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Children's use of geometry and landmarks to reorient in an open space

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Abstract

Eight experiments tested the abilities of 3–4-year-old children to reorient themselves and locate a hidden object in an open circular space furnished with three or four landmark objects. Reorientation was tested by hiding a target object inside one of the landmarks, disorienting the child, observing the child's search for the target, and comparing the child's performance to otherwise similar trials in which the child remained oriented. On oriented trials, children located the target successfully in every experiment. On disoriented trials, in contrast, children failed to locate the object when the landmarks were indistinguishable from one another but formed a distinctive geometric configuration (a triangle with sides of unequal length or a rectangle). This finding provides evidence that the children failed to use the geometric configuration of objects to reorient themselves. As in past research, children also did not appear to reorient themselves in accord with non-geometric properties of the layout. In contrast to these findings, children successfully located the object in relation to a geometric configuration of walls. Moreover, adults, who were tested in two further experiments, located the object by using both geometric and non-geometric information. Together, these ten experiments provide evidence that early-developing navigational abilities depend on a mechanism that is sensitive to the shape of the permanent, extended surface layout, but that is not sensitive to geometric or non-geometric properties of objects in the layout. © 2001 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

Any animal who is disoriented must be able to reorient itself by comparing features of its immediate surroundings to known places in the environment. In certain situations, both rats and humans reorient themselves primarily by analyzing the shape of the surrounding layout. For example, rats and human children who are disoriented in a rectangular chamber with a single wall of a contrasting color or brightness use the shape of the room to reorient themselves up to the 180-degree ambiguity imposed by the room's symmetry, but they fail to use the color or brightness of the distinctive wall to resolve this ambiguity and reorient themselves correctly (Cheng, 1986; Hermer & Spelke, 1994, 1996; see also Biegler & Morris, 1993, 1996; Dudchenko, Goodridge, Seiterle, & Taube, 1997; Stedron, Munakata, & O'Reilly, 2000; Wang, Hermer-Vazquez, & Spelke, 1999). In contrast, adult humans and non-human primates are able to use both types of spatial information (Gouteux, Thinus-Blanc, & Vauclair, 1999, in press; Hermer & Spelke, 1994, 1996). Because both rats and children are able to detect, remember, and use the wall coloring in other spatial memory tasks (see Biegler & Morris, 1993; Dudchenko et al., 1997; Gallistel, 1990; Hermer & Spelke, 1996; Wang et al., 1999), these findings suggest that reorientation depends in part on a phylogenetically and ontogenetically primitive system of representation that is sensitive only to a subset of the environmental information that many navigating animals detect and remember.

In the present research, we attempt to characterize the type of information to which the reorientation system is, and is not, sensitive. Although Cheng (1986) and Gallistel (1990) have described the reorientation system as a "geometric module", their research already suggested that this system is not sensitive to all geometric information. In the Cheng (1986) experiments, rats reoriented in accord with the three-dimensional shape of the test chamber, but they failed to reorient in accord with the two-dimensional shape of surface markings that distinguished different corners of the chamber. Similarly, the children in Hermer's experiments (Hermer, 1997; Hermer & Spelke, 1996) failed to reorient by the distinctive geometric patterning on the boxes in the corners of the testing room where a salient object was hidden, and those in the Stedron et al. (2000) experiments failed to reorient by the distinctive patterning on posters that decorated the room's walls. Moreover, children successfully reoriented themselves in a square room when a bulge in one wall broke the room's symmetry, but they failed to reorient themselves when that wall served as the background for a tall, movable object of similar dimensions to the bulge (Hermer, 1997; Wang et al., 1999). Although these two environments would receive very similar representations in a purely geometric description of the complete surface layout, the reorientation system evidently was sensitive to the information in one environment but not in the other.

One interpretation of these findings is that children, and perhaps other animals, reorient primarily in accord with the shape of the permanent surfaces in the layout (e.g. walls, cliffs, valleys, the ground), ignoring non-geometric properties of the layout (e.g. wall coloring) and geometric properties of surface markings and movable objects (e.g. object shapes and positions). Nevertheless, no experiment has directly compared children's sensitivity to the geometrical relationships among objects to their sensitivity to the geometrical relationships among permanent features of the layout, and so it is possible that other aspects of the experiments account for children's successes and failures.

In particular, the studies showing that children reorient to layout geometry have presented children with a continuous spatial layout that surrounds them, whereas the studies showing that children do not reorient to the geometry of objects have presented one or two objects or geometric patterns in widely separated locations. Therefore, it is possible that the system of reorientation is capable of representing and using geometrical relationships among objects when multiple objects encircle the child, such that their geometrical relationships are detectable from any direction. Alternatively, the reorientation system may represent and use geometric relationships only when the configuration of landmarks is connected.

Here we report ten experiments that were undertaken to investigate these possibilities. The first eight experiments were conducted with 3–4-year-old children, an age at which the children studied in past research have shown robust reorientation in accord with surface geometry but no reorientation in accord with indirect landmarks (Hermer, 1997; Hermer-Vazquez, Moffet, & Munkholm, 2001), and used the same method as in that research. Children were disoriented inside a cylindrical environment furnished with three or four large and salient objects or layout features (walls or corners). In Experiments 1–4 and 6, children were presented with three objects in an asymmetrical configuration that, in principle, specified their position and heading unambiguously. In Experiment 5, four objects were placed in the same symmetrical positions as the four corners of the rectangular room used in the Hermer and Spelke (1996) experiments, and so their geometrical arrangement specified the child's position and heading up to an 180-degree ambiguity. Experiments 7 and 8 presented a similar, ambiguous rectangular arrangement of spatially separated walls or corners rather than objects. Distinctive non-geometric information was presented in Experiments 2 and 6, along with the distinctive geometric configuration of objects. In all the experiments, children first were led to the middle of the geometric configuration, they hid a toy in one landmark object, they were then disoriented while remaining in the middle of the configuration, and finally their ability to reorient themselves was tested by encouraging them to find the hidden toy. In Experiments 9 and 10, adults were tested under the conditions used with children in Experiments 1 and 5.

If humans reorient by a pure geometric module, then the children should have reoriented successfully in all these experiments. In contrast to this prediction, children failed to reorient by the geometrical arrangement of the objects in any experiment. Children also failed to reorient by the non-geometric information, although they did learn a direct association between a target location and features of its container. In contrast, children successfully reoriented by the spatially separated walls of the room, and adults performed successfully under all conditions tested. Therefore, our findings accord with the findings of Hermer and Cheng: they provide evidence that preschool children reorient only in accord with the geometry of the extended surface layout, whereas adults reorient more flexibly.

2. General method

All the experiments took place in a cylindrical testing space surrounded by curtains and containing no obvious landmarks except for those on which an experiment focused. In Experiments 1–6, 9, and 10, the critical landmarks were boxes, in various arrangements, in which a target object could be hidden. In Experiments 7 and 8, the critical landmarks were boxes and walls or corners that partially enclosed the rectangular space within which the object was hidden. For the studies with children, participants were 3–4-year-olds whose parents had volunteered for research in an infant laboratory. In past research, children of this age have been found to reorient in accord with the shape of the testing room and not in accord with the room's non-geometric properties (Hermer, 1997). For the studies with adults, participants were university students.

Children's and adults' reorientation ability was tested through a procedure adapted from Cheng (1986) and Wang et al. (1999). First, subjects were allowed to explore the environment and its landmarks. Then they were asked to hide an object in one of the landmark boxes, and they retrieved the object on two kinds of trials. On oriented search trials, they retrieved the object after turning four times in place with their eyes open, a control condition that probed whether children remembered where they had hidden the object, were motivated to search for it, and could find it from a novel facing direction. On disoriented search trials, participants retrieved the object after turning four times in place with their eyes closed, a condition that has been found to induce a state of disorientation in children of this age (Hermer, 1997). If children and adults were able to use the configuration of landmarks to reorient themselves, they were expected to find the toy directly on the disoriented trials. Based on past findings, participants also were expected to find the toy directly on the oriented trials (Wang et al., 1999).

