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Mechanisms of Reorientation and Object Localization by Children: A Comparison With Rats

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Neurophysiological studies show that the firing of place and head-direction (HD) cells in rats can become anchored to features of the perceptible environment, suggesting that those features partially specify the rat's position and heading. In contrast, behavioral studies suggest that disoriented rats and human children rely exclusively on the shape of their surroundings, ignoring much of the information to which place and HD cells respond. This difference is explored in the current study by investigating young children's ability to locate objects in a square chamber after disorientation. Children 18–24 months old used a distinctive geometric cue but not a distinctively colored wall to locate the object, even after they were familiarized with the colored wall. Results suggest that the spatial representations underlying reorientation and object localization are common to humans and other mammals. Together with the neurophysiological findings, these experiments raise questions for the hypothesis that hippocampal place and HD cells serve as a general orientation device for target localization.

The brain systems that subserve navigation and spatial memory have been subjected to intense study at behavioral and neural levels, but two central questions remain unanswered. One question concerns the relation of spatial behavior to brain function. Studies of single neurons in actively moving rodents provide evidence that many neurons in the hippocampus are selective for an animal's position ("place cells") and that some neurons in the postsubiculum, thalamus, and striatum are selective for the animal's heading ("head-direction [HD] cells"; e.g., Dudchenko & Taube, 1997; O'Keefe & Nadel, 1978; O'Keefe & Speakman, 1987; Taube, Goodridge, Golob, Dudchenko, & Stackman, 1996; Taube, Muller, & Ranck, 1990). Do these cells form a cognitive map by which animals locate themselves and significant objects within the environment, or are their location- and direction-specificity consequences of other functions? A second question concerns the relation of spatial memory systems in nonhuman mammals to those in humans. Humans in modern societies navigate quite differently from other mammals, using unique information sources (e.g., maps and verbal directions) to find their way in unfamiliar environments and ignoring other information sources (e.g., solar angle) used by a broad range of animals. Has the evolution of primates and humans brought fundamental changes to the systems that subserve spatial memory and navigation, or do common mechanisms underlie these functions in all mammals?

Concerning the first question, neurophysiological studies indicate that rodent place and HD cells have specific receptive fields at certain spatial locations and directions, respectively. The activity of these cells persists when external sensory cues are removed, suggesting that the cells are selective for an animal's position rather than for any specific perceptible patterns (O'Keefe & Nadel, 1978). Moreover, disoriented animals sometimes show large and seemingly random rotations of the fields of place and HD cells, but the rotations of different neurons are correlated within a single animal, suggesting that these neurons form a unitary representation of the environment and of the animal's position and heading within it (Knierim, Kudrimoti, & McNaughton, 1995). In experiments in richer environments with multiple cues, however, repositioning of individual cues affects some place cells but not others, suggesting limits to the unity of this representation (Gothard, Skaggs, & McNaughton, 1996; O'Keefe & Speakman, 1987). Rodent place and HD cells clearly are involved in spatial memory and navigation, therefore, but their precise function is not known.

Concerning the second question, a series of behavioral studies of reorientation and spatial memory have yielded strikingly parallel findings in rats and human children aged 1.5 to 5 years. Cheng and Gallistel (1984; Cheng, 1986; Margules & Gallistel, 1988) and Hermer and Spelke (1994, 1996; Hermer, 1997) studied reorientation and spatial memory in participants placed in a rectangular chamber with multiple cues as potential landmarks. Participants were

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shown the location of a desired object (food for rats, a toy for children) that was subsequently hidden. Then they were disoriented and allowed to search for the hidden object. Rats and children searched with high and equal frequency at the location of the hidden object and at the geometrically equivalent location at the opposite side of the chamber. Their ability to confine their search to these locations indicates that they were sensitive to the shape of the enclosure and used this shape as a cue to target localization. Nevertheless, rats' and children's inability to choose the correct corner over the geometrically equivalent opposite corner suggests that their reorientation and target localization process is not sensitive to a wealth of nongeometric information, including the distinctive brightness or coloring of a wall (for children) or the distinctive texture, brightness, and odor of a corner panel (for rats). The closely similar performance of rats and human children suggests that a common system underlies reorientation and object localization in rats and humans and that this system computes the congruence between geometric representations of the perceived and remembered environmental layout.

There is a curious difference, however, between the findings of the above two sets of studies. Although disoriented rats and human children show striking insensitivity to nongeometric information in behavioral experiments, such information exerts a powerful influence on the firing patterns of place and HD cells in rats. If a rat explores an enclosed, cylindrical chamber with no landmarks except for one region of contrasting brightness (hereafter, a "cue card"), the activity of its place and HD cells typically becomes anchored to the card: When the card is rotated, for example, place and HD fields tend to rotate with it (e.g., Dudchenko, Goodridge, & Taube, 1997; Goodridge & Taube, 1995; Knierim et al., 1995; Muller & Kubie, 1987; Taube et al., 1990). If place and HD cell activity signals the rat's perceived position and heading within the environment, then this rotation implies that the rat has reoriented itself in accord with a nongeometric cue. Behavioral and neurophysiological studies therefore suggest different conclusions about the nature of the reorientation and object-localization process.

Two differences between the methods of the behavioral and neurophysiological experiments might account for their contrasting findings. First, behavioral studies of rats and children typically test participants in environments with a distinctive and informative shape, such as a rectangular chamber (Cheng, 1986; Hermer & Spelke, 1994) or a square chamber with geometrically distinctive internal landmarks (Biegler & Morris, 1993, 1996). In contrast, neurophysiological studies often situate rats in environments with minimal distinctive geometry: an enclosed cylindrical or square chamber devoid of geometric landmarks (Knierim et al., 1995; Taube et al., 1990). Second, behavioral studies in humans have tested participants in novel environments, whereas neurophysiological studies typically have situated rats in familiar environments. Animals may use nongeometric cues only when geometric information is minimized and when the cues are familiar and stable. Consistent with the latter possibility, Knierim et al. (1995) found that place and HD cell rotations are more strongly anchored to a cue card if an animal experienced the card at a constant location while it was oriented. When rats experienced the card only in a state of disorientation, the authors suggested, they had no opportunity to learn that the landmark occupied a stable environmental position (although see Dudchenko, Goodridge, Seiterle, & Taube, 1997).

