial tests. Because data from subsequent trials did not meet the independence criterion for these tests, they were subjected to analyses of variance (ANOVAs). In addition, paired two-tailed t-tests compared search rates at specific corners to one another to determine whether search at the correct corner exceeded search at its geometric or proximate twin (C vs. R and C vs. N, respectively), and to determine whether correct search in the room with the blue wall exceeded correct search in the all-white room.

2. Results

Table 1 presents the search rates at the four corners on the first trial of each subject's first condition, before subjects' performance could be modified by feedback. In the all-white room, subjects searched geometrically appropriate locations more often than geometrically inappropriate locations (binomial $p < .001$), but did not search proximate locations more often than distant locations

Table 1
Number of subjects searching at each corner on each trial of Experiment 1 ($N = 16$)

Condition:	All white				Blue wall			
Corner:	C	N	R	F	C	N	R	F
a. Trial 1, session 1	3	0	5	0	7	0	1	0
b. Both sessions								
Trial 1	8	0	7	1	14	0	2	0
Trial 2	8	0	8	0	16	0	0	0
Trial 3	10	0	6	0	16	0	0	0

($p = .59$). In the room with one blue wall, subjects again confined their search to geometrically appropriate locations ($p < .001$) but tended to search locations on the correct side of the chamber as well ($p < .001$). Adults therefore used both geometry and the blue wall to guide their search.

Further analyses tested whether these patterns held throughout each condition. Fig. 3(b) depicts the mean search frequency (and standard error) at each corner across all trials in each session. Preliminary analyses revealed no effects of sex, corner of hiding, side of hiding, or order of experimental conditions on search accuracy. We therefore collapsed across these factors in subsequent analyses. A 2 (condition: white vs. blue wall) × 2 (proximity: search at corners C and N vs. search at corners R and F) × 2 (geometry: search at corners C and R vs. search at corners N and F) ANOVA revealed significant effects of geometry ($F(1, 15) = 3002$, $p < .001$) and proximity ($F(1, 15) = 61$, $p < .001$), and significant interactions between condition and proximity ($F(1, 15) = 29$, $p < .001$), geometry and proximity ($F(1, 15) = 61$, $p < .001$) and condition, geometry and proximity ($F(1, 15) = 29$, $p < .001$). Subjects almost always searched geometrically appropriate corners and used the blue wall, when present, to confine search to the appropriate side of the chamber.

A third set of analyses tested whether search performance changed over the course of the experiment (see Table 1b). A 3 (trial) × 2 (proximity) × 2 (geometry) ANOVA was conducted on the data from the first three trials of each condition. In the all-white room, there was only a significant effect of geometry ($F(1, 15) = 529$, $p < .001$), with no effect of trial and no interactions between trial and proximity or geometry. In the room with one blue wall, there was a significant effect of proximity and a significant interaction between proximity and geometry (both $Fs(1, 15) = 259$, $p < .001$), and again no effects involving trial.

Comparisons of search at specific corners revealed that the rates of searching at the correct corner and at the geometrically equivalent opposite corner did not differ from each other in the white room ($t(15) = 1.33$, $p = .20$). In the room with the blue wall, in contrast, the search rate at the correct corner exceeded search at the geometrically appropriate opposite corner ($t(15) = 16.10$, $p < .001$). Search at the correct corner in the room with the blue wall also exceeded search at the correct corner of the white room ($t(15) = 4.58$, $p < .001$). Search at the geometrically incorrect corners never occurred and could not be analyzed (each $SD = 0$).

Finally, we probed for any influence of subject final facing position on search patterns. Because subjects always faced one of the four walls in the experiment room at the end of disorientation, two corners were visible from any given final facing position. Counterbalancing of hiding location and facing position assured that on approximately half the trials, the correct corner was in view, and the rotationally equivalent opposite corner was out of view, at the time that the subject first began to search for the object. Because the nearly perfect performance in the blue-wall condition ensured that searches were not biased toward the immediately visible corners in that condition, this analysis was performed only on the search data in the all-white condition. To determine whether subjects searched immediately visible corners in preference to nonvisible ones, we conducted a further analysis of variance on the proportion of searching at each corner with the additional factor of "visibility" (whether the correct corner was in or out of view at the end of disorientation). For the all-white condition, the 2 (visibility) × 2 (proximity) × 2 (geometry) ANOVA revealed only a significant effect of geometry ($F(1, 15) = 218$, $p < .001$), and no effects of facing position.

3. Discussion

Human adults used both geometric and nongeometric information to reorient themselves in this experiment. In the white room, subjects confined their search to the two geometrically appropriate corners, searching these locations equally often. Subjects' failure to search the correct corner more often than the rotationally equivalent opposite corner indicates that the disorientation procedure was effective and that neither visual information within the room nor nonvisual information from outside the room served as cues to reorientation. Subjects' ability to confine search in the white room to corners with appropriate metric and sense properties indicates that human adults, like rats, can reorient themselves in accord with the shape of the environment. Their first-trial and trial-by-trial performance indicates that they did not learn this strategy over the course of the experiment but relied on geometry throughout the session.

In the room with the blue wall, subjects confined their search to the correct corner with high consistency. Because only the presence of the blue wall distinguished this environment from the entirely white room, this finding indicates that the subjects were able to take account of a nongeometric property of the environment in finding the object. Subjects may have located the object either by combining use of geometric and blue-wall information (i.e., representing simultaneously that the object was hidden in a corner with appropriate geometry and that it was hidden near the blue wall) or by directly encoding the sense relation of the object to the blue wall (i.e., by representing that the object was hidden to the left of the blue wall). In either case, human adults clearly outperformed the adult rats tested in similar circumstances (Cheng, 1986; Margules and Gallistel, 1988).

It is interesting to ask how aware subjects were of the processes underlying their performance. At the end of the experiment, most subjects ($n = 12$) were asked how they decided where to search for the object in each condition. Regarding the condition with the blue wall, all 12 subjects mentioned the wall color; when pressed to say how they used the blue wall, they tended to describe the hidden object's location in relation to it (e.g., "it was in the corner just to the left of the blue wall"). For the condition in the white room, in contrast, only one subject mentioned the shape of the room spontaneously, and only one additional subject described the geometric configuration of the hiding place after further probing. Many subjects suggested that they had searched randomly at the four corners, contrary to their actual performance. These findings suggest that the process of reorienting in accord with the shape of the environment is not as consciously accessible to subjects as is the process involving nongeometric landmarks, at least under the present conditions.

EXPERIMENT 2

Given the successful performance of the adults in Experiment 1, we turned next to young children. In Experiment 2, children between 18 and 24 months of age were presented with a variant of the task given to adults, and their abilities to reorient using geometric and nongeometric information were assessed from their patterns of search for a valued object.

4. Method

The method was the same as in Experiment 1 except as follows.

4.1. Subjects

Participants were eight boys and eight girls ranging in age from 18.1 to 24.1 months (mean age, 20.9 months). Five additional subjects were eliminated for failure to complete at least three trials (three subjects), for experimenter error (one subject), or for parent error (describing the location of the hidden object to the child with respect to the blue wall, see below). Subjects were recruited from birth announcements for earlier studies in an infant laboratory, and they visited the laboratory with a parent.

4.2. Design, procedure, and analyses

The experiment was conducted jointly by an experimenter and by the child's parent. The procedure of the study was explained to the parent in advance, although the parent was not informed of the findings of previous studies with this task or of any experimental hypotheses. After bringing the infant and parent into the experimental chamber, the experimenter tapped on the two short walls until the subject noticed each action, with equal numbers of subjects seeing the white wall or the blue wall tapped first in the blue wall condition. The experimenter then indicated to the parent the corner where the object should be hidden and left the room to observe the experiment on a video monitor outside. The parent introduced a small toy brought from home, hid the toy in that corner, and then lifted the child, covered his or her eyes, and rotated the child at least four full revolutions, taking care to avoid subject dizziness[4]. Finally, the parent placed the child with his eyes still covered on the floor facing in a direction indicated by the experimenter, who

[4] Care was taken to rotate the children slowly, so that no processes other than maintenance of orientation would be impaired by vestibular disorientation. The possibility that this disorientation procedure nevertheless impaired children's performance is tested in Experiment 5.

called from outside the chamber behind the center of a previously chosen wall. On cue from the experimenter, the parent uncovered the child's eyes and encouraged the child to find the object. To guard against parents influencing the children's search, parents were instructed to stand against the center of a different wall on each trial, facing midway between each of the far corners, and to look only at the child and not at any of the corners during the search trial. Parents were asked not to describe any aspect of the room to the child, and to refer to the hidden object's location only as "here" (e.g., "watch me, I'm hiding the toy right here"). After the child found the object, it was taken by the parent and was hidden in the same corner, beginning the next trial. Hiding location was constant across subjects to minimize interference across trials (see footnote 3). Although subjects were encouraged to complete four trials, four subjects in the all-white condition and five subjects in the blue-wall condition contributed only three codable trials per condition because of fussiness, boredom, or temporary occlusion of the subject on the video camera. After the last trial in the first condition, the experimenter led the parent and child from the room for a 2–3 min break while she rearranged the chamber for the second condition.