The ten experiments to be reported were conducted in five testing sessions with four different groups of children (Experiments 1–8) and one group of adults (Experiments 9 and 10). Within a testing session, two experiments were presented in a counterbalanced order, such that about half the subjects participated first in Experiments 1, 3, 5, 7, or 9 and half participated first in Experiments 2, 4, 6, 8, or 10. If a subject completed one of the experiments but not the other, his or her data were included in the completed experiment.

3. Experiment 1

In the first experiment, children were tested in the open space with three indistinguishable landmark objects, placed so as to form a right triangle whose sides were of unequal length and whose center coincided with the center of the space (Fig. 1). After hiding the target object inside one of the landmarks, children stood in the center of the triangle surrounded by the objects, turned in place, and then searched for the object in a state of orientation (one trial) or disorientation (three trials). If children could remember where they hid the object and localize it from a new facing direction, they were expected to find it directly on the oriented trial. If children could use the geometric configuration of the landmarks to reorient themselves, then they also were expected to find the object on the disoriented trials.

3.1. Method

3.1.1. Subjects

Participants were five boys and four girls ranging in age from 3.1 to 4.2 years (mean age 3.8 years). One additional subject was eliminated for failure to complete at least three valid test trials. Subjects were recruited from birth announcements for studies in an infant laboratory, and they visited the laboratory with a parent. They were all born of full-term pregnancies and suffered from no known health problems.

3.1.2. Apparatus

Subjects were tested in a circular open space (diameter, 3 m) surrounded by tan curtains that hung from the ceiling of a large, windowless experimental room with no obvious sources of noise. The curtains were attached together with small binder clips that were hidden within the multiple, regular folds of the curtain when viewed from inside the room; the curtained enclosure therefore appeared to consist of a continuous circular environment. The floor of the testing space was covered with a homogeneous gray carpet. To enter this experimental environment, the experimenter and the child passed under one of the curtains. The experimental environment

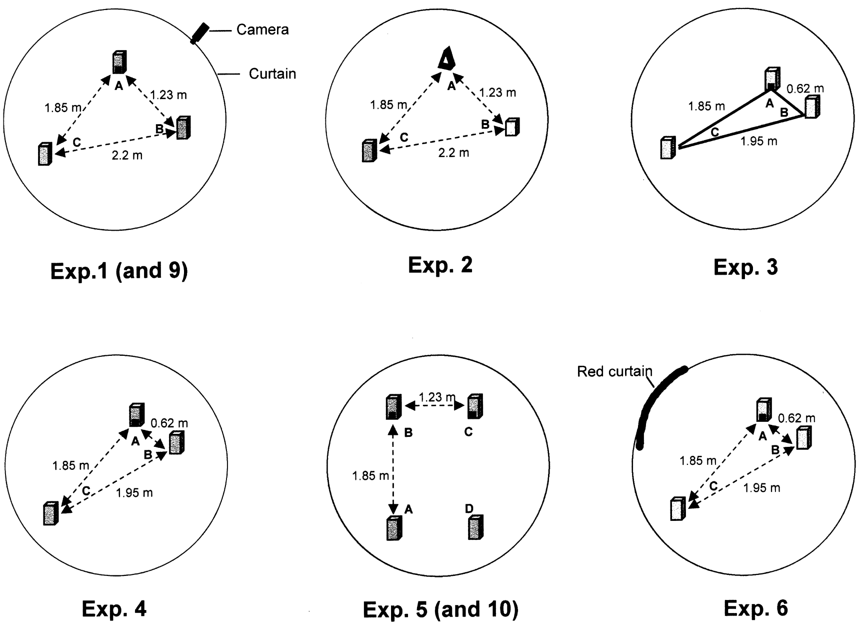

Fig. 1. Overhead view of the testing space with the locations of the different boxes (A–D) for Experiments 1–6, 9, and 10.

was completely isolated from the outside environment and provided no obvious landmarks.

Three indistinguishable rectangular purple plastic boxes ($1 \times 0.5 \times 0.3$ m) were placed in the experimental environment. Each box had a small opening on its front side (0.15×0.15 m) covered by a purple cloth, through which a toy could be hidden inside the box. The three boxes were arranged in a $1.23 \times 1.85 \times 2.22$ m right triangle in the center of the testing space, with each box facing into the center of the triangle (Fig. 1, Experiment 1). The open space was illuminated by one 100 W centrally-placed light fixed on the ceiling of the room. A video camera was mounted inconspicuously between two curtains, 2 m above the floor, to provide an overhead view of the open space, which was monitored on a VCR outside the testing space. A small plastic (7×7 cm) drawing of a smiley face served as the object for which children searched.

3.1.3. Design

Each child was given one oriented and three disoriented search trials. On each trial for a given child, the object was hidden in a different box. The sex of the subjects, the order of three hiding locations on the disoriented trials, and the order of the trials (oriented trial before vs. after disoriented trials) were orthogonally counterbalanced across subjects. The facing position of the subject at the end of the disorientation procedure varied from trial to trial and was randomly determined with the restriction that approximately equal numbers of trials ended with subjects facing between each pair of boxes. Nevertheless, variations in parents' and children's behavior precluded our controlling the child's facing position exactly.

3.1.4. Procedure

For most children, the experiment was conducted by an experimenter, who stood inside the testing space with the child. On rare occasions when a child was not cooperative, the child's parent also entered the space and helped to run the experiment. In that case, the procedure of the study was explained to the parent, who was not informed of the present hypotheses or of the findings of previous studies with similar tasks, and who was directed to change position during the study so as not to serve as a reorientation cue. On entering the testing space, the child freely explored for 5 min. During this time, he or she was encouraged by the experimenter to look into each of the three boxes. Then the experimenter told the child to hide the smiley face in a designated box and then to point to the box containing the object. If the child failed to point to the box, the experimenter retrieved it and the child hid it again in the same box. After the child clearly indicated the correct box, he or she was asked either to turn four full circles with eyes opened (oriented trial) or to cover his/her eyes with his/her hands and to turn four full circles (disoriented trials). During these trials, the experimenter walked around the subject at varying speeds so as not to serve as a landmark. Then the child was asked to stop turning by the experimenter, who continued walking around slowly so as not to cue him or her to any possible location. If a child failed to keep his/her eyes covered during the disorientation procedure, the procedure was stopped, he or she was encouraged to cover her eyes, and the procedure began again. When the child was facing in the predetermined direction, he or she was instructed to open his/her eyes and to search for the smiley face. The child was allowed to keep searching until he or she found the toy but was encouraged to retrieve it on the first choice. Analyses of the oriented control trials suggest that children were highly motivated to retrieve the object on the first try, even though they had the option of searching successively at multiple locations (see below). Once the child retrieved the smiley face, the experimenter took it and asked the child to hide it in a new location to begin the new trial.

3.1.5. Coding and data analysis

An assistant who was naive to the experimental design and hypotheses coded the videotapes after the experiment was completed. This coder determined that a trial was valid if the child made the correct number of turns with eyes closed or opened, depending on the trial condition. The coder considered a subject to have searched for the smiley face in a given box when the child touched the cloth opening of that box, regardless of whether the child successfully retrieved the object. (The object was retrieved successfully on most of these trials.) All analyses focused on the location on the subject's first search on each search trial.

3.2. Results

Fig. 2 (left) presents children's search performance during the three disoriented test trials of Experiment 1. The search patterns did not differ from chance (one-sample *t*-test, $t(8) < 1$), indicating that subjects' searches were conducted at

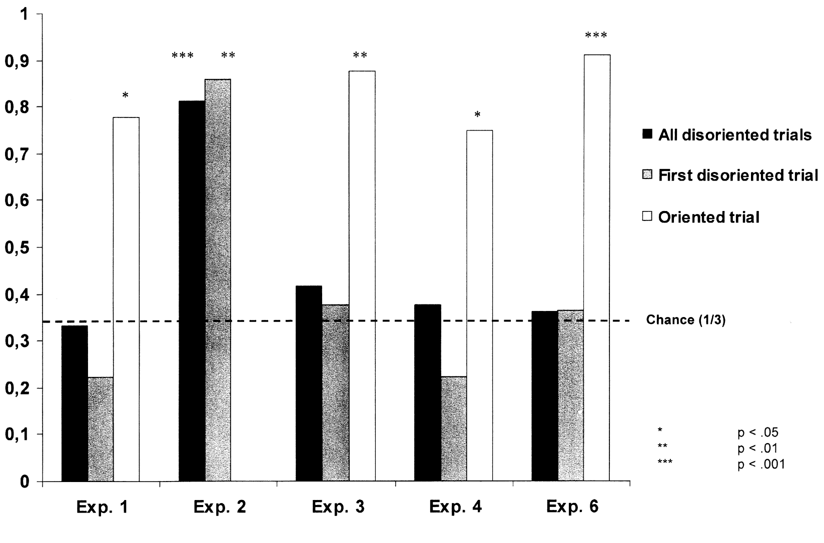

Fig. 2. Proportion of correct responses over all the disoriented trials (black bars), on the first disoriented trial (gray bars), and on the oriented trial (white bars) for the experiments with children tested with three search locations (Experiments 1–4 and 6).

random. Search patterns also were random if one considers only the first disoriented trial ($P > 0.2$, binomial test).