We conducted four experiments to investigate these possibilities by testing human children's object localization after disorientation under situations designed to approximate the situations faced by rats in neurophysiological studies. First, the task of Hermer and Spelke (1994, 1996) was given to young children in a square chamber with no distinctive markings (control condition, Experiment 1), with one distinctively colored wall (nongeometric cue condition, Experiment 1), or with one distinctively shaped wall (geometric cue condition, Experiment 2). If the disorientation procedure was effective and no unintended directional signals were present in the environment, children were expected to search the four corners equally in the control condition. If either distinctive cue served as a basis for object localization after disorientation, then children were expected to search the correct corner with higher frequency in the condition where that cue was present.

Experiment 1

Children aged 18 to 24 months were tested individually in two unfamiliar environments: a square chamber with four white walls (control condition) and the same chamber with a shiny red fabric covering the wall opposite to the chamber's point of entry (nongeometric cue condition). In both conditions, a child watched a parent hide a toy in one corner of the chamber, was lifted and turned with eyes covered to induce disorientation, and then was released and encouraged to find the toy.

Method

Participants. Participants were 10 young children (6 boys and 4 girls) aged 18 to 24 months ($M = 21.6$ months), born of full-term pregnancies, and suffering from no known health problems. Two of the children were eliminated from the sample because they failed to complete at least three valid test trials (see *Coding and data analysis*) in each experimental session.

Apparatus. The experiment took place within a 1.9 × 1.9 × 2.0-m chamber situated in a larger experiment room (see Figure 1). The walls and ceiling of the chamber were covered with white, soft acrylic fabric stretched onto a concealed wooden frame. The chamber was accessed through a 0.7 × 2.0-m door covered by the same white fabric. When the door was closed and the fabric was secured to the adjacent wall, to adults inside the chamber the four walls looked identical. The floor of the chamber was covered with a homogeneous gray carpet. At each corner of the chamber was a 1.1-m-tall red panel behind which a small toy could be hidden. Four 40-W lights were positioned symmetrically on the ceiling to illuminate the chamber. A camera was mounted in the middle of the ceiling providing an overhead view of the chamber and sending the image to a videocassette recorder outside the chamber. A radio also was positioned at the center of the ceiling to make soft constant noise that masked other sound sources.

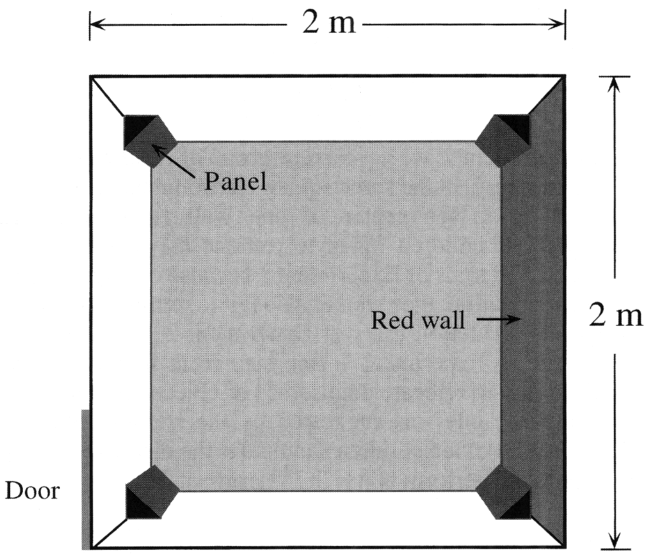


Figure 1. An overhead view of the square chamber with homogeneous gray floor, four identical white walls (one covered completely with a red fabric in one condition), four identical lights mounted on the ceiling (not shown), and one red panel at each corner behind which a small toy could be hidden. A video camera and a radio producing white noise were mounted at the center of the ceiling.

In the nongeometric cue condition, a bright 1.9 × 2.0-m red satin fabric was attached to the wall opposite the door. On entering the chamber, therefore, a child directly faced a smooth, shiny red wall flanked by matte, textured white walls. Informal observations of the children's behavior on entering the chamber suggested that the red wall was a salient feature of the environment (see Discussion below).

Design. Each child was given one oriented search trial followed by two test sessions, one in the white chamber and one in the chamber with the red wall. Each test session consisted of four disorientation trials in which the toy was hidden in the same corner as for the oriented search trial. The sex of the children, the corner at which the target was hidden, and the order of the two test sessions were orthogonally counterbalanced across participants. The test sessions were designed so that the child would begin each of the four trials in a session facing the center of a different wall, but variations in parents' and children's behavior precluded our controlling the child's facing position exactly (see *Coding and data analysis*).

Procedure. One experimenter worked outside the chamber, and one parent worked inside the chamber with the child. Detailed instructions about the procedures, but not the experimental hypotheses or previous findings, were given to the parent before the experiment. Then the parent brought the child into the chamber with a toy chosen from a collection outside the chamber. In each trial the parent showed the child the toy, played with it briefly, and then hid the toy behind a corner panel that was designated by the experimenter and shown to the parent before he or she went into the chamber. When the parent judged that the child had seen the hiding of the toy, he or she picked up the child and turned him or her one-half to one full circle with eyes open (oriented search trial, presented first) or four full circles with eyes covered (disorientation trials). While the parent turned the child on disorientation trials, the experimenter walked around the outside of the chamber so as not to serve as a stable cue to orientation and then knocked on the center of a prechosen wall. The parent was instructed to put the child down at the center of the chamber facing the indicated wall and to encourage him or her to retrieve the toy while looking only at the child and not indicating any corner location by pointing or other means. The child might keep searching until finding the toy. If the child failed to retrieve the object after about 2 min of encouragement, the parent indicated the correct corner.