5. Results

Table 2 presents subjects' search performance on the first trial of each condition, before they had the chance to benefit from feedback by finding the object. An analysis of subjects' first trial in the all-white condition revealed an effect of geometry (binomial $p < .003$) and no effect of proximity ($p > .40$) (see Table 2a). An analysis of subjects' first trial in blue-wall condition revealed an effect of geometry ($p = .011$) and no effect of proximity ($p > .20$, with subjects insignificantly searching distant corners more than proximate corners). This indicates that before children experienced the disorientation procedure or received any feedback about their performance, they relied exclusively on the shape of the room to reorient and find the object.

Fig. 4(b) gives the search frequencies and standard errors at each corner across all trials in each condition. Frequencies of search at each of the four corners were subjected to the same analyses of variance as in Experiment 1. In preliminary

Table 2
Number of subjects searching at each corner on each trial of Experiment 2 ($N = 16$)

Condition:	All white				Blue wall			
Corner:	C	N	R	F	C	N	R	F
a. Trial 1, session 1	5	0	2	1	4	0	3	1
b. Both sessions								
Trial 1	6	2	7	1	6	0	7	3
Trial 2	8	3	4	1	7	1	8	0
Trial 3	5	2	8	1	2	3	10	1

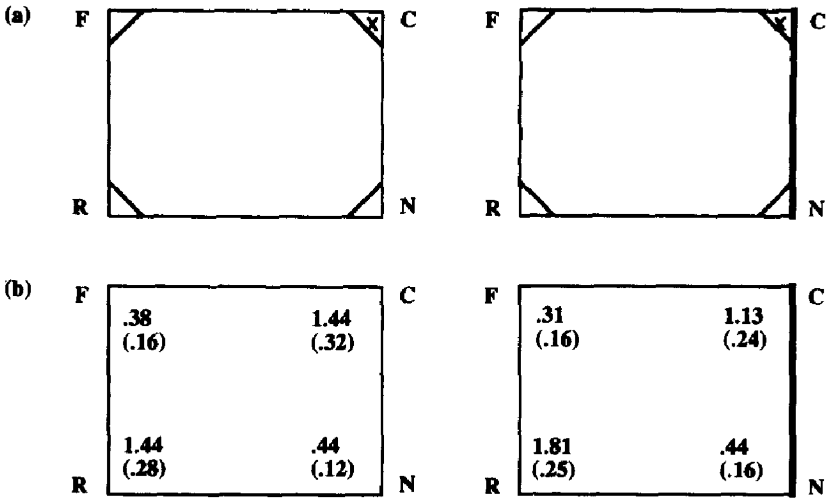

Fig. 4. Testing environments and search patterns for children in Experiment 2.

analyses, no main effects or interactions were found involving the factors side, corner, order, or sex, and so these factors were omitted from subsequent analyses. The 2 (condition) × 2 (proximity) × 2 (geometry) ANOVA revealed a significant effect of geometry ($F(1, 15) = 29$, $p < .001$) and no other effects.

Table 2(b) presents the number of subjects who searched at each corner location on the first, second, and third trials. Because children were rewarded for success on their first guess (i.e., they found the toy) and were corrected for failures (either by finding the toy themselves in a different location or by being shown the toy's location by the experimenter), any difference in performance across these trials would suggest that children are able to benefit from this feedback and to learn to use the nongeometric information. Two 3 (trial) × 2 (proximity) × 2 (geometry) ANOVAs performed on the trial-by-trial performance in each condition revealed no improvement in search accuracy, suggesting that children did not benefit from practice or feedback. In the all-white condition, the only significant effects were of geometry ($F(1, 11) = 14.19$, $p < .005$) and of trial with proximity ($F(1, 11) = 3.14$, $p < .05$), with subjects increasingly less likely to choose either corner near the object as the study progressed. In the blue-wall condition, the only significant effects were a main effect of geometry ($F(1, 11) = 29$, $p < .001$) and an interaction of proximity with geometry ($F(1, 11) = 6.49$, $p = .027$), with subjects more often choosing the diagonally opposite corner than the correct corner. These effects involving proximity were opposite in direction to what would be expected if children had learned to reorient by the blue wall.

Comparisons of search at individual corners revealed no difference in search frequencies at the two geometrically appropriate corners in the all-white room ($|t| < 1$). Children searched the correct corner significantly less than they searched the rotationally equivalent opposite corner ($t = -2.21$, $p < .05$), contrary to the findings with adults. Children searched the correct corners of the white room and of the room with the one blue wall with equal frequency ($|t| < 1$).

As in Experiment 1, we tested for possible effects of subject final facing position on search patterns, for the 15 of 16 subjects whose facing positions were codable (in one case the child's facing positions were occluded on video). The 2 ("visibility:" whether the correct corner was in or out of view at the end of disorientation) × 2 (geometry) × 2 (proximity) ANOVA performed on each condition revealed no effect of the visibility of the correct corner and no interactions between this factor with the other factors. A final analysis with the additional factor of "age" compared the search patterns of young children to those of the adults in Experiment 1. This analysis revealed significant effects of geometry ($F(1, 30) = 171$, $p < .001$) and proximity ($F(1, 30) = 13.1$, $p < .005$), and significant interactions of age with geometry ($F(1, 30) = 5.60$, $p < .05$) and age with proximity ($F(1, 30) = 24$, $p < .001$). The interaction of age and geometry reflects adults' more consistent use of geometric information to guide search; the interaction of age and proximity reflects adults' use of the blue wall. There were also significant interactions between geometry and proximity ($F(1, 30) = 12$, $p < .001$), between age, geometry and proximity ($F(1, 30) = 36$, $p < .001$), between age, condition, geometry and proximity ($F(1, 30) = 11.13$, $p < .005$), and between age, condition and proximity ($F(1, 30) = 11.22$, $p < .005$). The last three interactions reflect the fact that adults reliably outperformed children in using the blue wall and geometry to guide search.

6. Discussion

Like adult rats and human adults, young children reoriented themselves in accord with the shape of the environment. They revealed this ability by searching for a hidden object at the two corners with appropriate metric and sense relations, relative to the two corners with opposite sense relations. Because children did not search the correct corner of the white room more often than the rotationally equivalent opposite corner, the experiment provides evidence that the disorientation procedure was effective and that children were not able to find the object by detecting any subtle perceptual beacon. The 1.5- to 2-year-old children evidently reoriented themselves in accord with the shape of the environment, aligning the currently perceived environment with a representation of its metric and sense properties.

Children's successful reorientation in accord with the shape of the environment is surprising, because it suggests that very young children form a representation of the environment that preserves its metric and sense relations. In this task, the corner of the room in which the object was hidden differed from the geometrically inappropriate corners only with respect to the lateral positioning of two walls of different lengths: If the object was hidden in a corner whose longer wall was on the left, for example, the geometrically inappropriate corners were identical, except that their longer wall was on the right. Moreover, differences in wall length were not extreme (the walls of the rectangle stood in a ratio just barely over 1 : 1.5), and no effort was made to call children's attention to this difference. These findings suggest that young children are strikingly sensitive to room geometry, detecting this information and retaining it over a potentially distracting disorientation procedure.

In contrast, the experiment suggests that young children were not able to reorient themselves by analyzing a nongeometric property of the environment, the color of a wall, even though their attention was drawn to the two walls with distinct colors. Children's failure to search for the object at the corner with appropriate coloring cannot be attributed to lack of motivation or understanding of the task, because children successfully used geometric information to find the object. This failure also cannot be attributed to a lack of attention to the walls of the room, since encoding of wall length was required for children's successful use of geometric information. Finally, the failure cannot be attributed to an inability to encode sense relations in any form (determining, for example, that the toy lies to the *left* of something), or to conjoin sense information with other properties, because only some form of a conjunction of metric and sense relations distinguished the geometrically appropriate and inappropriate corners.

Overall, children's performance resembled that of rats tested by Cheng (1986) and by Margules and Gallistel (1988), who were adept at using the geometric properties of their cages but not the salient nongeometric features. Also like rats, children this age and younger are able to use nongeometric landmarks such as distinctive surface color for other aspects of navigation (e.g., Acredolo, 1978; Bremner, 1978; Keating et al., 1986; McKenzie, 1988), so their failure does not stem from a general inability to encode and use such landmark information. Children's failure to benefit from the blue wall suggests that they are predisposed to use geometric information to reorient themselves.