Fig. 2 also presents children's search performance during the single oriented trial. Children searched in the correct container significantly more than expected by chance ($P < 0.05$, binomial test), indicating that they remembered where the toy was hidden and were able to keep track of that location as they turned.

3.3. Discussion

On the disoriented trials, children failed to search the correct box on their first attempt to find the object. Their chance search patterns suggested that they failed to use the spatial relationship between the three boxes to locate the object after disorientation. These results also indicated that our disorientation procedure was effective, and that no other landmark (such as subtle sounds, odors, or the inconspicuous camera) allowed children either to maintain or to reestablish their orientation in our experimental environment: if any external and/or internal cue had been used, the children would have been able to locate the target without ambiguity. Finally, children's accurate search patterns on the oriented trial indicated that they were able to perceive and remember the object location and return to that location after turning to face in a new direction. These findings suggest that the object search task was appropriate for children and that the turning procedure used to disorient them did not disturb their cognitive functioning in extraneous ways (for further evidence that this disorientation procedure does not disturb children's memory for the environment or reduce their motivation to find a hidden object see Hermer, 1997; Hermer & Spelke, 1996).

Children's failure to search in the correct box was striking and surprising both to the parents and to the investigators, because their behavior suggested that they were trying to retrieve the hidden object on their first choice. After disorientation, children typically looked around before choosing a box to visit – they did not simply rush to the nearest box. After looking into an incorrect box, moreover, many children reacted with disappointment or surprise and returned to that box to verify that the smiley face was not there. These informal observations suggest that disoriented children believed erroneously that they knew where the toy was hidden.

Experiment 1 indicates that children failed to reorient themselves and locate the toy in accord with the geometric arrangement of the boxes, even though they succeeded in locating the toy when they remained oriented. These findings suggest that children failed to reorient by the geometrical configuration of the boxes, but other interpretations are possible. In particular, it is possible, despite our informal observations and analyses of other strategies, that the disorientation procedure diminished either children's memory for the object location or their motivation to retrieve the object. The next experiment investigated these possibilities by presenting the same reorientation task as in Experiment 1, under a condition in which rats and children have been found to locate an object effectively (e.g. Hermer-Vazquez, et al., 2001; Suzuki, Augerinos, & Black, 1980). In Experiment 2, the box containing the object had a distinctive color and shape, such that children could find the object by forming a direct association between the object and its container.

4. Experiment 2

In Experiment 2, children were given the object search task used in Experiment 1 with three boxes of different shapes and colors, arranged in the same locations as in Experiment 1.

4.1. Method

Experiment 2 was conducted before or after Experiment 1, with a 5 min break separating the studies. The method was the same as in Experiment 1 except as follows.

4.1.1. Subjects

Participants were the same as in Experiment 1, minus two subjects who were tested first in Experiment 1 and refused to be tested further after the break. Therefore, completing the experiment were seven children (four males and three females) ranging in age from 3.1 to 4.1 years (mean age 3.6 years).

4.1.2. Apparatus

Three different boxes were placed in the same configuration as in the previous experiment. The boxes were a yellow pyramid (base, 0.5 m; height, 0.7 m), a red cube ($0.8 \times 0.8 \times 0.8$ m) and a blue rectangular solid ($1 \times 0.5 \times 0.3$ m). The distances between these boxes were identical to the distances in the previous experiment (see Fig. 1, Experiment 2).

4.2. Results

In this experiment, disoriented children succeeded in retrieving the toy from the box with the appropriate shape and coloring (Fig. 2). Correct search significantly exceeded the chance rate of 1/3 per box, both across all the disoriented trials ($t(6) = 7.22$, $P < 0.001$) and on the first disoriented trial ($P < 0.01$, binomial test). An analysis of the data from the seven children who completed both experiments revealed that search at the correct box in this experiment reliably exceeded search at the correct box on the disoriented trials in Experiment 1 ($t(6) = 7.78$, $P < 0.001$, matched sample test).

4.3. Discussion

When distinctively shaped and colored boxes were arranged in the same pattern as in Experiment 1, children were able to find the hidden object quite accurately. This finding indicates that disoriented children did not use a random strategy or a strategy of choosing the closest location to find the object. As in previous research (Hermer, 1997; Hermer & Spelke, 1996), moreover, the disorientation procedure did not impair children's memory for the object's location or their motivation to find it. We conclude that the children in Experiment 1 were unable to find the object because they were unable to use the geometric configuration of the three boxes to reorient themselves or specify the object's position.

Children's successful search in Experiment 2 could be interpreted in two different ways. First, it is possible that children used the color of the boxes as landmarks for reorientation: contrary to the findings of Hermer and Spelke (Hermer, 1997; Hermer & Spelke, 1996; Wang et al., 1999), children may reorient in accord with non-geometric properties of movable objects in the scene. Alternatively, it is possible that children located the toy not by reorienting themselves but by forming a direct association between the toy and the properties of the box that contained it. We investigate these two possibilities further in Experiment 6.

Why did children fail to use the geometric configuration in Experiment 1 – the positions of boxes relative to one another – to reorient? Because the boxes were as tall as the children, on average, it is possible that children had difficulty assessing the boxes' relative distances and angular positions. To test that hypothesis, we provided more salient geometric information to the children in the next experiment, by arranging the three identical boxes such that two boxes were very close together and the third was far across the open space. This arrangement made the asymmetry of the object positions more salient to adults and more immediately visible to the children, whose viewpoint encompassed two objects when they faced the short side of the triangle and one object otherwise.

5. Experiment 3

In Experiment 3, a new group of subjects was given the reorientation task of Experiment 1 in the same open space and with the same boxes, but with the distance between the two closer boxes reduced by half. If children were able to reorient themselves and find the object in this experiment, their success would imply that they were sensitive to the geometry of the arrangement, and that they failed to notice the distinctive geometry in Experiment 1 because it was too subtle. If the subjects failed to find the correct box in Experiment 3, in contrast, their failure would suggest a pervasive inability to reorient in accord with geometric information about the arrangement of objects.

5.1. Method

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

5.1.1. Subjects

Participants were four boys and four girls ranging in age from 3.0 to 4.1 years (mean age 3.7 years), recruited from the same population as in Experiment 1.

5.1.2. Apparatus

The same three identical boxes were used in this experiment as in Experiment 1, but the distance between the two closer boxes was reduced by half. The boxes were arranged so as to form a right triangle, whose sides measured $1.85 \times 0.62 \times 1.95$ m (see Fig. 1, Experiment 3).

5.2. Results

Fig. 2 presents the findings of Experiment 3. The children searched randomly among the three boxes across the three disoriented trials ($t(7) < 1$) as well as on the first disoriented trial ($P > 0.2$, binomial test). On the oriented trial, in contrast, children reliably searched at the correct location ($P < 0.01$, binomial test).

Disoriented children searched no more accurately in the present experiment than in Experiment 1, in which the triangular configuration of the boxes was less prominently asymmetrical ($t(15) < 1$). Children searched reliably less accurately than in Experiment 2, in which the object was hidden in a box of a distinctive shape and coloring ($t(13) = 3.029$, $P < 0.01$, independent sample tests).