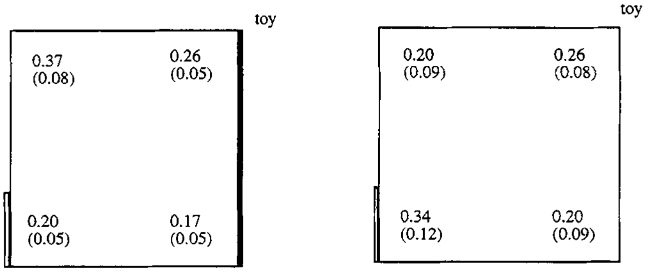
The child and parent left the chamber for a short break between the two test sessions, during which time the experimenter either introduced or removed the red wall. To maintain the child's interest throughout the experiment, breaks could be taken and the toy changed at any time, although the hiding location of the toy remained the same.

Coding and data analysis. An assistant who was naive to the experimental design and hypotheses coded the videotapes after the experiment was completed. First, for both the oriented search and disorientation trials, the coder determined the actual facing position of the child at the point where he or she was released; the facing position was coded as the wall or corner where the child appeared to be looking as soon as he or she stood stably. Second, the coder determined whether or not a trial was valid, excluding trials from the analysis if the parent pointed at one of the corners before the child overtly indicated a search, if the child refused to search for the object, or (for the disorientation trials) if the child was rotated less than two circles or with eyes open most of the time. Finally, the coder determined the location of the child's first search on each valid trial. We determined the child to have searched for the toy if he or she moved one of the panels, opened the bottom of the panel, or pointed at one of the corners and had the parent open it.

Results

Figure 2 presents the mean search rates at the four corners of the chamber for the two disorientation conditions. In the white chamber, the children searched randomly among the corners, $F(3, 21) = 0.43$, $p = .73$, indicating that the disorientation procedure was effective. The children still searched randomly with the red wall present, $F(3, 21) = 1.88$, $p = .16$. Children's search accuracy in the two test sessions did not differ ($t < 1$).

Further analyses investigated the effects of target corners, sex, and order of sessions on the percentage of correct searches on the disorientation trials. The repeated sample analysis of variance (ANOVA) revealed no significant main effects or interactions involving the three factors (all Fs < 3, ps $> .13$). Finally, we analyzed the relationship between the



Red wall

All white wall

Figure 2. The mean proportion of search at each corner in the two disorientation conditions of Experiment 1. Standard errors are given in parentheses.

initial visibility of a corner at the start of a search trial and the child's tendency to search at that corner. If the child faced a wall after disorientation, the immediately visible corners were those adjacent to that wall; if the child initially faced a corner, we counted that corner alone as immediately visible. On average, 76% of searches in the red wall session and 74% of searches in the white chamber session were directed at an immediately visible corner, $t(7) = 3.0, p < .02$, and $t(7) = 2.4, p < .05$, respectively.

A final analysis focused on children's performance on the oriented search trials. Of the 6 children with a valid oriented search trial, 5 (83%) correctly retrieved the toy (with chance = 25%), $t(5) = 3.5, p = .017$. Participants did not confine their search to an immediately visible corner on the oriented search trials ($p = .68$).

Discussion

On the oriented search trials, children found the toy by searching directly the corner at which it was hidden. This finding indicates that the children understood the search task, were motivated to perform it, remembered the object's location, and acted successfully to retrieve the object when in a state of orientation. On the disorientation trials in the white chamber, children searched the four corners randomly, providing evidence that they were disoriented and that no unintended cues from the parent or the chamber allowed them to reorient themselves or find the object. Most important, the children's search did not improve on the disorientation trials in the chamber with the red wall. Their random search suggests that they failed to use the red wall as a directional cue to locate the object after disorientation.

Children's failure to search the corner with the correct relation to the red wall was striking and surprising both to the parents and to the investigators, because children's behavior suggested that they were well aware of the red wall's existence. Many children touched the red fabric, pointed at it, said "red," or tried to remove it. These informal observations suggest that children may detect and remember information about a chamber but fail to use that information to locate objects after disorientation (Cheng, 1986; Hermer & Spelke, 1996).

Alternative interpretations of the findings nevertheless may be offered. Children may have reoriented themselves effectively by the red wall but failed to find the object for other reasons. For example, the disorientation procedure or the passage of time may have led children to forget the object's location or lose interest in the search task. Previous research in a rectangular environment casts doubt on these possibilities, because children subjected to the same disorientation procedure and given the same search task successfully used a different cue—the shape of the chamber—to reorient themselves and find the object (Hermer, 1997; Hermer & Spelke, 1996). Nevertheless, the present study differed from previous studies by its use of a square chamber and a single polarizing cue that specified the child's orientation uniquely. The next experiment distinguished between these two classes of interpretations by presenting children with the disorientation trials of Experiment 1 within a square chamber with a single geometric cue.

Experiment 2

In Experiment 2, we gave a new group of children the task of Experiment 1 in the same square environment, but with a large bump in the center of one wall (geometric cue condition). If children failed to retrieve the object on the disorientation trials of Experiment 1 because of forgetting or lack of motivation, they should also fail to retrieve the object on the disorientation trials of Experiment 2. In contrast, if the failure in Experiment 1 stemmed from limits on children's ability to relocate themselves or objects in relation to nongeometric cues, as suggested by the studies with rats (Cheng, 1986), then children should use the distinctive room geometry and perform better in Experiment 2.

Method

Participants were 16 children (10 boys and 6 girls) aged 18–24 months ($M = 19.6$ months), selected from the same participant population as in Experiment 1. We eliminated 8 additional children (5 boys and 3 girls) from the sample because they failed to complete the session. The apparatus was the same square chamber as in Experiment 1, with the red wall removed and replaced by a single distinctive geometric cue: a 1.8 × 0.7 × 0.25-m projection at the center of that wall (Figure 3). Purple fabric covered both the wall with the projection and the wall opposite to it. Each child received four disorientation trials, following the same procedure as in Experiment 1.