Because children's search differed from the search of adults, it is unlikely that children's performance in this task was influenced by any subtly biasing behavior by their parents (who tended not to notice their children's successful use of geometry and were often astonished by their errors). Nevertheless, one might argue that wall color is not a very salient nongeometric property for young children. In the next experiment, children were given reorientation tasks in which the identity of distinctive and interesting objects could serve to mark the child's position and heading, and in which children were allowed to interact with those objects prior to the test.

EXPERIMENT 3

Children participated in one search task in the room with the blue wall and one search task in an all-white room furnished with two solid object landmarks of similar shape and size but with different colors, textures and categorical identities: a large toy truck and a large toy bear (Fig. 5a). To attempt to ensure that children noticed all these landmarks, the experimenter pointed to the landmark(s) before the first search session, and the child played with the landmark(s) before the second search session. As in Experiment 2, children's ability to reorient on the basis of geometric and nongeometric information was assessed from their patterns of search for a hidden object.

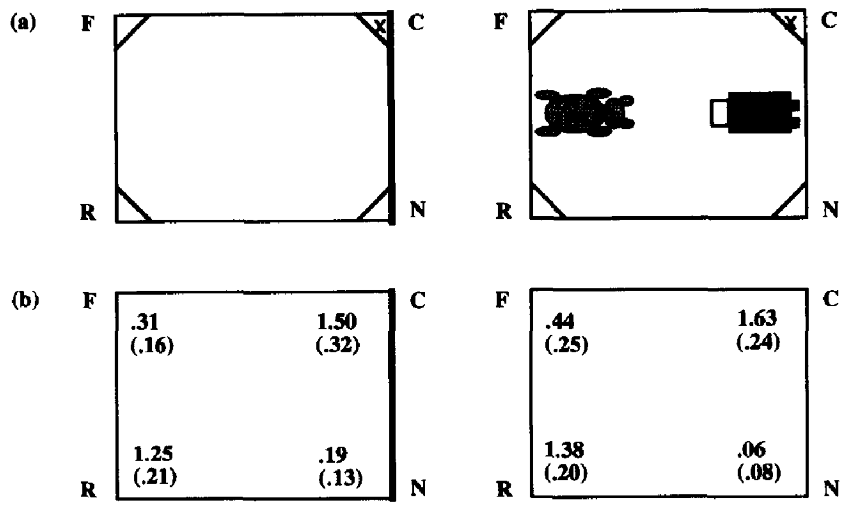

Fig. 5. Testing environments and search patterns for children in Experiment 3.

7. Method

The method is the same as Experiment 2, except as follows.

7.1. Subjects

Participants were a separate group of eight boys and eight girls ranging in age from 18.3 to 23.9 months (mean age, 21.2 months). Two additional subjects were omitted from the sample because of experimenter error.

7.2. Apparatus, design and procedure

Fig. 5(a) depicts the experimental chambers for the two conditions of this study. Children were tested once with the blue wall and once with white walls and with a toy truck and bear placed in symmetrical locations in the chamber. The truck and bear each measured approximately 9 in. long, 5 in. wide, and 6 in. tall, and they were placed in the room such that the front of each object faced the center of the room. Although the global dimensions of these objects were similar, they differed in color, texture, material composition, and specific shape. The order of test sessions and the locations of the truck and bear, like that of the blue wall, were counterbalanced across subjects.

At the start of the first session, the experimenter pointed to the four walls of the display (blue wall condition) or to the truck and bear (objects condition). At the end of the session, the experimenter led the child from the room and presented the landmark(s) to be used in the next session. For subjects to be tested with the blue wall, she played a game of peekaboo with the child, using the blue fabric to hide behind. For subjects to be tested with the objects, the experimenter and child played a game with the objects that involved exposure to some of their distinctive properties (e.g., the dumping mechanism on the dump truck and the softness of the toy bear). Play with the landmarks lasted for 3–5 min. At the end of the play period, the experimenter brought the landmark(s) and the child into the white chamber, positioned them appropriately in the chamber with the child watching, called the child's attention to them again, and began the session. At no time did the experimenter name the landmarks used in the study, referring to them instead with deictic terms (e.g., "this").

The only difference in design between this experiment and its predecessors was that the location at which the toy was hidden was changed between the first test session and the second. For equal numbers of subjects, the toy was hidden during the second session at the corner which, during the first session, had served as corner C, R, N, or F.

8. Results

Table 3 presents the number of subjects who searched at each corner on the first trial of each session. Subjects tended to search geometrically appropriate corners in both the condition with the blue wall (binomial $p = .002$) and the condition with the toys ($p = .011$). In contrast, children did not tend to search proximate corners in either condition (both $ps > .20$). Again, subjects relied only on the geometry of the room at the start of each session.

Fig. 5(b) presents the search rates at each corner for the two landmark conditions of this experiment. Search patterns were analyzed once as a function of the factor landmark type (blue wall or toys) and again as a function of the factor attention-drawing procedure (pointing/ pointing and playing). Preliminary ANOVAs that included the factors sex, order, corner and side as well as landmark type, proximity and geometry revealed a significant interaction between side, landmark type, proximity and geometry and no other significant effects. The factor side therefore was included in further analyses. An overall 2 (side) × 2 (landmark type) × 2 (proximity) × 2 (geometry) ANOVA showed a significant effect of geometry ($F(1, 14) = 45$, $p < .001$) and a significant interaction among side, landmark type, proximity and geometry ($F(1, 14) = 10.03$, $p < .01$). The former effect reflects subjects' strong reliance on geometric information to guide search,

Table 3
Number of subjects at each corner on each trial of Experiment 3 ($N = 16$)[a]

Condition:	Blue wall				Solid objects			
Corner:	C	N	R	F	C	N	R	F
a. Trial 1, session 1	7	0	1	0	3	1	3	1
b. Both sessions								
Trial 1	10	0	4	2	6	1	7	2
Trial 2	6	1	9	0	8	0	7	1
Trial 3	7	2	6	0	10	0	3	2

[a] $N = 15$ for trial 3 in both conditions.

and the latter effect reflects their success at locating the hidden object in the blue-wall condition with the blue wall on the right side of the chamber, even when the object was hidden in corners opposite the blue wall. There was no such effect in our first reorientation study. In the ANOVAs by attention-drawing procedure, there were no effects of sex, order, corner, or side in the preliminary analysis and only an effect of geometry ($F(1, 14) = 44$, $p < .001$) in the main analysis.

Table 3(b) presents the number of subjects who searched each corner on each of the first three trials of each session. The analysis of data across trials, performed separately on each landmark-type condition, revealed only effects of geometry (for the blue-wall condition, $F(1, 12) = 27$, $p < .001$, and for the solid-object condition, $F(1, 12) = 24$, $p < .001$).

Collapsing across the two attention-drawing conditions, subjects tested with the blue wall did not search more often at the corner with correct coloring than at the rotationally equivalent opposite corner ($t(15) < 1.5$). Likewise, subjects tested with toys as landmarks did not search more often at the corner near the correct object than at the rotationally equivalent corner near the other object ($t(15) < 1$). Search rates at the correct corner did not differ across the two landmark conditions ($|t(15)| < 1$)), or across the two attention-drawing procedures ($|t(15)| < 1$).

Possible effects of subject final facing position on search patterns (which could be coded for 15 of 16 subjects) were analyzed as before with an additional factor of landmark type corresponding to the nongeometric information used in each condition (blue wall vs. toys). The 2 (landmark-type) × 2 (in or out of view) × 2 (proximity) × 2 (geometry) ANOVA revealed no effect of whether the correct corner was in or out of view and no interaction between this and any other factor.

9. Discussion

The present findings closely resembled those of Experiment 2: Children reoriented themselves in accord with the shape of their surroundings, searching for the object at geometrically appropriate corners more than at inappropriate corners, and they failed to reorient in accord with nongeometric properties of the environment. Neither the color of a wall nor the identities and properties of two movable objects served as effective landmarks for the children, even though both sets of landmarks were pointed out before the disorientation procedure began and children played with one set of landmarks immediately before the test.

The finding that children's search was unaffected by nongeometric landmarks suggests that they reoriented themselves through a purely geometric process, but other potential explanations remain. First, it is possible that children did not notice the configuration of the landmarks at the critical time when the object was hidden, despite our efforts to call attention to all the landmarks. Because the toy always occupied a different spatial position from any landmark (e.g., it moved from the mother's hand to the left of the blue wall or truck but never coincided with the blue wall or truck), it is possible that the event of hiding the toy drew the child's attention away from the landmark. Note that an attentional limitation cannot explain the difference between the effectiveness of geometric versus nongeometric information, because both sources of information were located at a distance from the path of the object. Nevertheless, it is possible that children will use nongeometric landmarks to reorient themselves if a toy moves on a path that calls attention to the landmark. We tested this possibility in the next experiment by hiding the toy directly behind a distinctively colored, patterned and textured panel.