5.3. Discussion

When presented with three boxes that formed a strikingly asymmetrical configuration, young children failed to use this configuration to break the symmetry of the environment and locate a hidden object. As in Experiment 1, children's ability to find the hidden toy did not exceed chance levels. In contrast, children successfully found the toy when they were tested in a state of orientation. This finding, combined with children's success in Experiment 2, suggests that their failure to use the geometric information does not stem from limits on memory of toy location, motivation to search for the toy, or ability to understand and perform the task. Rather, it seems that even when salient geometric information is provided by the arrangement of the boxes, children fail to use the geometric arrangement of the identical boxes in order to reorient themselves and find the object.

Why do children fail to reorient by the geometric arrangement of the boxes in Experiments 1 and 3, when children of this age successfully reoriented by the geometric arrangement of the walls of a rectangular room in previous experiments? Gallistel (1990) and Hermer (1997) suggested that the critical difference lies in the fact that the surface layout is permanent and unmovable, whereas objects are movable: animals and children may reorient primarily by attending to the shape of the permanent aspects of the layout. An alternative possibility is that three objects may be encoded and remembered independently from one another because they are three separate things, whereas the four corners of a room may be encoded and remembered in relation to each other as features of a single form.

A series of experiments by Stedron et al. (2000) provides suggestive support for this last possibility. In one experiment, 1.5–2-year-old children were disoriented in a rectangular room whose walls were decorated by eight spatially separated posters; children's reorientation was strongly affected by the shape of the room and was not affected by these non-geometric landmarks. In two further experiments, distinctive non-geometric information was presented in a continuous pattern: either the four walls were painted different colors such that each corner presented a distinctive color boundary, or the walls were all painted white on top and black below, with an irregular, continuous contour providing distinctive patterning at each corner. Again, children reliably reoriented in accord with the shape of the room and showed no reliable reorientation in accord with its non-geometric properties. On the first trial, however, some children appeared to use the non-geometric information, and their tendency to do so was reliable when first trial data were pooled across the experiments. These findings raise the possibility that connected non-geometric information can serve, weakly, as a cue to reorientation. Alternatively, however, some children may have used the distinctive non-geometric information as a direct cue to the object's location, as in Experiment 2. In the next experiment, we tested the effects of connected information further, with older children than those in the Stedron et al. (2000) experiments and with a salient array of object landmarks.

6. Experiment 4

The same subjects from Experiment 3 participated in Experiment 4. For this experiment, the initial configuration of Experiment 1 was used, but the shape of that configuration was indicated by means of lines on the floor (Fig. 1). Children's attention was called to the configuration of lines and boxes before the experiment began. If this more salient geometric information connecting the objects allowed the children to reorient themselves, then children should have succeeded at finding the object in this experiment. In contrast, if the children still did not rely on the geometric information to reorient themselves after being informed visually and verbally of the shape of the boxes' configuration, then they should have performed as in Experiment 1 and searched all locations at chance.

6.1. Method

The method was the same as in the previous experiments except as follows.

6.1.1. Subjects

All of the subjects from Experiment 3 participated in Experiment 4.

6.1.2. Apparatus

The boxes' configuration was the same as in Experiment 1. Gray tape, 5 cm in width, was placed on the floor so as to connect the centers of the boxes and mark the shape of their arrangement (see Fig. 1, Experiment 4).

6.1.3. Procedure

Before the experiment began, each child was asked to walk at least once all around the geometric shape formed by the tape. As he or she did so, the experimenter described the shape of the configuration. Then the experiment proceeded as in Experiments 1–3.

6.2. Results

The search patterns, summarized in Fig. 2, indicate that children searched among the three boxes at random, both across the three disoriented trials ($t(7) < 1$) and on the first disoriented trial ($P > 0.2$, binomial test). In contrast, children tended to search correctly on the oriented trial ($P < 0.02$, binomial test). Children searched no more accurately in the room with tape marking the configuration than did the children in Experiment 1, who were tested in the same environment without the tape ($t(15) < 1$). In the present study, children searched reliably less accurately than those in Experiment 2, who retrieved the object from a box of a distinctive shape and color ($t(13) = 3.941$, $P < 0.005$, independent samples tests).

6.3. Discussion

The geometric information provided by the triangular figure on the floor evidently was not used by children to reorient themselves and retrieve the object. Thus, Experiment 4 provides no evidence that children are able to use either the geometric arrangement of the objects or the geometric form of the floor markings in order to reorient themselves.

The contrast between the negative findings of Experiments 1, 3, and 4, and children's successful use of room geometry in previous experiments (Hermer, 1997; Hermer & Spelke, 1996; Stedron et al., 2000; Wang et al., 1999) strongly suggests that children selectively reorient by detecting the geometrical arrangement of the extended surfaces in their environment (i.e. its walls) but not the geometric arrangement of the movable objects in this environment. Nevertheless, an alternative interpretation of these findings remains: it is possible that children are sensitive to the geometric arrangements of features of their surroundings when there are four such features forming a square or rectangle (i.e. the rectangular room in Hermer & Spelke, 1996; the square room in Wang et al., 1999), but not when there are three such features forming a triangle. In the next experiment, we tested this alternative interpretation by investigating whether children are able to reorient themselves and locate an object in accord with the geometric configuration of four identical boxes arranged in a rectangle of the same dimensions as the room in the Hermer and Spelke (1996) experiments.

7. Experiment 5

In Experiment 5, a new group of children was given the tasks of Experiments 1–4 in a rectangular configuration of four identical boxes. If the children were able to use the geometric arrangement of the movable boxes to reorient themselves, they should have searched for the toy equally often in the correct box and in the rotationally equivalent box, and both boxes should have been searched more often than the remaining, geometrically inappropriate boxes. This is the pattern of search found when children are disoriented in a rectangular chamber of the same dimensions, both at this age (Hermer, 1997) and at younger ages (Hermer & Spelke, 1996). If children are not able to use the geometric configuration of the boxes to reorient themselves, then they should search the two geometrically inappropriate boxes as often as the two geometrically appropriate ones.

7.1. Method

The method was the same as in the previous experiments except as follows.

7.1.1. Subjects

Participants were four boys and four girls ranging in age from 3.1 to 4.5 years (mean age 3.7 years). Three additional subjects were eliminated from the sample because they failed to complete the disorientation procedure successfully. The children came from the same population as in Experiments 1–4.

7.1.2. Apparatus

Four identical rectangular boxes were arranged in a 1.23×1.85 m rectangular configuration in the same open space used in the other experiments (see Fig. 1, Experiment 5).

7.1.3. Procedure

The procedure was the same as in the previous experiments except that the number of disoriented trials was raised from three to four, with one search trial at each of the four landmarks. Half the children participated first in Experiment 6 (see below).

7.2. Results

Fig. 3 (top) presents children's search patterns in relation to the geometry of the configuration. On the disoriented trials, children searched with approximately equal frequency at the geometrically appropriate and the geometrically inappropriate boxes, both over the trial sequence ($t(7) = 1.00$) and on the first trial ($P > 0.20$, binomial test). On the oriented trials, there was a non-significant trend toward geometrically appropriate responding (with chance = 0.50, $P > 0.20$, binomial test).

Fig. 3 (bottom) presents children's rates of search at the absolutely correct box. On the disoriented trials, children's rates of correct search did not exceed the chance value of 0.25, either over the trial series ($t(7) = 1.43$, $P > 0.15$) or on the first trial ($P > 0.20$, binomial test). On the oriented trials, in contrast, the rate of correct responding was well above chance (with chance = 0.25, $P < 0.005$, binomial test).