Results

In this experiment, children searched the correct corner on 58% of the trials (Figure 4). Correct search significantly exceeded the chance rate of 25%, $t(15) = 2.8, p = .012$, and

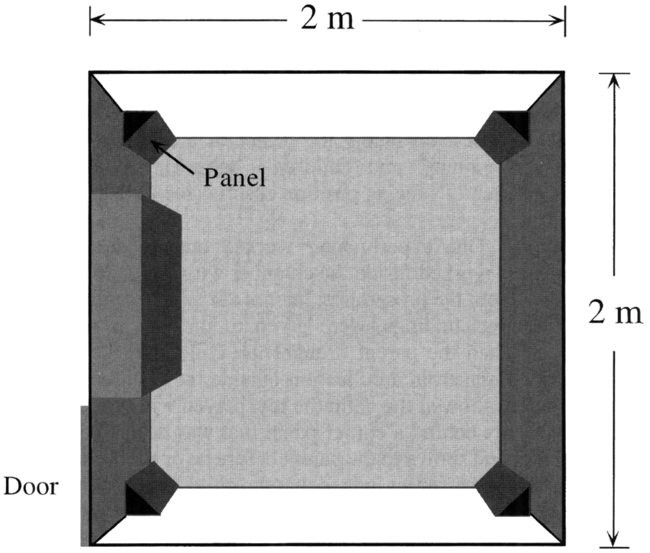


Figure 3. An overhead view of the square chamber with the geometric cue used in Experiment 2. The lights, video camera, and white noise generator are the same as in Experiment 1.

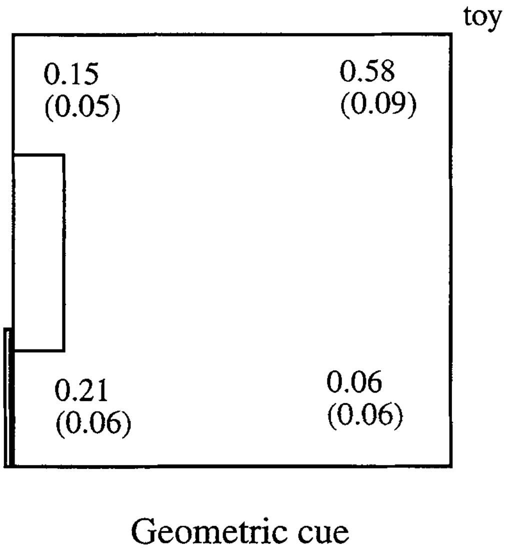


Figure 4. The mean proportion of search (and standard errors) at the four corners in the chamber with a distinctive geometric cue (Experiment 2).

the rate of correct search in the red wall condition of Experiment 1, $t(22) = 2.5, p < .02$. Search accuracy on the disorientation trials of Experiment 2 did not differ from the accuracy on the oriented search trials of Experiment 1, $t(20) = 1.7, p > .1$.

Discussion

In Experiment 2, children who were disoriented in a square chamber with a geometric cue successfully found an object previously hidden at one of the corners. Their successful search provides evidence that the children remembered the object's location over the course of the disorientation procedure, were motivated to find it, and used the geometric cue to locate the object.

Children's successful search on the disorientation trials of Experiment 2 contrasts with their failure on the disorientation trials of Experiment 1. In that experiment, children underwent the same disorientation procedure and performed the same object search task in an environment that was the same in all respects save one: It provided a nongeometric cue (a colored fabric on a wall) instead of a geometric cue (a bulge in the wall). Children's contrasting performance in these two experiments provides evidence that the failure to locate the hidden object in Experiment 1 is not attributable to general limits on motivation or memory but to a specific limit on children's use of nongeometric information to reorient themselves or locate objects.

These findings extend those of previous research on children (Hermer, 1997; Hermer & Spelke, 1994, 1996) and rats (Biegler & Morris, 1993; Cheng, 1986; Margules & Gallistel, 1988) in two ways. First, they provide evidence that disoriented children locate hidden objects not only in relation to the redundant geometric cues provided by a rectangular chamber but also in relation to a single geometric cue: a protuberance in one wall. Second, they provide a focused comparison of the use of geometric and nongeometric information after disorientation. Children's contrasting performance with the two kinds of cues strongly supports the thesis that disoriented children relocate objects by computing the congruence between the perceived and remembered shape of their surroundings.

The present findings cast doubt on one account of the difference between behavioral and neurophysiological studies of disorientation. The activity of place and HD cells in rats has been found to be linked to nongeometric cues under conditions that are very similar to those of the nongeometric cue condition of Experiment 1. In particular, rats tested in a gray square chamber with a white card covering one wall have shown rotations of the fields of their HD cells anchored to rotations of the white card (Taube et al., 1990), even though the geometry of the chamber was the same for the rats as for the children in Experiment 1, and it is unlikely that the salience of the white cue card was higher for the rats than was the salience of the red wall for the children.[1]

We turn next to the second account for the difference between behavioral and neurophysiological studies: Animals use nongeometric cues only when they learn that the cues occupy stable locations in the environment. A salient difference between the experimental paradigm of Hermer and Spelke (1996) and Experiment 1, on one hand, and the paradigms used in most neurophysiological studies, on the other, is that rats in neurophysiological experiments usually receive hours of familiarization training in the experimental chamber before they are tested in a state of disorientation, whereas children and rats in behavioral experiments often use tasks in novel surroundings.[2] Although some experiments suggest that hippocampal neurons establish place fields rapidly in novel environments (Wilson & McNaughton, 1993), it is not clear whether nongeometric cues are encoded during that period. The next experiments therefore investigated whether children would learn to use a nongeometric cue (again, a single red wall in a square chamber) when given sustained exposure to it.