A second potential reason for children's failure to search in accord with nongeometric information appeals to the memory requirements of the search task. Perhaps the position of an object in relation to the shape of the environment is more memorable for children than is the position of an object in relation to the environment's nongeometric landmarks. If a general memory limitation, rather than a task-specific geometric process for reorientation, accounts for children's failure to use nongeometric landmarks in these studies, then the landmarks also should fail to guide children's search in a memory task involving no disorientation. Accordingly, we compared the performance of children who searched for an object after disorientation to the performance of oriented children who searched for the same object in the same environment after displacement of the object.

EXPERIMENT 4

Children searched for an object that was hidden directly inside one of two triangular boxes that were identical in shape but which differed in color, texture and pattern. In one condition, the children were disoriented between hiding and test, and the boxes remained in stable positions ("reorientation task"). In the other condition, the children's eyes were covered between hiding and test but they were not disoriented, and the boxes were moved ("find-the-object task"). At the time the children's eyes were uncovered, children in both conditions viewed identical rooms and faced the identical task of finding the toy (see Fig. 6a,c). If the children in Experiments 1 and 2 had failed to find the object because they attended only to the path of the toy, then children in both conditions of Experiment 4 should retrieve the toy successfully. If children had a general difficulty attending to or remembering the nongeometric properties of one object while searching for another object, then the children in both conditions should fail to find the object. Finally, if children are unable to use nongeometric information to reorient themselves because reorientation depends on a task-specific system that is sensitive only to environmental shape, then children might fail to find the object in the reorientation task but succeed in the find-the-object task.

10. Method

10.1. Subjects

Thirty-two children participated in the experiment. The eight girls and eight boys in the disorientation condition ranged in age from 18.2 to 23.9 months (mean

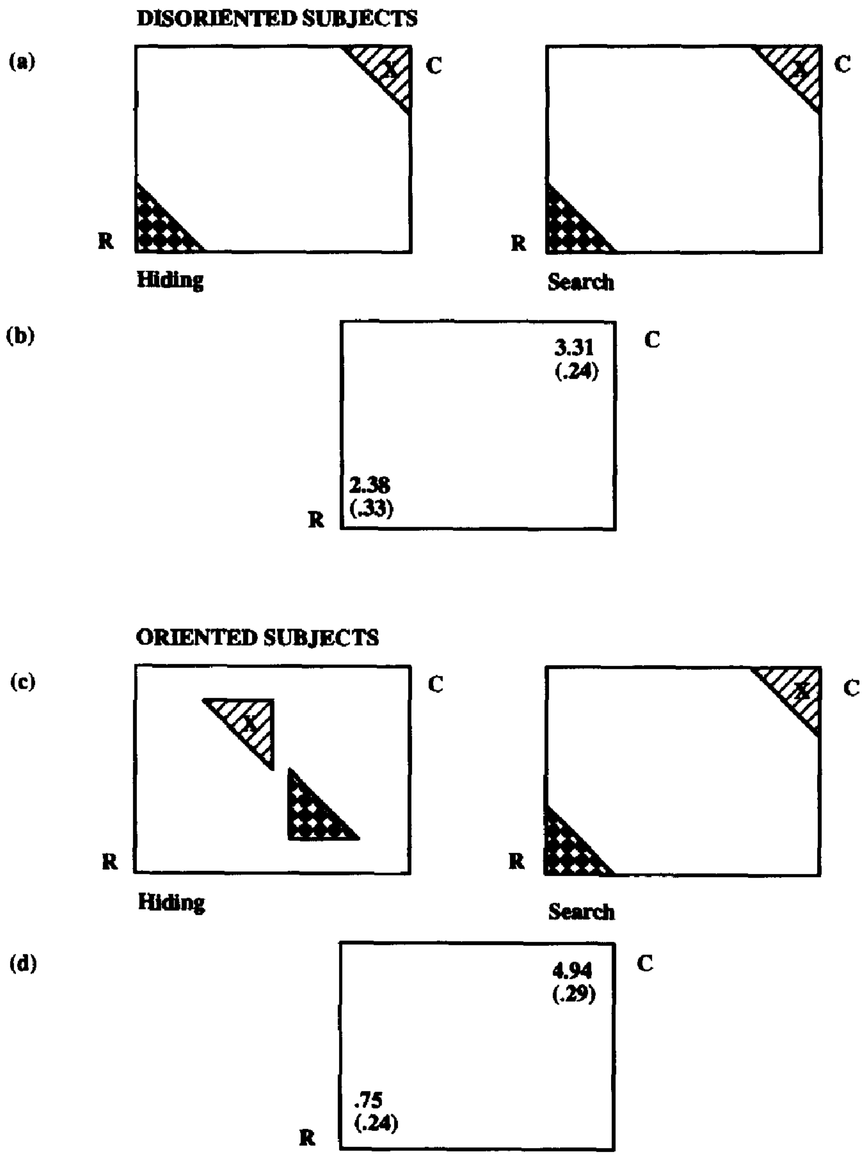

Fig. 6. Testing environments and search patterns for children in Experiment 4. In (a) and (c), the two diagrams depict the testing environment at the beginning and end of each trial for each subject group.

age, 21.1 months). The eight girls and eight boys in the find-the-object condition ranged in age from 18.8 to 23.4 months (mean, 21.3 months). One additional subject failed to complete the experiment because of fussiness, and four additional subjects had to be omitted from the sample because their parent used proscribed language during the experiment ($n = 3$, see below) or because of experimenter error (1).

10.2. Apparatus

Children were tested in the white rectangular chamber with no corner panels and no blue wall. The room contained two triangular-solid containers, with triangles 16 in. × 16 in. × 30 in. and depth 9 in., made of heavy foamcore and covered either with bright blue paint and large pink construction-paper dots or with dark gray paint and large red and yellow stripes. The longest side of the blue and pink box was covered by a shiny pink satin curtain that could serve to hide an object; the identical portion of the gray, red and yellow box was covered by a red velour curtain. When a box was placed in a corner of the chamber, only its top surface and this curtain were visible.

10.3. Design

Separate groups of children were given the reorientation task and the find-the-object task. Within each group, the identity of the box in which the object was hidden, the corner in which that box (and the object) was located, and the subject's sex were orthogonally counterbalanced. For the reorientation task, the facing position of each subject on each trial was randomly determined with the restriction that the number of trials at each facing position were equated across subjects. For the find-the-object task, each subject was tested with the same order of facing positions as the subject in the reorientation task for whom the object was hidden in the same box and corner.

10.4. Procedure

Each subject received four to six test trials in a single session. Before the session began, the experimenter pointed out the curtains and interiors of each box. Then the experimenter hid a toy in the box to be used for that session, closed the curtain, and asked the child to retrieve the toy. Subjects usually but not always retrieved the toy immediately; test trials did not proceed until a subject had successfully gone to the box and attempted to lift the curtain to retrieve the hidden object. In the reorientation condition, the two boxes remained in two opposite corners of the room throughout the session. The procedure was the same as in Experiments 2–3. In the find-the-object condition, the two boxes were placed near the center of the room at the start of each trial. While the parent hid the toy in a designated box, the experimenter remained in the chamber, circling the room so that her presence could not serve as a landmark. After the parent hid the toy, he or she covered the child's eyes while the experimenter moved the two boxes to diagonally opposite corners of the room. In both conditions, the experimenter then directed the parent to orient the child toward a predetermined wall, the child's eyes were uncovered, and the child searched for the object. Each parent was instructed not to mention to the child any of the distinctive properties of the containers, for example, stripes versus dots or red versus pink curtain color.

11. Results

Table 4, line 1 presents subjects' search performance on the first trial, before they had the chance to benefit from feedback. Oriented subjects tended to search the correct container (binomial $p = .038$) whereas disoriented subjects did not

Table 4
Number of subjects searching in each corner on each trial of Experiment 4 ($N = 16$)

Condition:	Disoriented		Oriented	
Corner:	C	R	C	R
Trial 1	9	7	12	4
Trial 2	11	5	12	4
Trial 3	12	4	13	3
Trial 4	8	8	15	1

($p > .40$). On the first trial, oriented subjects chose the correct container more often than disoriented subjects ($t(15) = 2.24$, $p < .05$).

Fig. 6(b,d) presents the mean search rates at each corner for each condition of the experiment. Preliminary ANOVAs including the factors sex, corner, and container found no effects involving these factors, and therefore we collapsed across them in subsequent analyses. Because children in both groups confined their search to the two corners containing boxes ($SD = 0$), the planned ANOVAs could not be performed and were replaced by t tests. Disoriented subjects searched with equal frequency at the correct corner and at the rotationally equivalent opposite corner ($t(15) = 1.68$, $p < .15$). In contrast, children whose orientation remained intact searched more often at the correct corner ($t(15) = 8.35$, $p < .001$). Search at the correct corner in the find-the-object task exceeded search at the correct corner in the reorientation task ($t(15) = 4.21$, $p < .001$). Conversely, search at the rotationally equivalent corner in the reorientation task exceeded search at the rotationally equivalent corner in the find-the-object task ($t(15) = 4.47$, $p < .001$).