7.3. Discussion

The findings of Experiment 5 are similar to those of Experiments 1, 3, and 4. As in those experiments, children failed to reorient in accord with the geometrical configuration of landmark objects. The findings of Experiment 5 also contrast strikingly with those of Hermer and others (Hermer, 1997; Hermer & Spelke, 1994, 1996;

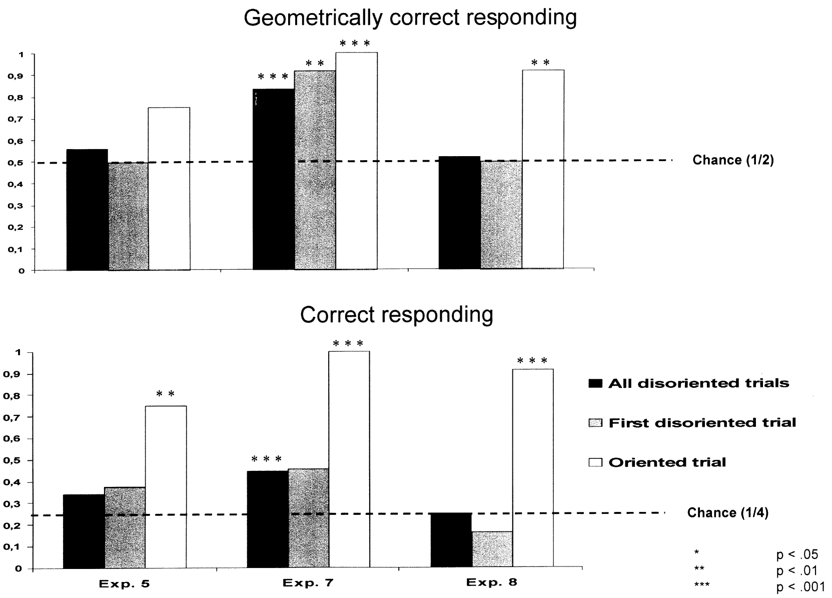

Fig. 3. Proportion of geometrically correct responses (top) and of correct responses (bottom) over all the disoriented trials (black bars), on the first disoriented trial (gray bars), and on the oriented trial (white bars) for Experiments 5, 7, and 8.

Stedron et al., 2000; Wang et al., 1999), in which children successfully reoriented in accord with the shape of the test chamber. Although the children in Experiment 5 were presented with exactly the same rectangular configuration as in Hermer and Spelke's experiments, they failed to use this configuration to reorient themselves. Together with past research, these findings provide clear evidence that children reorient in accord with the shape of the permanent spatial layout but not in accord with the shape of a configuration of surrounding objects.

The next experiment with children investigated further the contrast between Experiments 1 and 3–5, in which children failed to locate the object in relation to a geometric configuration of identical landmarks, and Experiment 2, in which children successfully located the object inside a landmark of a distinctive color. Why did children succeed in the presence of non-geometric information, but fail in the presence of geometric information? One possibility, suggested by experiments on navigation and object search in rodents, is that children were able to use the color of the target box as a direct cue to the location of the object: children may have located the hidden object by associating it with a box color or shape. A different possibility, suggested by some electrophysiological studies of reorientation by rodents in a cylindrical environment (e.g. Knierim, Kudrimoti, & McNaughton, 1995; Taube, Muller, & Ranck, 1990), is that salient non-geometric information can serve as a cue to reorientation, even when it is not directly associated with an object. The most effective non-geometric information that has been used in behavioral and physiological experiments with rats is a "cue card" placed directly against the cylindrical wall of the test chamber and contrasting from the rest of the wall in brightness (e.g. Taube et al., 1990).

In the next experiment, we attempted to distinguish these possibilities by presenting the task of Experiments 1–5 in the presence of a salient non-geometric cue that was not directly associated with any specific hiding place. A red satin curtain that contrasted in color, brightness, and texture from its surroundings was hung against the tan circular curtain so that it covered 20% of the cylindrical enclosure. This red curtain served as a non-geometric landmark that was very similar to the cue card used with rats.

A further motivation for Experiment 6 comes from recent findings by Learmonth, Newcombe, and Huttenlocher (1998), who tested children's reorientation in a rectangular room similar to that of Hermer and Spelke (1996), furnished with various landmarks. In contrast to all the findings reported above, Learmonth's subjects searched in accord with both geometric and non-geometric information. Learmonth and collaborators suggested that children's success in their experiments stemmed from the use of a larger testing environment (their 8 × 12 foot, 8.9 m^2 room was four times the area of Hermer and Spelke's initial test chamber) and stable non-geometric landmarks (their children participated in a single session with landmarks continuously present). Experiment 6 begins to test the first of these suggestions by presenting a stable non-geometric cue within an environment that is larger than that used by Hermer and Spelke (1996), although not quite as large as that of Learmonth et al. (1998).

8. Experiment 6

Experiment 6 was conducted with the same group of children as Experiment 5. The object configuration was the same as in Experiment 3, a prominently elongated triangle. In addition, a non-geometric cue (a bright red silk curtain) covered 1/5 of the cylindrical background of the open space (Fig. 1). If children can reorient either by the non-geometric cue alone or by the combination of non-geometric and geometric information, then they should find the object accurately, as in Experiment 2. In contrast, if children can only reorient by the shape of the extended surface layout, and if the children in Experiment 2 retrieved the object by the strategy of forming a direct association between the object and its container, then the children in Experiment 6 should search randomly for the target after disorientation.

8.1. Method

The method was the same as in the previous experiments except as follows.

8.1.1. Subjects

Participants were five boys and six girls ranging in age from 3.1 to 4.5 years (mean age 3.6 years). All but three of these children also participated in Experiment 5.

8.1.2. Apparatus

The environment was the same as in Experiment 3 except for the presence of a bright (1.9 × 2.0 m) red satin curtain attached to the wall behind and between two boxes (see Fig. 1, Experiment 6). On entering the test environment, the children directly faced the red curtain contrasting with the tan curtains of the open space. To call the child's attention to this landmark, the experimenter asked the child to designate the color of that curtain. Informal observations of the children's behavior on entering the open space suggested that even before this question was asked, the red curtain was a salient feature of the environment.

8.2. Results

As indicated in Fig. 2, the children in this experiment performed at chance levels in finding the toy both over the three disoriented trials ($t(10) < 1$) and on the first such trial ($P > 0.20$, binomial test). In contrast, ten of the 11 children searched correctly on the oriented trial ($P < 0.001$, binomial test). Performance on the disoriented trials was no more accurate in the presence of the red curtain (Experiment 6) than in its absence (Experiment 3) ($t(17) < 1$, independent samples test). Disoriented performance when the non-geometric landmark was the red curtain was reliably worse than disoriented performance when the non-geometric landmark was a direct cue to the object's location (the distinctively colored box in Experiment 2) ($t(16) = 3.03$, $P < 0.01$, independent samples test).

8.3. Discussion

As in the previous experiments, children failed to reorient themselves and locate a hidden object when they were disoriented in a circular chamber with three asymmetrically placed objects and a distinctively colored curtain. Even when spatial information provided by the arrangement of the three identical boxes was maximized and when a stable non-geometric landmark was present and elicited the children's attention, children still performed at chance in locating the hidden toy. This finding replicates the findings of Hermer and Spelke (1996) and Wang et al. (1999) and provides evidence that neither an arrangement of objects nor a salient, distinctively colored covering on the wall of a symmetrical enclosure serves to break the symmetry of the enclosure for children. The finding also bears on the suggestion by Learmonth et al. (1998) that children can reorient by non-geometric landmarks in large spaces (see also Stedron et al., 2000), because the present space was substantially larger than that used in previous research in our lab (Hermer & Spelke, 1996; Wang et al., 1999). Nevertheless, the space used in the present experiments was smaller than that of Learmonth et al. (1998) and different in shape, and so it remains possible that reliable responses to non-geometric landmarks would have been observed if we had used a larger rectangular room.

The findings of Experiment 6 provide an interesting comparison to studies of navigation and spatial memory in rodents. Many behavioral and physiological experiments have tested rodents' spatial memory in a cylindrical chamber with a non-geometric landmark that is very similar to the red curtain used in the present study (for a review see Thinus-Blanc, 1996). Because rats typically are tested in a solid cylindrical chamber and are colorblind, the non-geometric landmark is usually a stiff cardboard panel contrasting in brightness from the rest of the enclosure. In all other respects, however, the "cue card" used with rats resembles the red curtain we used with children. These experiments provide mixed evidence, however, concerning rodents' abilities to reorient by this non-geometric cue. Behavioral studies testing rats in a moderately motivating appetitive task typically find no effect of the landmark on rats' reorientation (e.g. Biegler & Morris, 1993; Dudchenko et al., 1997). In contrast, behavioral studies using a highly motivating escape task and electrophysiological studies of "head direction cells" in parahippocampal regions of the cortex suggest that rats do reorient by the non-geometric cue. Our findings agree with the findings of experiments with rats in the more similar behavioral tasks and provide no evidence for reorientation in accord with this non-geometric landmark (see also Wang et al., 1999).