In a preliminary study, we attempted to train 1 child to use

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[1] It might be suggested that the contrasting findings of Taube et al. (1990) and the present experiment stem from the use of a brightness cue in their experiment (walls that were gray vs. white) versus a color cue in the present study (walls that were white vs. red). This possibility cannot account for the discrepancy between behavioral and neurophysiological studies, however, because the behavioral studies by Cheng (1986) and Biegler and Morris (1993) used a brightness cue even more extreme than that of Taube et al. (1990; walls that were white vs. black) and found no evidence for use of the cue. Because rats are colorblind, it obviously makes no sense to use color cues in that species. Because human children are sensitive to color and attentive to it, the color contrast used in this experiment should have enhanced the salience of the nongeometric cue.

[2] In the behavioral studies of Margules and Gallistel (1988), oriented rats were given extensive training in the test environment with nongeometric cues occupying fixed locations relative to the test box. Because the test box was rotated relative to the global environment, however, this training did not indicate that the cues occupied stable positions.

a nongeometric cue by giving him repeated experience with a disorientation test in the square chamber with one red wall. Instead of searching for a hidden object in a fixed corner of the chamber, the disoriented child was asked to find the door of the chamber so that he could go out to find a new toy. This child showed correct search on 2 of the 10 disorientation trials, performance not differing significantly from chance, $t(9) = 0.4$, $p = .71$. Moreover, there was no correlation between success and trial order ($r = .44$, $p > .19$), suggesting no learning effect over the trials. It is possible, however, that 10 trials in one visit were not sufficient for learning. Moreover, the disorientation procedure may have led the child to perceive the red wall as unstable, impairing the child's learning to use it as a directional cue. Indeed, the findings of Knierim et al. (1995; although see Dudchenko, Goodridge, & Taube, 1997) suggest that a nongeometric cue to orientation is more effective if the animal experiences it in a constant location over an extended period of time while in a state of orientation. Accordingly, Experiments 3 and 4 investigated whether children would use a nongeometric cue (the red wall) when that cue was both familiar and stable.

Experiment 3

Children were given a single free play session in a square chamber with one red wall. During this session, they remained oriented and moved between the chamber and the larger environment repeatedly. Then children watched the hiding of an object in the chamber, were disoriented, and were encouraged to find the object.

Method

Participants were 2 boys and 2 girls aged 18 to 24 months ($M = 20.8$ months), selected from the same population as in Experiments 1 and 2. The experiment took place within the same apparatus as the nongeometric cue condition of Experiment 1. Each child first participated in a .5-hr free play session during which he or she was introduced into the test chamber with a parent and was encouraged to play with toys inside the chamber. Every 5–7 min, the experimenter opened the door and led the child out of the chamber for a short break to refresh his or her sense of orientation relative to the outside environment. During the break, the child selected new toys to bring into the chamber. Throughout the familiarization session, music was played from a fixed location outside the chamber to provide an additional directional cue. After the familiarization session, the music was turned off and the child was given four disorientation trials, following the same procedures as in Experiments 1 and 2.

Results

Figure 5 presents the findings of this experiment. The children searched the correct corner of the chamber on 27% of the disorientation trials, performance not differing from chance ($t < 1$). All 4 children searched randomly among the four corners (χ^2s < 5, ps $> .25$).

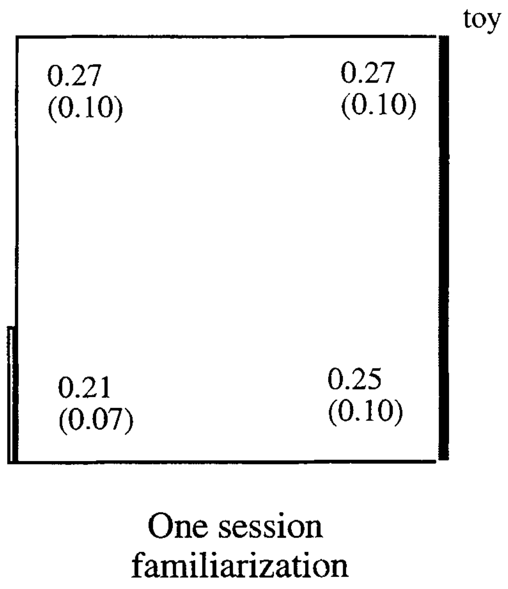


Figure 5. The mean proportion of search (and standard errors) at the four corners on the disorientation trials after the children had one free-play session in the chamber (Experiment 3).

Discussion

After a single play session in which children repeatedly entered and departed from the test environment, children still failed to use a nongeometric feature of that environment to guide their search for a hidden object. This finding suggests that children fail to use nongeometric information even in familiar environments, but that suggestion must be qualified in two ways. First, it is possible that one .5-hr session with five visits to the chamber is not sufficient for learning that the red wall occupied a stable location. Second, the play session with toys, designed to resemble rats' scavenging session with food pellets in the experiments of Taube et al. (1990) and Knierim et al. (1995), might have drawn children's attention away from the red wall.

To test further the effect of familiarization of the red wall on object localization, we conducted a final experiment in which four children were familiarized with the chamber over multiple sessions and in which they played games designed to focus attention on the chamber and its nongeometric landmarks. One game in particular drew the children's attention to the fixed location of a hidden object seen from multiple perspectives and served as a basis for testing children's object localization after disorientation.

Experiment 4

Four children participated in a study in the square chamber with one red wall. The children made multiple visits to the laboratory during a 3-week period, accumulating 2.5 hr of familiarization with the environment. During these sessions, the children searched for hidden objects and played games with the red wall while remaining oriented to the environment. During two final visits, the children received the disorientation test trials of Experiment 1 with the red wall present. If children learn to use a nongeometric cue when it is familiar and stable, then they should have been able to find the toy on these test trials.

Method

Participants were 3 girls and 1 boy, aged 19.0 to 25.2 months (M = 22.4 months) at the beginning of the study. The children had no reported medical problems and had never participated in any related research. The apparatus was the same square chamber with one red wall as in Experiments 1 and 3.