Trial-by-trial search patterns are given in Table 4. A repeated-measures analysis with the factors condition (disoriented or oriented), corner (correct vs. incorrect) and trial (4) revealed no effect of trial, only an effect of corner ($F(1, 30) = 29$, $p < .001$) and an interaction of that factor with condition ($F(1, 30) = 4.21$, $p < .05$). Across all the trials, oriented subjects searched the correct corner more often than disoriented subjects.

For the analysis of the effect of final facing position on search patterns, data from 4 of the 32 subjects could not be included because of occlusion of their facing position on the video record. The 2 (visibility) $\times$ 2 (choice of C vs. R) ANOVA revealed no effect of facing position alone or in interaction with correct container choice.

12. Discussion

As in the previous experiments, disoriented children reoriented themselves by geometry alone. Children failed to reorient in accord with nongeometric information, even though nongeometric properties such as the color and texture of a container directly specified which container held the hidden object. This finding suggests that children's failure to use nongeometric information does not result from lack of attention to landmarks at a distance from the hidden object. Children's failure to use nongeometric information in this task is comparable to the failure of rats to benefit from salient odors emanating from the very corner at which food is hidden (Cheng, 1986).

The present findings also cast doubt on the thesis that children's failure to reorient by nongeometric information stems from limits on their ability to remember that information. When children were disoriented in an apparently stable environment, they reoriented themselves and searched for an object without taking account of the color or pattern of the object's container. In contrast, when children were not disoriented and sought an object in a movable container, they did take account of the color and pattern of the container in finding the object. Children evidently can represent and remember nongeometric properties of a container and use those properties to locate an object that has moved, but they do not use the same properties to reorient themselves so as to find an object whose location has not changed. Children's successful use of nongeometric properties of the container to constrain search for a movable object accords with the findings of many experiments with rats in tasks in which direct cues allow an animal to locate an object by a nonspatial strategy (e.g., McDonald and White, 1993; Rudy, 1991).

The power of the comparison of object search by children in the reorientation and find-the-object tasks stems from the fact that the children who performed these two tasks received roughly the same exposure to the relevant nongeometric information before closing their eyes. Children's competent performance in the find-the-object task suggests that this exposure was sufficient to enable encoding of the nongeometric information, at least as a direct associative cue rather than as part of a larger representation of the environment. Nevertheless, subjects in the disorientation condition received somewhat different exposure to the room than their counterparts in the find-the-object task (who initially encountered the two containers in the room's center), and they underwent a disorientation procedure that may have affected their performance. Perhaps the disorientation procedure itself is confusing or distracting to a child and causes her to forget the color or pattern of a container in which an object is hidden. Perceptual or memory limitations, rather than a task-specific system for reorientation, might therefore explain children's failure to use nongeometric information in a reorientation task. Experiment 5 tested these possibilities by presenting a find-the-object task to children who viewed exactly the same initial environment as the disoriented children in Experiment 4 and who received exactly the same disorientation procedure.

EXPERIMENT 5

In Experiment 5, *dis*oriented children were presented with a spatial task that required no *re*orientation. Each child viewed a toy hidden exactly as in the disorientation condition of Experiment 4 and then was disoriented. After the disorientation procedure, both the child and the two containers were taken from the experimental chamber, and the child searched for the object (Fig. 7a). Because the

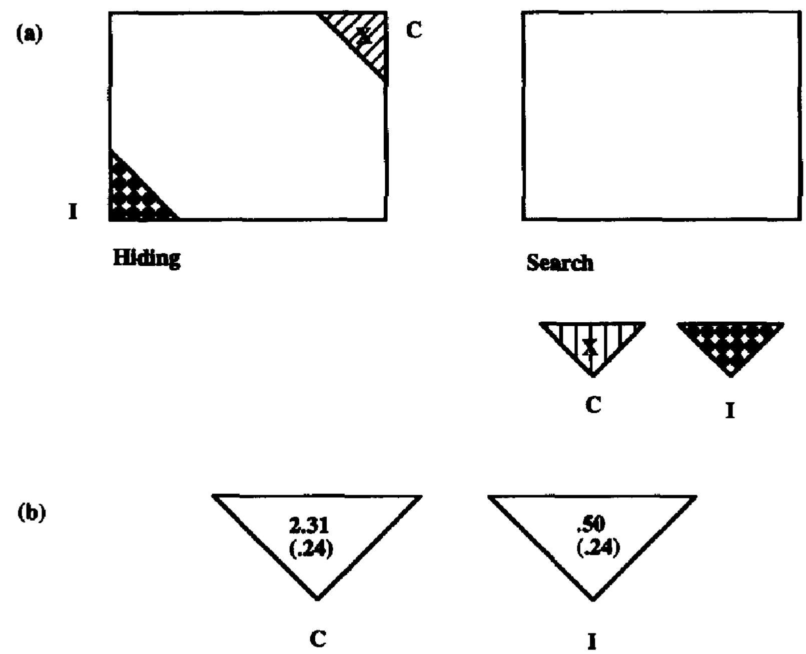

Fig. 7. Testing environments and search patterns for children in Experiment 5. In (a), the two diagrams depict the testing environment at the beginning and at the end of each trial. "C" and "I" stand for "correct" and "incorrect."

child now found herself in a different environment, she could not reorient herself by comparing the currently visible surroundings to those she experienced immediately before disorientation. Because the box containing the hidden toy evidently had moved, moreover, the child did not need to reorient and return to the object's previous location; instead, she needed to search the correct box at the object's new location. If children failed to use nongeometric information in previous studies because memory for that information was impaired by the disorientation procedure, then children should fail to find the object in the present task. In contrast, if children's previous failures reflect a task-specific system for re-establishing their sense of position and heading after disorientation, then children might succeed at finding the object in the present situation by searching the box with the correct nongeometric properties.

13. Method

13.1. Subjects

Participants were eight boys and eight girls ranging in age from 18.0 to 22.9 months (mean, 20.5 months). Four additional subjects were omitted from the sample because of experimenter error (2) or failure to complete at least two trials because of fussiness (2).

13.2. Apparatus, design, and procedure

The experiment took place both inside and immediately outside the rectangular chamber. The first half of each search trial was identical to that of the reorientation task of Experiment 4: The child, parent, and experimenter entered the room with the two triangular containers already in the corners, the parent or the experimenter hid the object in one of the containers, and the child received a preliminary search trial. Once the child had retrieved the object on this practice trial, the object was hidden again as the child watched and then the child was disoriented. While the parent held and turned the child, the experimenter removed the two boxes from the room and set them side by side on the floor. The lateral positioning of the boxes outside the room was randomized across trials. After the boxes were positioned outside the room and the subject had been disoriented, the parent brought the child out of the room with eyes still closed, turned her two more times, uncovered her eyes, set her down facing the curtained panels of the two boxes, and encouraged her to find the object. Because the video camera did not extend outside the room, search behavior was coded by the experimenter, who was not blind to the goals of this research or to the location of the object.

14. Results

Table 5, line 1, presents the search patterns on the first trial. Children showed a nonsignificant tendency to search the correct container on the first trial ($p = .11$).

Fig. 7(b) presents the distribution of subjects' search in each container across all trials. Because the preliminary analyses of the factors sex, corner and container found a significant interaction between the last two factors, we included these factors in all subsequent analyses. An overall ANOVA on search rate data by the factors choice (correct or incorrect), corner (4) and container (2) revealed a significant effect of choice ($F(1, 5) = 37$, $p < .001$) as well as a significant interaction of choice with container and corner ($F(3, 15) = 9.16$, $p < .005$). The interaction is not interpretable. Overall, subjects highly reliably chose the correct container in this experiment.

Analyses of the trial-by-trial data for all subjects completing at least three trials ($n = 9$) and for all subjects completing at least two trials ($n = 16$) revealed a highly significant effect of choosing the correct container ($F(1, 8) = 15.1$, $p < .005$) that interacted with container and corner ($F > 10$, $p < .005$) but did not interact with trial (all Fs < 1).

Table 5
Number of subjects searching in each box on each trial of Experiment 5 ($N = 16$)

Box	Correct	Incorrect
Trial 1	11	5
Trial 2	13	3

Further analyses compared the search performance of the children in Experiment 5 to the performance of their counterparts in each condition of Experiment 4. The analyses used the percentage of search in the two containers to equate for the different average number of trials per subject in the two experiments. Subjects in Experiment 5 searched the correct container reliably more than the disoriented subjects in Experiment 4 ($t(15) = 4.41$, $p < .001$) and with the same frequency as subjects whose orientation remained intact in Experiment 4 ($|t(15)| < 1$).