Further analyses of the findings of Experiments 1–6 also can serve to address suggestions by Learmonth et al. (1998) and Stedron et al. (2000) concerning children's use of non-geometric information for reorientation. Learmonth et al. suggested that children reorient by geometric and non-geometric landmarks when they are tested within a single session in which the landmarks are continuously present. This suggestion can be tested by analyzing the data collected during the first sessions of Experiments 1, 3, 4, and 6, before any landmarks were moved or altered. A total of 18 children participated in one of these experiments as their first testing session, and during that session they searched at the correct box on 30% of the trials, a value that is non-significantly lower than the chance value of 33% ($t(17) < 1$). Thus, children failed to reorient by the objects or the red curtain during their first test session, when these landmarks were continuously present and so appeared to be stable.

Stedron et al. (2000) suggested that children may reorient by non-geometric landmarks after their first disorientation experience, but fail to reorient by such landmarks after successive disorientation experiences (even though such children continue to reorient by geometric properties of the layout). To test this suggestion, we analyzed children's performance on the first trial of the first session of Experiments 1, 3, 4, and 6. Of the 18 children who contributed to this analysis, seven searched at the correct location on their first trial, a rate that does not exceed the chance level of 33% ($P > 0.2$, binomial test). Children therefore failed to reorient by objects or by non-geometric properties of the layout, even on their first exposure to a new setting and after their first disorientation experience in that setting.

Why do children fail to reorient using geometric information provided by the configuration of a set of objects, but succeed in using geometric information provided by a configuration of walls in the experiments of Hermer (Hermer & Spelke, 1994, 1996) and others (Stedron et al., 2000; Wang et al., 1999)? One possible explanation for this difference is that the geometric information used in previous studies consists of connected surfaces, whereas that used in our studies consists of separated objects. The suggestive evidence of Stedron et al. (2000) that children can use non-geometric information that forms a connected pattern is consistent with this possibility, although they note that their evidence is open to other interpretations. A second possibility is that children reorient in accord with the geometric properties of any extended surface layout, regardless of whether or not the surfaces in the layout are connected. The next experiments were undertaken to distinguish these possibilities. In Experiment 7, we presented children with four separated walls that partly defined a rectangular room, without corners or other connecting surfaces.

9. Experiment 7

In Experiment 7, we investigated the ability of children to retrieve the hidden object by relying on the shape of four walls that were separated by large gaps and so only partly defined a rectangular configuration of the same dimensions as the rectangular arrangement of objects in Experiment 5 (see Fig. 4). If children only are sensitive to the geometrical form of a connected space, they should fail to reorient in this experiment, as in Experiment 5. If children are sensitive to a geometrical configuration of walls, in contrast, then they should reorient successfully, as in past research using a connected, rectangular room (Hermer & Spelke, 1994, 1996; Stedron et al., 2000).

9.1. Method

The method was the same as in the previous experiments except as follows.

9.1.1. Subjects

Participants were six boys and six girls ranging in age from 3.4 to 4.5 years (mean age 3.9 years), recruited from the same population as in Experiment 1. Half of the group were tested in Experiment 7 (see below) after Experiment 8 and half were tested in the reverse order.

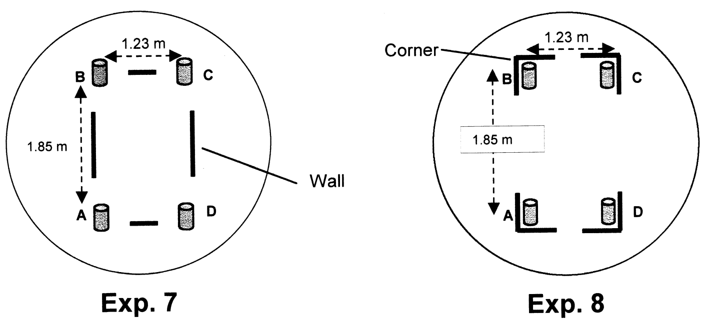

Fig. 4. Overhead view of the testing space with the locations of hiding cylinders (A–D) and of walls or corners for Experiments 7 and 8.

9.1.2. Apparatus

The experiment used the same open space as in all previous experiments. Four red small cylinders (height, 20 cm; diameter, 10 cm) were placed in the same rectangular configuration as in Experiment 5 and served as hiding locations for the object. Four walls (two narrow, 62×100 cm; and two wide, 124×100 cm) made of white foam core were placed respectively in the center of each side of the rectangular configuration so as to partially define the shape of the rectangular configuration made by the four red cylinders. Because these walls did not touch one another or the hiding containers, the larger cylindrical room was clearly visible behind them. The arrangement of walls created a 616 cm rectangular perimeter consisting of a total of 372 cm of walls and 244 cm of gaps.

9.1.3. Procedure

As in Experiment 5, children were tested on four disoriented trials and one oriented trial.

9.2. Results

Fig. 3 (top) presents children's search choices in relation to the geometry of the configuration. Children searched geometrically appropriate hiding locations more than inappropriate ones, both on the first disoriented trial ($P < 0.01$, binomial test) and over the trial series ($t(11) = 7.09$, $P < 0.001$). All the subjects searched a geometrically appropriate corner on the oriented trial ($P < 0.001$, binomial test). Search at the geometrically correct locations in this experiment reliably exceeded search in the same locations in Experiment 5 ($t(18) = 3.52$, $P < 0.002$, independent samples test).

Fig. 3 (bottom) presents children's search rates at the correct location in this experiment. Children searched the correct corner on 46% of the trials, a rate that significantly exceeds the chance rate of 0.25 over all the trials ($t(11) = 5.00$, $P < 0.001$) but not on the first trial ($P > 0.10$, binomial test). The above-chance rate of correct responding stems from the effect of the geometrical configuration and not from other factors such as incomplete disorientation: comparing search at the two geometrically appropriate corners, subjects showed no tendency to search the correct corner more than the opposite corner on the first trial ($P > 0.05$, binomial test) or on all trials ($t(11) = 1.1$, $P > 0.05$, matched samples test), indicating that they were successfully disoriented. Rates of search at the correct corner on the oriented trial were highly significant ($P < 0.001$, binomial test).

9.3. Discussion

When the rectangular shape of the object configuration was partly defined by four spatially separated walls, children were able to find the hidden object quite accurately, relying on geometrical information. This finding provides further evidence that 3–4-year-old children, like infants, use geometrical information about extended surfaces to reorient themselves, as in past research (Hermer, 1997). Moreover, the experiment provides evidence that young children reorient by the shape of a configuration of walls, even when the walls are not connected to one another. The findings contrast with those of Experiment 5, in which children were tested in the same environment, with the same procedure and the same geometric arrangement, but with movable objects rather than walls. This contrast indicates that the failure of children to reorient by the configuration of objects in our experiments does not stem from general problems with our experimental methods or subject population. Rather, reorientation performance appears to depend on a distinction between objects and surface markings on one hand, and extended surfaces on the other, and on a predisposition to represent geometric properties of the latter.

10. Experiment 8

In Experiment 8, we reversed the layout configuration of Experiment 7 and presented children with four identical corners in a rectangular arrangement without connecting walls. Children again searched for an object in one of four indistinguishable containers, now placed directly at each of the four spatially separated corners. Because the gaps between the corners were about as large as the gaps between the walls in Experiment 7, the cylindrical walls of the larger space were clearly visible. If children reorient by corners as well as by walls, then their performance in this experiment should resemble that of Experiment 7 and contrast with that of Experiment 5.

10.1. Method

The method was the same as in Experiment 7 except as follows.

10.1.1. Apparatus

The environment used in Experiment 7 was altered by removing the four walls and replacing them with four identical corners, each made of two foam core panels (62×100 cm) attached at right angles and placed at each corner of the rectangular configuration, directly behind a cylindrical hiding box. The arrangement of corners created a 616 cm rectangular perimeter consisting of 496 cm of walls and 120 cm of gaps between walls, with each gap centered on a side of the rectangle.

10.2. Results

Children's search patterns in relation to the geometry of the configuration are given in Fig. 3 (top). On disoriented trials, children searched with equal frequency at the geometrically appropriate and inappropriate boxes both on the first trial ($P > 0.20$, binomial test) and over the trial series ($t(11) < 1$). On the oriented trial, in contrast, 11 of 12 children searched at a geometrically correct location ($P < 0.01$, binomial test). Performance on the disoriented trials was no more accurate in the presence of the four corners than in their absence (Experiment 5) ($t(18) < 1$, independent samples test), and it was reliably less accurate than in the presence of the four straight walls (Experiment 7) ($t(11) = 3.36$, $P < 0.01$, matched samples test).