The procedure was explained to the children's mothers in detail, but the mothers were not informed about the research design or hypotheses until the experiment was completed. During the familiarization period, each child was given a series of oriented search trials similar to those of Experiment 1. A variety of toys were introduced to the mother and child, and the mother hid a succession of different toys at a single test corner, picked up the child, knocked at the red wall to draw the child's attention to it, and then turned the child up to two circles without covering his or her eyes. Then she put the child down in the center of the chamber facing a wall indicated by the experimenter, and she encouraged the child to find the toy. These trials were interspersed with other games designed to enhance the child's interest in the environment, including a ball game played in the chamber, and a naming game in which the mother knocked at the red wall and encouraged the child to say "red." At no time during these familiarization sessions was the child turned with eyes closed or otherwise disoriented. Breaks were taken about every 10 min, during which the child left the chamber and chose new toys for the hiding game.

After the familiarization procedure, each child was given the standard disorientation trials of Experiments 1–3. In addition, 3 of the 4 children were given a new test of the child's ability to learn a direct response to the red wall in a disorientation condition: a new "music wall" game. The experimenter put a xylophone behind the red wall outside of the chamber and asked the mother to knock at the red wall. While she knocked, the experimenter played notes on the xylophone. Then the mother lifted the child, covered her eyes and rotated her for at least four circles to disorient her. After the child was put down facing a wall indicated by the experimenter, the mother asked her "where's the music?" If the child tapped the red wall and only the red wall, the experimenter again presented the xylophone music.

The first child (a girl) visited the lab three times during the first week and two times during a second week, with a 1-week pause between the two blocks of visits because of a family vacation. During the first three visits the child and mother played games in the room, and the child received a total of 16 valid oriented search trials. In all, the familiarization sessions lasted a total of 155 min. The fourth visit consisted of four music game trials, followed by seven disorientation trials. Finally, the fifth visit consisted of six disorientation trials.

The second child (a boy) had four familiarization sessions including a total of 16 oriented search trials, followed by two test sessions including three disorientation trials (session 5), and five disorientation trials (session 6). The third and fourth children (both girls) had three familiarization sessions that included a total of 10 oriented search trials, a fourth session that consisted of two oriented search trials followed by six to eight disorientation trials, and a fifth session that consisted of five to six music game trials.

An assistant who was unaware of the experimental hypotheses reviewed the videotaped records of all sessions. The assistant determined the child's facing position, eliminated invalid trials, and determined the position of the child's first search on every oriented search, music, and disorientation trial, following the criteria for Experiment 1.

Results

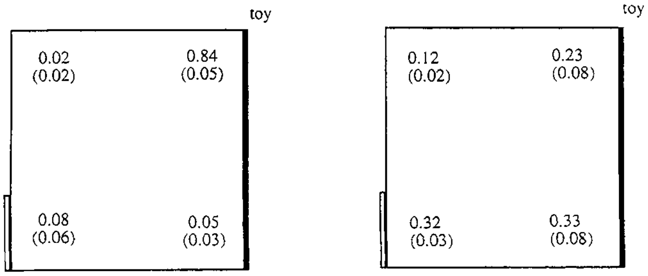
The principal results for this experiment appear in Figure 6. For the oriented search trials, each child successfully retrieved the toy (mean accuracy = 85%, ts > 5.0, ps $< .004$). For the disorientation trials, in contrast, none of the children retrieved the toy with above-chance accuracy (mean accuracy = 23%, ts < 0.7, ps $> .51$). All children searched among the four corners randomly (χ^2s < 3.3, ps $> .34$). All 3 children who were given the music game trials successfully tapped on the correct (red) wall (mean accuracy = 94%, ps $< .017$). Overall, search accuracy on both the oriented search trials and the music trials was significantly higher than on the disoriented trials, oriented search paired $t(3) = 5.8, p = .01$; music paired $t(2) = 6.1, p = .026$.

For the 2 children who received disorientation trials on two successive visits, a further analysis compared changes in search performance over the two test sessions. For the girl, performance dropped nonsignificantly from 43% to 17%, $t(11) = 1.0$, $p = .35$. For the boy, performance increased nonsignificantly from 0% to 60%, $t(6) = 1.8, p = .12$. No significant changes occurred across both children, $F(1, 16) = 1.30, p = .33$.

Discussion

Experiment 4 provided no evidence that familiarization with a stable nongeometric landmark allows children to use the landmark to reorient or relocate objects. In this experiment, the children spent nearly 3 hr running around and playing in the square chamber with one bright red wall. During that time, they watched their mother knocking on the red wall dozens of times, and they were encouraged to talk about the red wall. Moreover, 3 of the children learned to play a game in which they were disoriented and then immediately turned to the red wall and knocked on it to make music. Despite all this experience with the room and its nongeometric landmark, the children never learned to use the red wall to locate the hidden toy.

In contrast, the children successfully found the toy when they were tested in a state of orientation. This finding, combined with children's success in Experiment 2 and in previous research (Hermer & Spelke, 1996), suggests that



Oriented search

Reorientation

Figure 6. The mean proportion of search (and standard errors) at each corner in the familiarization sessions (oriented search trials) and the test sessions (disorientation trials) of Experiment 4.

their failure with the red wall does not stem from limits on memory of toy locations; motivation to search for the toy; ability to notice, remember, and respond to the red wall itself; or ability to understand and perform the task. Rather, the failure seems to reflect an inability to use a nongeometric cue to relocate objects after disorientation.

The findings of Experiments 3 and 4 contrast with those of Knierim et al. (1995) and Dudchenko, Goodridge, and Taube (1997) by showing no learning effect on children's performance in an environment with a stable, salient nongeometric cue. Although different results might be obtained in an experiment with a longer period of familiarization with nongeometric landmarks, or in an experiment with older children who have a more mature hippocampus, these findings suggest that degree of familiarity of the test environment does not account for the difference between behavioral and neurophysiological studies of disorientation and object search.

General Discussion

In the present studies, disoriented children aged 18–24 months failed to use a distinctively colored wall to locate an object in a square chamber, even after they were familiarized with the chamber over multiple sessions. In contrast, disoriented children did use a distinctive geometric cue to locate the object when tested under the same conditions. These findings provide further evidence that disoriented children, like rats, rely on geometric but not nongeometric information to locate objects (Cheng, 1986; Hermer & Spelke, 1994, 1996).