15. Discussion

Experiment 5 provides evidence that children who have experienced a disorientation procedure can remember the coloring and patterning of a container and can use this information to locate an object that was hidden inside the container. Children's successful search performance in Experiment 5 contrasts with the performance of children who were given the reorientation task in Experiment 4. Although children were presented with exactly the same environment and were disoriented in both these conditions, the children in Experiment 4 were given the task of reorienting themselves by the nongeometric properties of the boxes, whereas those in Experiment 5 were not. Children's more successful search in Experiment 5 suggests that the disorientation procedure does not produce a general impairment in children's memory or search performance. Instead it seems that the reorientation process itself is impervious to nongeometric information, in accord with the thesis of an encapsulated reorientation system (Cheng, 1986).

Once again, however, there is an alternative to this suggestion. It is possible that a single salience hierarchy determines the information that children use to solve all the present tasks, and that geometric information is favored over nongeometric information within this hierarchy. Perhaps children always encode, remember, and act on geometric information in preference to nongeometric information when both sources of information are available. If that were the case, children in all the reorientation tasks studied so far would use the shape of their surroundings, but not the colors, textures, and identities of objects in their surroundings, to reorient themselves. In contrast, children might have relied on nongeometric information in Experiment 5, and in the find-the-object task of Experiment 4, because no geometric information was available to guide their search: The displacement of the containers in both experiments destroyed any geometric correspondence between the environment at the time of object hiding and at the time of object search. In the final experiment, we tested the thesis of a task-specific reorientation mechanism against the perceptual salience alternative, by comparing children's performance on two search tasks within the same environment.

EXPERIMENT 6

This experiment investigated how children performed two different search tasks within an environment in which both geometric and nongeometric information uniquely specified both their own position and the position of a hidden object. Separate groups of children were tested, one group in a condition involving disorientation prior to search and the other group in a condition involving no disorientation. In each condition, an object was hidden, children's eyes were covered and they either were turned or remained at rest, the room was quietly transformed, and then children were allowed to look at the room and search for the object. On different trials, the room was transformed in two ways (Fig. 8). On *concordant* trials, the containers were moved diagonally across the room such that one search location corresponded to the original hiding location both geometrically and nongeometrically, whereas the other location differed from the original location in these respects. This rearrangement corresponded to a rotation transformation of the room. On *conflict* trials, each container was moved directly across the room to the far but adjacent corner, such that one search location corresponded to the original location in shape but not in color and pattern, whereas the other location corresponded to the original location in color and pattern but not shape. This rearrangement corresponded to a reflection transformation of the room.

The two conditions of this experiment presented both oriented and disoriented children with exactly the same configurations of surfaces and objects, but they challenged children with deeply different tasks. A child in the disoriented condition has lost track of his position and heading, and his task is to use relationships between the visible appearance of the room before and after disorientation to determine his own new heading. If the disorientation procedure was successful, the displacement of the containers should not be detectable on concordant trials and might not be detectable on conflict trials (see discussion below). A child in the orientation-intact condition, in contrast, has not moved and should be able to use knowledge of his own constant position, plus memory for the object's hiding location, to infer that the corner containers have been displaced. This child therefore must use relationships between the visible appearances of the room before and after his eyes were closed to determine the new position of the object.

Where should children search for the object? Consider first how children might perform on the conflict trials, in which geometric and nongeometric specifications of the hiding place differ. If children's search is constrained by a salience hierarchy that favors geometric over nongeometric information in all tasks, then both oriented and disoriented children should search primarily at the location that corresponded in shape to the original hiding place. In contrast, if children are guided by distinct, task-specific systems for reorienting themselves and for finding movable objects, then children might rely on different information in the different orientation conditions, using geometric information to reorient themselves and nongeometric properties of the container to locate the object. Performance on the conflict trials therefore tests whether reorientation and object search depend on task-specific systems.

If children's performance on the conflict trials suggests a task-specific process for reorientation, a comparison of search performance on conflict trials versus concordant trials should shed light on the encapsulation of that process. Children's

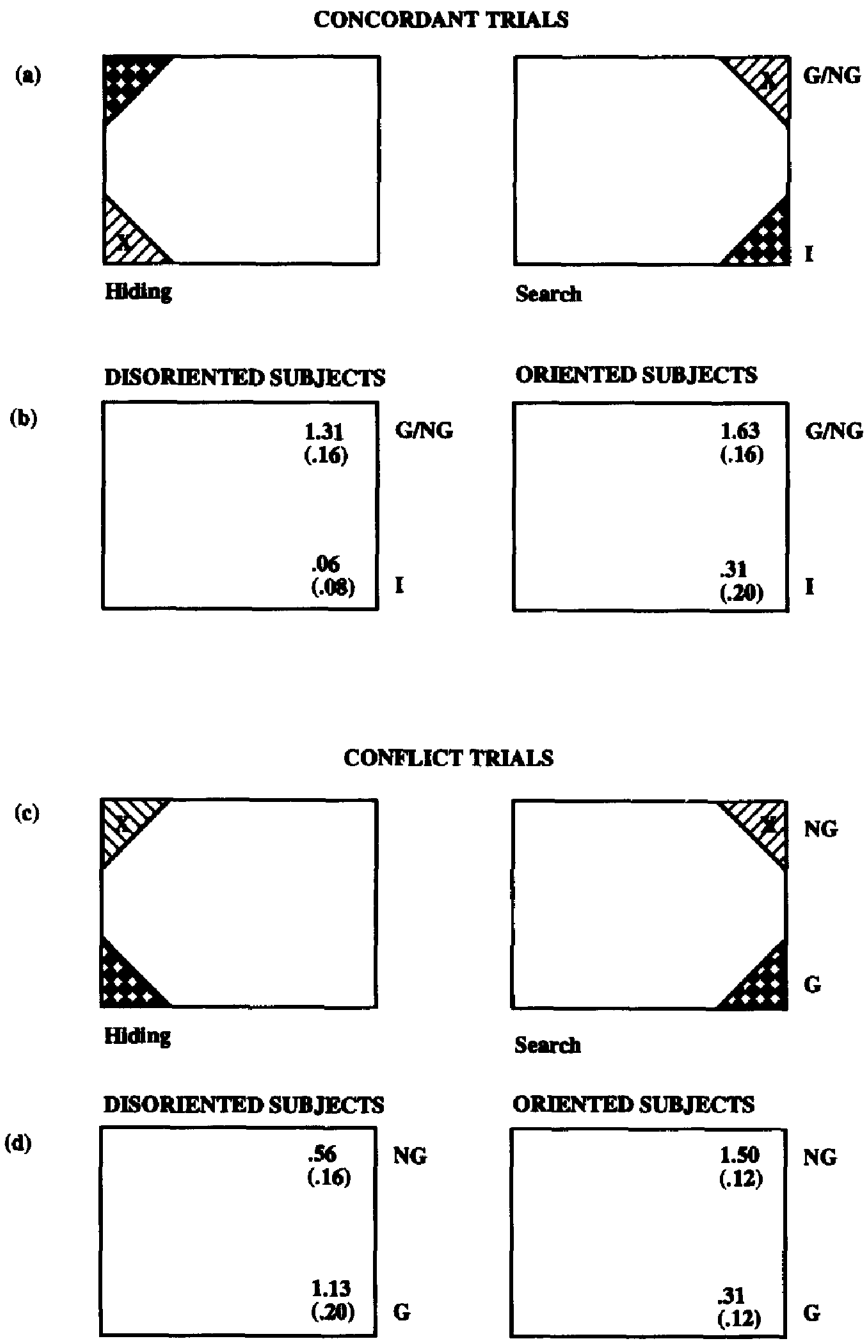

Fig. 8. Testing environments and search patterns for children in Experiment 6. In (a), the two diagrams depict the testing environment at the beginning and end of each concordant trial, and in (c) the two diagrams depict the environment at the beginning and end of each conflict trial.

reorientation may depend exclusively on a representation of the shape of the environmental layout, irrespective of nongeometric properties of the layout. In that case, disoriented children should search for the object at the geometrically appropriate corner at equally high levels regardless of whether or not the container at this corner corresponded to the original container in color and pattern: Performance on concordant and conflict trials should not differ. In contrast, children may be influenced by nongeometric properties of the object's container but weight them less heavily than the room's geometry in a reorientation task. In that case, children may show greater search at the geometrically appropriate corner when nongeometric properties of the corner specify the object's location as well. In order to maximize children's chances of detecting and using the nongeometric information, we left the toy inside the container in which it was hidden. On conflict trials, therefore, all the children received positive feedback for searching the corner with the correct nongeometric properties and incorrect geometry.

16. Method

16.1. Subjects

Participants were 32 children. The eight boys and eight girls in the reorientation task ranged in age from 19.0 to 23.5 months (mean, 22.0). The eight boys and eight girls in the find-the-object task ranged in age from 18.2 to 23.6 months (mean, 22.1). Two additional subjects were omitted from the sample because of parent error (failing to keep the child's eyes covered during the disorientation procedure, as judged by a video coder blind to our hypotheses).