Children's rates of search at the correct location are given in Fig. 3 (bottom). The search rate at the correct corner did not differ from the chance rate of 0.25, either across all the disoriented trials ($t(11) < 1$) or on the first disoriented trial ($P > 0.20$, binomial test). On the oriented trial, in contrast, 11 of the 12 children searched directly at the correct box ($P < 0.001$, binomial test).

10.3. Discussion

The findings of Experiment 8 contrast with those of Experiment 7: although children successfully reoriented in accord with a configuration of walls not connected by corners, they failed to reorient in accord with a configuration of corners not connected by walls. This difference cannot be attributed to the subjects or procedure, which were identical for the two experiments, or to the amount of filled perimeter of the rectangular space, which actually was larger in the corners experiment (496 cm) than in the walls experiment (372 cm). We suggest four possible accounts of these findings. First, the walls in Experiment 7 were presented in two distinctive lengths, whereas the corners in Experiment 8 all were indistinguishable in length or other properties; children may detect the differing wall lengths and use this information to reorient. Second, two different walls surrounded each hiding location in Experiment 7, whereas a single corner marked each hiding location in Experiment 8; the former arrangement may have increased children's attention to the layout configuration, whereas the latter may have increased attention to the individual landmarks. Third, the walls projected a wider extent in the child's visual field than did the corners because of their shape; children therefore may have perceived the walls more clearly perceived as extended surfaces. Fourth, the system of spatial representation that underlies children's reorientation may treat extended surfaces (walls) and junctures between surfaces (corners) differently, allowing reorientation only in accord with the former. Further research is needed to test these possibilities.

Whatever accounts for children's successful performance with the walls, their success presents a striking contrast to their failures to reorient in accord with a configuration of objects or corners. This contrast corroborates the findings of Hermer-Vazquez (1997) that children reorient by geometric properties of extended surfaces (a bulge in a wall) but not by similar geometric properties of objects (a manikin of the approximate size of the bulge, standing against a wall).

In the last two experiments, we ask whether adults perform more flexibly than children. Adults were tested in the same space and with the same tasks used with children. To maximize the potential contrast between adults' and children's performance, we tested adults with the configurations of three and four landmarks that provided the most subtle geometric information in the preceding experiments: the triangular arrangement of objects used in Experiment 1 and the rectangular arrangement of objects used in Experiment 5.

11. Experiment 9

In Experiment 9, we tested adults in the same environment as in Experiment 1: an open space with three identical boxes placed so as to form a right triangle. If adults performed like children, they would locate the hidden object on the oriented trial but search at random on the disoriented trials. If adults perform more flexibly in this situation, as they have done in past research (Hermer & Spelke, 1994; Hermer-Vazquez, Spelke, & Katsnelson, 1999), they might search correctly on disoriented as well as oriented trials.

11.1. Method

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

11.1.1. Subjects

Participants were four male and four female university students ranging in age from 19 to 30 years (mean age 24.3 years). Students were recruited through announcements on campus and were offered course credit for their participation. One subject was omitted from the original sample because she actively sought (according to her own report) and found (determined by performance and report) strategies to maintain her orientation during the disorientation procedure. All subjects also participated in Experiment 10, and half received that experiment first.

11.1.2. Apparatus

The experiment was conducted in the same open space, with the same objects and configuration as in Experiment 1, except that the room lights were dimmed to reduce the visibility of subtle cues in the environment such as the location of the video camera (see Fig. 1, Experiment 9).

11.1.3. Procedure

Before the experiment, the experimenter told the participants 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 participant entered the open space with the experimenter, who asked him/her to walk and look all around the open space, and then hid the object in one of the boxes. The participant then was instructed to begin rotating slowly with eyes open (on one oriented trial) or closed (on three disoriented trials). He or she continued to turn for at least ten full rotations, changing direction on cue from the experimenter, who walked around the space at varying speeds so as not to serve as a landmark himself. Finally, the participant was told to open his/her eyes and locate the target.

11.2. Results

Fig. 5 presents the findings of the experiment. Correct search on the disoriented trials significantly exceeded the chance rate of 1/3 per box both across the trial

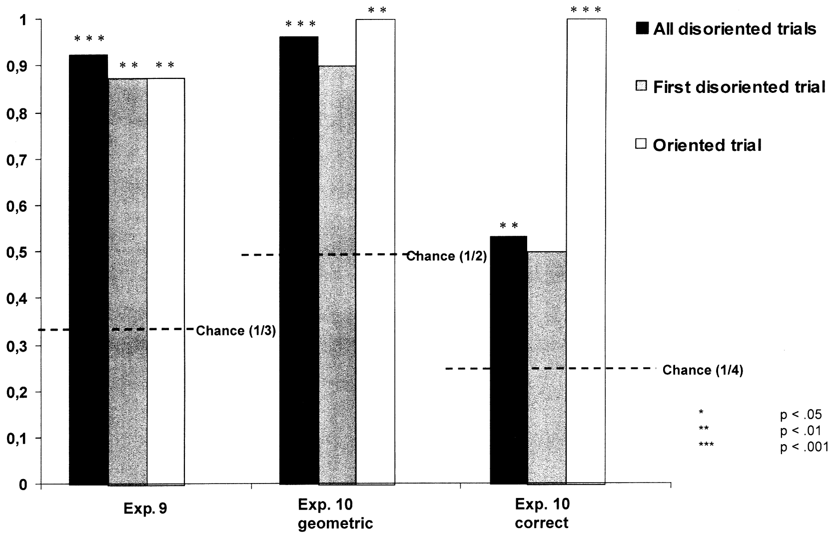

Fig. 5. Proportion of correct responses in Experiment 9 (left), and of geometrically appropriate responses and correct responses in Experiment 10 (middle and right) over all the disoriented trials (black bars), on the first disoriented trial (gray bars), and on the oriented trial (white bars).

sequence ($t(7) = 10.88$, $P < 0.001$) and on the first trial ($P < 0.005$, binomial test). Seven of the eight adults also searched correctly on the oriented trial ($P < 0.005$, binomial test). Adults' performance on the disoriented trials was reliably better than the performance of children tested in the same environment (Experiment 1) ($t(15) = 14.98$, $P < 0.001$, independent samples test).

11.3. Discussion

Human adults successfully retrieved the object on both the oriented and the disoriented trials. These findings suggest that they used the geometric information provided by the arrangement of three identical boxes in order to relocate the object, in contrast to the young children.

There is, however, an important alternative interpretation of the present findings: it is possible that adults successfully retrieved the toy on the disoriented trials because they were tested in a state of orientation. Although we used a procedure that has been found to induce disorientation successfully in other experiments (e.g. Hermer & Spelke, 1994; Wang et al., 1999), we cannot rule out the possibility that subtle cues in the present environment (e.g. unintended sounds or odors) allowed adults either to maintain or to reestablish their orientation in the present study. The next experiment addressed this possibility while testing adults' sensitivity to an ambiguous, rectangular arrangement of objects.

12. Experiment 10

In Experiment 10, adults were presented with the rectangular configuration of boxes used in Experiment 5. Because this configuration only specified one's orientation up to a 180-degree ambiguity, Experiment 10 tested both whether subjects were disoriented effectively in the present studies and whether they would reorient themselves in accord with the shape of the boxes' arrangement. If adults are effectively disoriented and no subtle, unnoticed cues allow them to reorient themselves, then they should search the incorrect but geometrically appropriate box as much as the correct box. If adults use the shape of the configuration to reorient themselves, then they should search the two geometrically appropriate boxes more than the other boxes.

12.1. Method

The method was the same as in Experiment 9 except as follows.

12.1.1. Apparatus and procedure

The experiment used the same open space, objects, and configuration as in Experiment 5, with dim illumination (see Fig. 1, Experiment 10). Subjects were tested on four disoriented trials, as in Experiment 5.