The present results could be explained in two different ways. One explanation proposes that children followed a *reorientation strategy* for locating the object: After disorientation, they first reestablished their sense of orientation and then localized the object whose position had been encoded in the same framework. The other explanation proposes that children followed an *associative learning strategy* for locating the object: They directly encoded and retrieved the spatial relationship between the hidden object and one or more features of the chamber. We discuss each potential explanation in turn.

Cheng and Gallistel were the first to propose that disoriented rats use a reorientation strategy to locate objects in a stable environment (Cheng, 1986; Margules & Gallistel, 1988). In their experiments, rats searched for food in the correct relationship to the shape of the room, but not in the correct relationship to the room's nongeometric properties, after only minutes of exposure to the room and the target. In other experiments, rats have been found to learn to locate objects in relation to nongeometric landmarks, but this ability either required weeks of training in which the landmarks and the goal move together from trial to trial (e.g., Dudchenko, Goodridge, Seiterle, & Taube, 1997; O'Keefe & Speakman, 1987) or showed incomplete learning, with rats learning to search for the goal near the landmark but not in a specific place relative to it (Biegler & Morris, 1993, 1996). In view of this contrast, Cheng and Gallistel proposed that rats preferentially locate objects by encoding their geocentric positions. When rats are disoriented, therefore, they locate objects by first reorienting themselves and then returning to the objects' geocentric positions. Specifically, reorientation depends on a process for aligning a representation of the remembered shape of the environment with its currently perceived shape, irrespective of its nongeometric properties.

Several predictions follow from the thesis that disoriented children use a reorientation strategy to locate objects in a stable environment. First, disoriented children should search for objects in correct relation to the shape of the environment and not in correct relation to nongeometric landmarks. These findings have been confirmed in numerous studies (Hermer, 1997; Hermer & Spelke, 1994, 1996; Hermer-Vazquez, 1997), including the present one.

Second, children should use geometric cues to locate an object after minimal exposure to the chamber and the object, whereas they should learn a relationship between a hidden object and a nongeometric landmark only after extensive exposure. Both Experiment 2 of the present series and experiments by Hermer and Spelke (1994, 1996) provide evidence that children learn to use geometric information after very brief exposure to the object and environment. In addition, research by Hermer-Vazquez (1997), testing children with a method similar to the method Biegler and Morris (1993, Experiment 1) used, provides evidence that children fail to learn to locate a movable hidden object in a constant relation to a movable landmark over the course of one test session. Like rats (Biegler & Morris, 1993, 1996), the children learned that the target was near the landmark but not that it bore a specific spatial relationship to it.

A third prediction follows from the hypothesis that children use a reorientation strategy in our experiments: When a child is reoriented by a geometric cue, he or she should be able to localize all invisible environmental features in coherence, even if they are not specifically learned as targets. Hermer (1997) tested children 3–4 years old in the same reorientation task as in the current studies, except that the children learned two target locations in a rectangular chamber with a blue wall. When asked to indicate the two targets and the door of the chamber after disorientation without feedback, they indicated the correct locations and the geometrically equivalent, opposite locations with equal frequency, suggesting that they located each target in relation to the room geometry but not the wall color. More important, children's representations were coherent: If one target was localized 180° displaced from its true location, so were the other targets and the door. The simplest interpretation of these findings is that children used reorientation strategy to locate the hidden targets and reoriented by the shape but not the color of the environment.

Finally, the reorientation hypothesis predicts that disoriented children will rely on geometric information when searching for objects in a stable environment but that oriented children will not rely on this same information when objects move. Hermer and Spelke (1996) tested and confirmed this prediction in three experiments. In one study, for example, children watched a toy hidden in one of two distinctively colored and patterned boxes placed in two adjacent corners of a rectangular chamber with no other distinctive landmarks. Then the children's eyes were closed and the boxes were moved quietly across the chamber, so that the geometric and nongeometric properties of the hiding locations were dissociated (e.g., if a pink striped box previously appeared in a corner with a long wall on the left, that box now appeared in a corner with a long wall on the right). In one condition, children were disoriented while the boxes moved. In the other condition, children remained oriented (with eyes closed) during this time. Children who were disoriented searched primarily at the corner box in the correct geometric configuration, ignoring that box's incorrect nongeometric properties. In contrast, children who were oriented first looked at the boxes' former positions (now visibly empty corners), then located the boxes on the other side of the chamber and searched the box with the correct nongeometric properties, ignoring its new geometric configuration. This double dissociation is striking, because children in the two conditions viewed exactly the same environment during encoding and testing, and they were given the same search task. Those findings provide clear evidence for a linkage between the use of geometric information and disorientation, in accord with the reorientation hypothesis.

The hypothesis that rats and children use a reorientation strategy faces two difficulties. First, it does not account for the findings of two very recent behavioral studies, focusing on learning to escape to a hidden platform (Dudchenko, Goodridge, Seiterle, & Taube, 1997; Martin, Harley, Smith, Hoyles, & Hynes, 1997). In Dudchenko et al.'s studies, disoriented rats successfully located the platform in relation to a nongeometric landmark with little training, even though they failed to locate food in relation to a nongeometric cue when tested in a very similar environment. Dudchenko, Goodridge, Seiterle, & Taube (1997) proposed that rats reorient by nongeometric information in both foraging and escape tasks but that the disorientation procedure to which they are subjected impairs either memory or motivation selectively, allowing the animals to use information about the location of a safe haven but not information about the location of food. If that interpretation is correct and applies to humans, then it supports the associative learning hypothesis, to be discussed below, and casts doubt on the view that children's search errors in the present studies stem from limits on their ability to reorient by nongeometric cues.