16.2. Apparatus

All testing took place within the white rectangular room with the two containers used in Experiments 4 and 5. The containers appeared at one pair of adjacent corners of the room at the beginning of a search trial, and they appeared at the opposite pair of adjacent corners at the end of the trial (Fig. 8). For the concordant trials, each container was moved to the diagonally opposite corner, preserving the relation between the geometric and nongeometric information. For the conflict trials, each container was moved to the adjacent corner on the far side of the chamber, changing the relation between the room's geometric and nongeometric properties. In both conditions, the object remained inside the container in which it was hidden and therefore was found at the corner with the appropriate nongeometric properties.

16.3. Design

Half the subjects participated in the disorientation condition and half in the orientation-intact condition. Each condition consisted of at least one concordant trial and at least one conflict trial, with 15 subjects receiving two trials of each type. Half the subjects in each condition were presented with a concordant trial first; concordant and conflict trials subsequently were presented in a quasi-random order. Subject sex, hiding container, hiding location and facing position were roughly equated but not strictly counterbalanced within each condition.

16.4. Procedure

In the disorientation condition, the child watched an object being hidden in one of the two containers and then was disoriented as in previous studies. After the disorientation procedure, the parent brought the child outside the experiment room, eyes still covered, while the experimenter quietly moved the boxes to the two previously unoccupied corners of the room. Then the child was returned to the testing room with eyes covered, underwent further disorientation (four more turns), was put down facing the center of a predetermined wall, and was allowed to search for the object. The procedure for subjects in the orientation-intact condition was identical to that of the disorientation condition, except that subjects underwent no disorientation. After the toy was hidden, the parent covered the child's eyes for 10 s (roughly the duration of the disorientation procedure) without turning the child. The child was then brought outside the experiment room while the experimenter moved the boxes and was brought back, eyes still covered, to face a randomly predetermined position before being allowed to search for the object.

17. Results

Table 6, line 1, gives the search patterns on the first trial, before subjects received any feedback. On the first concordant trial, subjects in both conditions searched the geometrically and nongeometrically correct container (for the disoriented children, binomial $p < .001$; for the oriented children, $p = .002$). On the first conflict trial, in contrast, disoriented subjects searched the geometrically appropriate container ($p = .011$), whereas oriented subjects searched the nongeometrically appropriate container ($p = .038$). A t test comparing search by the two groups found no difference on the first concordant trial ($|t(15)| < 1$), but a large difference on the first conflict trial ($t(15) = 3.42$, $p < .004$).

Table 6
Number of subjects searching in each corner on each trial of Experiment 6 ($N = 16$)[a]

Trial type:	Concordant		Conflict	
Corner:	G[b]/NG[c]	Incorrect	G	NG
Disoriented condition				
a. Trial 1, session 1	8	0	6	2
b. Both sessions				
Trial 1	15	1	13	3
Trial 2	6	0	6	5
Oriented condition				
a. Trial 1, session 1	8	0	3	5
b. Both sessions				
Trial 1	13	3	4	12
Trial 2	13	1	1	12

[a] *N*s vary across subject group and testing condition for trial 2, but are all less than 16.
[b] G: geometrically appropriate corner.
[c] NG: nongeometrically appropriate corner.

Fig. 8(b,d) presents the search rates across all the trials of this experiment. Preliminary analyses found no effect of sex on search patterns, and so we collapsed across this factor in subsequent analyses. Because all the children confined their search to the two corners containing boxes ($SD = 0$), the planned ANOVAs could not be performed and were replaced by t tests. Disoriented subjects tended to choose the correct container on concordant trials, when the original association between geometric and nongeometric information was intact ($t(15) = 6.46$, $p < .001$). On conflict trials, disoriented subjects tended to choose the container in the geometrically correct position but with the wrong nongeometric markings ($t(15) = -1.78$, $p < .10$). Oriented subjects also tended to choose the correct container on concordant trials ($t(15) = 4.79$, $p < .001$). On conflict trials, they tended to choose the container with the appropriate markings but in the geometrically incorrect position ($t(15) = 5.22$, $p < .001$). Rates of searching the correct container did not differ across the oriented and disoriented conditions on concordant trials (unpaired $|t(30)| < 1$). On conflict trials, however, oriented subjects chose the container with appropriate coloring and markings more often than disoriented subjects ($t(15) = 4.04$, $p < .005$).

In order to assess how performance changed over trials and as a result of feedback, the data from the two concordant trials and from the two conflict trials were analyzed by separate ANOVAs with an additional factor of trial (2) for the 20 subjects who completed two concordant trials and the 23 subjects who completed two conflict trials. The analysis of the concordant trials revealed only a main effect of location, with subjects tending to search the correct corner on both trials ($F(1, 18) = 55$, $p < .001$). The analysis of the conflict trials revealed a significant interaction of condition by location ($F(1, 21) = 9.42$, $p < .01$) and of trial by location ($F(1, 21) = 13.87$, $p < .001$). Oriented subjects were more likely than disoriented subjects to search the corner with the correct nongeometric features over both trials, and the subjects in both groups were more likely to search the corner with the correct nongeometric features on the second trial than on the first.

A final analysis tested for encapsulation of the search process for each group of subjects by comparing performance on the first concordant and conflict trials. For disoriented subjects, a 2 (trial type: concordant or conflict) $\times$ 2 (location: geometrically correct vs. incorrect) ANOVA revealed a significant main effect of corner, reflecting children's use of geometric information ($F(1, 30) = 45$, $p < .001$), and no interaction of corner with trial. For oriented subjects, a 2 (trial type) $\times$ 2 (location: *non*geometrically correct vs. incorrect) ANOVA revealed a main effect of corner, reflecting use of nongeometric information ($F(1, 30) = 19$, $p < .001$), and no interaction with trial type. On the first trial, disoriented subjects' search was affected only by geometric information, and oriented subjects' search was affected only by nongeometric information.

18. Discussion

Both disoriented and oriented children searched the appropriate location on concordant trials, in which both geometric and nongeometric information specified the object's position. On trials in which geometric and nongeometric information specified distinct locations, disoriented subjects searched for the object in the corner with appropriate geometry, and oriented subjects searched for the object in the corner with appropriate nongeometric markings. This double dissociation in search performance was observed on the first conflict trial, when children had no reason to expect the containers to move and had received no differential feedback for searching at different locations. The dissociation cannot be explained in terms of a single salience hierarchy and suggests instead that distinct processes underlie performance in the two memory tasks.

It is striking that this double dissociation in performance was observed on children's first search trial. When children view the object being hidden at the start of the first search trial, no features of the displays or procedure distinguish the disorientation condition from the orientation-intact condition. As a child's eyes are closed, therefore, she has no way to know whether she will be called on to use her memory for the room to reorient herself, to locate a displaced object, or for some other purpose. Because children in the orientation-intact condition reliably searched the container with the appropriate nongeometric properties on their first trial, we may conclude that all children, including those in the disorientation condition, detected and remembered the distinctive properties of the container in which the object was hidden. Nevertheless, disoriented children made no detectable use of this information in reorienting themselves. On the first search trial (i.e., before children received any information that the object moved with its container), children in the disoriented condition searched the geometrically appropriate corner just as strongly when geometric and nongeometric information were in conflict as when they were concordant. Nongeometric properties of the container therefore appeared to have no effect on the child's initial searching. These findings provide evidence that children's reorientation depends on a process that is both encapsulated and task-specific: a process that is guided by only a subset of the information that the child detects and remembers.

Further findings that may bear on the encapsulation of the reorientation system come from a consideration of changes in children's performance over the course of the experiment. Across the first two trials in which geometric and nongeometric information were placed in conflict, performance appeared to be influenced by feedback favoring the nongeometric information: Both disoriented and oriented subjects showed greater searching of the container with appropriate coloring and patterning on the second conflict trial than on the first. What accounts for this effect? One possibility is that the reorientation process is not fully encapsulated: Disoriented subjects' reorientation process may have been modified by feedback. A second possibility is that the reorientation process is fully encapsulated, and that children reoriented in accord with geometry alone. Once children were oriented and fail to find the object in the geometrically specified location, however, they may have inferred that the object had moved. On subsequent trials, therefore, some children may have redefined their search task from that of reorienting so as to return to a stable environmental location to that of tracking an object inside a distinctive container that has moved from one location to another.

Whatever the explanation for the feedback effect in this experiment, it contrasts with the marked absence of effects of feedback in the previous studies. In Experiments 2, 3, and 4, children successfully retrieved the toy every time they searched at the corner with the appropriate nongeometric properties, and they failed to retrieve the toy when they searched at the rotationally equivalent corner with inappropriate nongeometric properties. Despite this feedback, children continued to search the two geometrically appropriate corners with equal frequency throughout the three- or four-trial sequence. Feedback influenced children's search only when geometric and nongeometric information are placed in conflict, perhaps because this conflict provides information that an object has moved.

GENERAL DISCUSSION

Our experiments suggest that young children, like adult rats, reorient in accord with the shape of the environment. Children rely only on geometry to reorient in these tasks, even when nongeometric information is available, is detected and remembered by the children, and would improve their performance. In contrast, human adults solve our tasks both by using room geometry (in the all-white environment) and by combining nongeometric information with some form of geometric information (in the room with one blue wall).

Our experiments rule out a number of potential explanations for children's failure to reorient by nongeometric information. First, this failure cannot be explained by a strategy of searching only the immediately visible corners of the experimental chamber, which included the correct corner on roughly half the trials and the geometrically equivalent, opposite corner on the other trials. The facing position analyses confirmed what is apparent to observers of these studies, that children often faced the correct location, stared at it, and then turned to search at the opposite location. Margules and Gallistel (1988) observed the same phenomenon in their rats; they remark that "it was both comical and poignant to see a rat munch Cocoa Puffs directly in front of, for example, a black corner panel in the exposure box and then, when placed in the test box, run to the white panel diagonally opposite the black and dig there" (p. 409).

Comparisons of children's performance in reorientation tasks with their performance in tasks involving hidden objects in movable containers show that children's failure to reorient by nongeometric information also cannot be explained by limits on attention or memory, by effects of the disorientation procedure itself, or by reliance on a single salience hierarchy applicable to all spatial tasks. Children's contrasting abilities in reorientation tasks and object-search tasks also parallel the findings of studies with rats (see O'Keefe and Nadel, 1978 for discussion). Like children, oriented rats readily use nongeometric properties of the environment to locate a movable object, but disoriented rats do not use such properties to relocate themselves without considerable training (Knierim et al., 1995). These findings suggest that the limits on disoriented children's performance stem from constraints on the reorientation process itself. Both the task specificity and the relative encapsulation of the reorientation process suggest, to a first approximation, that children's reorientation process depends on a "geometric module" (Cheng, 1986; Gallistel, 1990)[5].

Although children and rats appear unintelligent in relying on this modular reorientation process, the process may have served an adaptive purpose in the kinds of environment in which humans and other mammals evolved. Natural outdoor settings tend to be asymmetrical, with an unequal distribution of hills, valleys, and gorges. A geometric reorientation process specifies one's position and heading accurately and unambiguously when it operates in such environments. Only in the laboratory, or in other artificial environments humans lately construct for themselves, is this process likely to lead to error. Moreover, the macroscopic shape of a natural environment is its most enduring property (see Gallistel, 1990). Whereas most nongeometric surface properties change with the days or seasons, the relations among mountains, hills, valleys, ravines, and large boulders seldom change over an animal's lifespan. If few ambiguities arise in using this system, moreover, then selective pressure favoring the use of additional sources of information may not have been strong, although findings with birds suggest it may not have been absent (Vallortigara et al., 1990).

The existence of a geometric process for reorientation provides evidence against the thesis that all developmental mechanisms are shaped by the environment in which the child grows and therefore make use of the most reliable information in that environment (e.g., Johnson, in press; McClelland, 1992; Thelen and Smith, 1994). In the carpentered environments of children and laboratory rats, the macroscopic shape of the layout typically contains significant symmetries broken by distinctive nongeometric features of surfaces and objects. Nevertheless, the rats in Cheng's and Gallistel's experiments and the children in our experiments did not use such nongeometric information to reorient themselves. Although other cognitive systems might be altered by experience, to make use of whatever information is most reliable, reorientation appears to depend on a system of a different sort. Children's reorientation process appears to have an intrinsic structure, possibly reflecting our evolutionary history but not shaped by our past experience as individuals.

In contrast to children, adults performed more flexibly in our reorientation tasks,

[5] Because we did not give our subjects extensive training over hours or days, comparable to that used in some experiments with rats (see footnote 1), our work does not address whether it is possible for children to learn to reorient by nongeometric information. Rather, our work addresses a point in common with the work of many animal investigators: The information an organism uses, with some exposure to fixed features of the environment but not a longstanding familiarity with them, to re-establish position and heading after disorientation. Our subjects, and the adults rats of Cheng, Gallistel and Margules, were familiarized with many features of the environment before the experiment began, while they were oriented. Furthermore, the attention of our subjects was specifically called to these nongeometric features when they entered the room. Despite this exposure, children relied only on geometric information to reorient themselves. It would be interesting to see whether young children, like rats, can be trained to use nongeometric information by repeatedly exposing them to the fixed positions of nongeometric landmarks when they are not disoriented. Such studies are now in progress.

using nongeometric as well as geometric information when both were available. How might one account for this developmental change in performance? Although the research reported here does not address this question, two possible answers can be outlined. First, the reorientation process itself may become more flexible – that is, less modular or task-specific – over the course of development (Karmiloff-Smith, 1992; Rozin, 1976). Alternatively, the original geometric process may persist over cognitive development, and new processes may emerge that allow one to locate objects even in a state of disorientation. Instead of finding the hidden object by computing its current egocentric position from stored information about its allocentric position and current information about their own position and heading, the disoriented adults in our experiment may have located the object by storing and using information about the direct spatial relation between that object and other perceptible features of the environment (for example, information that the object was hidden "to the left of the short white wall") In the latter case, subjects may or may not also orient by the nongeometric information as they locate the object. Ongoing studies of normal and neurologically impaired adults, as well as studies of developing children, are attempting to distinguish these possibilities.

Regardless of the nature of the developmental change here observed, our studies suggest there is a core cognitive process for representing the shape of the surrounding environment and for using this representation to compute one's own position within the environment. Operating beneath the level of conscious awareness, this process appears to contribute importantly to our sense, as adults, of where we are. As with the systems of knowledge underlying human language, number, reasoning about objects, and social understanding, the core properties of this system of geometric knowledge appear to emerge early in life and to be conserved over human development. In distinction to some of these other knowledge systems, the system of geometric knowledge may have emerged early in mammalian evolution, and its central features appear to be found in other mammals (see Gallistel and Gelman, 1992 for parallel claims about the system of knowledge of number).

Claims for homologous systems of knowledge in humans and other animals, and for a common evolutionary history to those systems, must be made cautiously: They have a chance of being valid only when the systems show deep similarities behaviorally, at the level of cognitive process and function, and anatomically and physiologically. The rich body of behavioral, anatomical, and physiological research on mammalian navigation and spatial representation has revealed considerable similarity at all levels of investigation (e.g., Gallistel, 1990; McNaughton et al., 1995; O'Keefe and Nadel, 1978). For example, mammals as diverse as rodents and humans build up similar representations of their environments allowing navigation along novel paths (Loomis et al., 1993; Landau et al., 1984; Tolman, 1948) and supporting the accomplishment of various behavioral goals (Markus et al., 1994; Qin et al., 1994; Roitblat, 1982). Adults, children and rats are even similar in the sexual dimorphisms apparent in their spatial behaviors (Bever, 1992; Williams et al., 1990) and in the seasonal changes in spatial abilities of each sex (Kimura and Hampson, 1994). Anatomically and physiologically, the structures in the hippocampus and the parietal cortex that appear critical for the formation of allocentric spatial representations show detailed similarities in many mammals (Miller, 1991; Seifert, 1983). This body of comparative work suggests that what one learns about navigational processes in any mammal will apply to a first approximation to other mammals, including humans.

Although claims for common cognitive processes across species are difficult to substantiate, there are strong reasons to expect such commonalities to exist, especially when different species are compared at early points in ontogeny. Natural selection tends to operate not by effecting fundamental changes in pre-existing, adaptive traits but by conserving those traits and building new processes on top of them (Ridley, 1993). Evolutionary changes therefore tend to be implemented late in an organism's development, when they are less apt to disrupt other viable processes (Gould, 1977; Ridley, 1993). Cognitive capacities are likely to follow these general rules.

These considerations forecast a bright future for an emerging enterprise: a comparative, developmental, cognitive neuroscience (Gallistel, 1990; Gallistel and Gelman, 1992; Johnson, 1993). Through comparative and developmental studies, both the computational and the neural properties of the building blocks of human cognition can be explored. As humans' cognitive foundations are better understood, studies can focus on the further cognitive processes that are built upon them: the processes that may distinguish us from other mammals and may distinguish adults from children. For example, our experiments suggest that humans share with other mammals an early-developing, task-specific mechanism for re-establishing their spatial position and heading, and that the limitations of this system are overcome, in some way, with further development. Studies that begin from a comparative and developmental perspective and that ask how humans overcome these limits could shed light on one feature of human cognition that may be unique to us: Our capacity to extend our systems of knowledge into realms for which our biology has not prepared us.

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