The second difficulty faced by the reorientation hypothesis comes from the findings of neurophysiological studies of place and HD cell activity. As discussed before, the place and HD cell system uses nongeometric information even when rats are disoriented, suggesting that the system has "reoriented itself" according to the nongeometric cues. Most dramatically, HD cell activity provides evidence for reorientation in accord with a nongeometric cue when rats are tested in the very same environment in which they fail to use this cue to guide their search behavior (Dudchenko, Goodridge, Seiterle, & Taube, 1997; Dudchenko, Goodridge, & Taube, 1997). As many investigators have noted, however, alternative interpretations of place and HD cell activity are possible. For example, these cells may capture richer information about the environment than animals typically use in order to reorient themselves and return to stable locations. Within the neurophysiological literature, numerous findings are consistent with this suggestion. For example, place cells have been found to show directional specificity in many environments (Gothard et al., 1996; O'Keefe & Burgess, 1996). Place cell activity also typically changes dramatically when an animal performs a new task in an unchanging environment (Wiener, Paul, & Eichenbaum, 1989). Place and HD cell activity is affected by the movements of behaviorally significant landmarks even when those movements occur in the animal's presence (Gothard et al., 1996; Taube & Burton, 1995; Taube et al., 1990). Because it is unlikely that a rat represents a change in its position when it changes direction, starts a new task, or views a moving pattern, these findings suggest that place and HD cells do more than record an animal's sense of its own position and heading. When an HD cell rotates with rotation of a nongeometric cue, therefore, it may be encoding a change in the environment rather than a change in the animal's sense of orientation.

We turn now to the alternative account of disoriented children's performance in object search tasks, whereby their search depends on an associative learning strategy. According to this account, both oriented and disoriented participants locate targets by drawing on knowledge of the spatial relationship between the target and relevant cues. If disoriented rats used this strategy, then the findings of the experiments of Cheng (1986), Biegler and Morris (1993), and others would imply that rats encode and use the relationship of a target to a geometric cue easily and readily but encode and use the relationship of a target to a nongeometric cue only with difficulty. Those who accept this hypothesis are free to interpret the activity of place and HD cells as pure reflections of the animal's global sense of position and orientation. By this interpretation, animals compute their own sense of orientation according to a set of landmarks and reorient themselves accordingly when the landmarks move. Failure to locate a hidden object does not stem from a failure of reorientation, on this view, but from a failure of learning about or remembering the target's position in relation to those landmarks. This version of the associative learning hypothesis provides a natural explanation for the finding that rats' localization of objects is affected by task and motivational factors (Dudchenko, Goodridge, Seiterle, & Taube, 1997): When rats are disoriented in a foraging task or an escape task, they may use all the available cues in the chamber to reorient themselves (as suggested by their HD cell activity). Those cues may be associated with the escape platform more strongly than they are associated with the food location, however, and so they may guide the rat's behavior in an escape task but not in a foraging task.

The associative learning hypothesis can explain various findings from studies of children. Children used geometric cues and not nongeometric cues to locate an object after disorientation, because they encoded the relationship of the object to the shape of the room but not its relationship to nongeometric landmarks. Children learned to use geometric cues immediately because they encoded that relationship readily. Moreover, children located multiple targets coherently, because they encoded the spatial relationships among the targets. Finally, children used the red wall to locate the music after disorientation, because they encoded that relationship. When a target has a directly visible nongeometric feature (e.g., the red music wall in Experiment 4), children can find the target easily by searching for that feature.

Nevertheless, the hypothesis that children followed an associative learning strategy faces difficulties. First, in the current Experiments 1 and 4, children succeeded in finding the object when they were in a state of orientation. If the red wall allowed the children to reorient, then it is not at all clear why children should succeed at finding the object when oriented but fail when disoriented and reoriented. Second, if children can immediately encode and use the spatial relationship between two targets, between the targets and the door (Hermer, 1997), and between the target and the wall with a bulge (current Experiment 2), it is not clear why they should fail in encoding and using the spatial relationship between a target and a colored wall, which is exactly the same spatial relationship as in the case of the bulged wall.

Third, when children found the target in relation to the nongeometric feature, the coherence reported by Hermer (1997) for geometric reorientation did not occur. In Experiment 4, the first girl looked for and acted on the red wall to make music but then failed to locate the hidden object in correct relation to the red wall or to the music on her first disorientation trial. The child's behavior on this trial was quite revealing. Immediately after disorientation, the child ran to the red wall, banged it, and looked puzzled when no music ensued. When asked for the toy, she then searched in the opposite corner from the correct one. Therefore, even when this child succeeded in using the red wall–music relationship, she did not search coherently at multiple locations in relation to the nongeometric landmark. The lack of coherence between use of the red wall in the music task and in the disorientation task, which we replicated with the two other participants who were given both tasks, calls into question any explanation of children's performance based on general limits to children's learning or memory.

Finally, the associative learning hypothesis fails to explain why children used one set of relationships (involving nongeometric cues) to find an object when they were oriented and a different set of relationships (involving the geometric configuration) to find the same object, in the same environment, when they were disoriented (Hermer & Spelke, 1996). These differences cannot be explained by task factors at the time of encoding or search, because the environments and search tasks were exactly the same for the oriented and disoriented children. Indeed, the methods and procedures of the two conditions were identical except for the presence or absence of disorientation.

These difficulties do not rule out the hypothesis that children used an associative learning strategy. As earlier debates over associative models of spatial memory have shown (cf. Tolman, 1948), the associative learning hypothesis can always be amended so as to provide a post hoc account of any findings. Simple versions of this account, however, do not appear to be compatible with the evidence from studies of children.

However one interprets the findings of behavioral studies of disorientation, these studies provide evidence for striking similarities between the performance of adult rats and young humans. The similarities suggest that reorientation and object localization depend on homologous mechanisms in the two species. Moreover, although the hippocampus is not fully mature in 2-year-old children, the similarities suggest that basic, mammalian mechanisms of navigation and spatial memory are present. If these suggestions are correct, then continued study of these systems across species and across development, using the widening array of tools of cognitive neuroscience, holds considerable promise for revealing these mechanisms and their interrelations.

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