12.2. Results

As Fig. 5 indicates, disoriented adult subjects tended to search geometrically appropriate boxes more than inappropriate ones, non-significantly on the first trial ($P < 0.08$, binomial test) and reliably over the trial series ($t(7) = 15.00$, $P < 0.001$). All the subjects searched at a geometrically appropriate location on the oriented trial ($P < 0.01$, binomial test). Disoriented search in the geometrically correct diagonal in this experiment reliably exceeded search in the same diagonal in Experiment 5 (the same experiment but with children) ($t(14) = 6.99$, $P < 0.001$, independent samples test).

Fig. 5 also presents the rates of correct responding. Subjects tended to search at the correct corner about half the time, a rate that fails to exceed the chance value of 0.25 on the first trial ($P > 0.10$, binomial test) but exceeds chance over the trial series ($t(7) = 3.81$, $P < 0.01$). Where search at the correct location exceeded chance, this effect was due entirely to subjects' tendency to confine their search to geometrically appropriate corners rather than to any ability to maintain their orientation: comparing search at the two geometrically appropriate corners, subjects showed no tendency to search the correct corner more than the opposite corner on the first trial ($P > 0.20$, binomial test) or over all the trials ($t(7) < 1$, matched samples test), indicating that they indeed were disoriented. All the subjects searched correctly on the oriented trial ($P < 0.001$, binomial test).

12.3. Discussion

On disoriented trials, adults searched equally often in the correct box and in the geometrically appropriate but incorrect box. These findings provide evidence that our experimental procedure effectively disoriented them. Furthermore, adults searched the two geometrically appropriate boxes reliably more than the other, geometrically inappropriate ones. This finding provides evidence that they were able to rely on the geometry of the object configuration to locate the object, confining their search in the open space to boxes with appropriate metric and sense relationships.

It is interesting to ask how aware subjects were of the processes underlying their performance in Experiments 9 and 10. At the end of the two experiments, subjects were asked how they decided where to search for the object. Most of the subjects mentioned that the distances between the boxes were not equal and that the shape of the configuration was useful to retrieve the hidden object. These observations suggest that the process of analyzing the shape of the object configuration was consciously accessible to subjects. They contrast with the informal observations of Hermer-Vazquez (1997), whose adult subjects reported little awareness of using the shape of the experimental chamber to locate the object.

It is not clear, either from subjects' performance or from their reports, whether they located the object by first reorienting themselves. Adults may have used the triangular or rectangular configuration to reorient themselves (up to a 180-degree ambiguity in the latter case) so as to retrieve the object by returning to its remembered allocentric position. Alternatively, adults may have encoded directly the position of the object in relation to the triangle or rectangle so as to retrieve it irrespective of their own state of disorientation. For example, a subject may have remembered that the target in Experiment 9 was hidden in the box that was furthest from the other two boxes, and that the target in Experiment 10 was hidden in a box whose nearest neighbor was to its left. In either case, the findings show that adults are sensitive to the geometry of the object configuration and use that configuration to locate the object. Comparisons of the findings with adults to those with children suggest that this ability develops in humans after 3–4 years of age.

Whatever processes caused their flexible performance, the adults in Experiments 9 and 10 clearly used a geometric configuration of objects to locate a hidden object when they were disoriented. Because adults performed near-perfectly when tested with the most subtle triangular and rectangular arrangements used with children, it is very likely that they would perform at ceiling levels in all the environments that we have studied with children. The present tasks therefore were not used to test adults further.

13. General discussion

The present experiments shed further light on the early-developing system for reorientation found in humans. When young children are disoriented, they appear to reorient themselves by analyzing the shape of the surrounding surface layout but not by analyzing either the shapes of configurations of objects or the distinctive coloring of the surface layout. Young children failed to reorient in accord with a non-geometric property of the layout, despite the fact that the particular non-geometric property we presented to them was the one that appeared most promising from studies of reorientation in other animals: a circular surrounding containing a single sector of a distinctive color and brightness. Young children also failed to reorient in accord with the geometric relationships among objects, despite our attempts, in six experiments, to emphasize those relationships by presenting highly asymmetrical configurations and by presenting lines that connected the objects into a unitary figure. In contrast to these failures, young children succeeded in our tasks when they remained oriented, when they were disoriented but could retrieve an object by forming a direct association between the object and a property of the container that hid it (Experiment 2), and when they were disoriented but could reorient themselves in accord with a configuration of rectangular walls (Experiment 7). We conclude that the early-developing reorientation system is relatively encapsulated and privileges information about the shape of the extended surface layout.

Our findings partly complement and partly contrast with those of Stedron et al. (2000). As in the present experiments, Stedron et al. found that young children reliably reorient in accord with the shape of a rectangular room and fail to reorient, over a series of trials, in accord with non-geometric properties of the room such as distinctive wall coloring or patterning. Stedron et al. nevertheless reported that children show a weak tendency to reorient in accord with non-geometric landmark features when only first trial performance is considered, a tendency that becomes significant when data are pooled across multiple experiments. To test for this tendency in the present studies, we analyzed first trial performance across all the experiments testing triangular arrays of indistinguishable landmarks, but we found no tendency for children to use those landmarks to guide their search on their first trial.

One possible reason for our differing findings is suggested by the findings of a further experiment by Stedron et al. (2000), in which reorientation was tested in a square room with eight distinctive posters placed on the room's walls, and in which children showed no tendency to reorient by non-geometric landmarks on the first or any trial. In our experiments and in Stedron et al.'s experiment with posters, non-geometric landmarks did not directly indicate the correct hiding location, and so children could only use them if they could represent them in relation to one another or to geometric properties of the room. In the Stedron et al. (2000) experiments with distinctively colored or patterned walls, in contrast, each potential hiding location had distinctive, though subtle, non-geometric properties, and so children could have located the hidden object by following the strategy of directly associating the hidden object with a perceptible cue, as in Experiment 2 of the present series. It is not clear why this tendency was observed only on the first trial of the Stedron et al. (2000) experiments, however, whereas it was observed consistently over trials in Experiment 2. Children's cue-guided performance therefore needs to be studied further in reorientation tasks.

The present findings, like past findings from several investigators (Hermer & Spelke, 1996; Stedron et al., 2000; Wang et al., 1999) contrast with those of Learmonth et al. (1998), who reported that children reliably reorient in accord with a single, indirect non-geometric landmark when tested in a large room during a single session. Because analyses of first-session performance in the present studies revealed no tendency for children to reorient by non-geometric information, the divergent findings from these laboratories likely stem from differences in the sizes or configuration of the rooms and landmarks presented to children, factors that require further study as well.

It is interesting to compare the present findings with children to the findings of research with other animals. Past research has revealed a close correspondence between the navigational performance of children and of rodents in disorientation tasks, when reorientation abilities were tested with similar measures. For example, rats who were disoriented in a symmetrical chamber with a single sector of contrasting brightness failed to use the geometrical relationships among landmark objects within the testing space to reorient themselves and locate a hidden food source (Biegler & Morris, 1993). Rats also failed to locate food when they remained in a state of orientation and the food's location was specified by its relation to a set of movable objects that retained a constant geometric configuration (Biegler & Morris, 1993, 1996).

Further parallels between the navigation systems of rodents and human children come from studies of object search by subjects who are not disoriented. Rodents who are oriented and who explore an environment of stable objects are highly sensitive to the locations of multiple objects, as were the children on the oriented trials of the present experiments. For example, in a series of reaction-to-change tests, hamsters explored four different objects in an open-field until they habituated to the objects (as measured by a decline in contacts with the objects), and then the shape of the initial object configuration was changed. Such changes induced a renewal of exploratory activity directed either selectively to the displaced object(s) or to all the objects, even if the objects were perceptually indistinguishable (Poucet, Chapuis, Durup, & Thinus-Blanc, 1986; Thinus-Blanc et al., 1987). These findings have been extended to non-human primates (Gouteux, Vauclair, & Thinus-Blanc, 1999). All these findings suggest that the spatial memory systems found in young humans show considerable homologies to those found in other animals.

It is also interesting to compare the performance of children to that of adults. Adults performed more flexibly than children in the present experiments, using the geometric configuration of the landmark objects to locate the hidden object. Adults also reoriented more flexibly than children in past research. In experiments using the present disorientation task, adults used non-geometric properties of the surface layout in order to locate a hidden object (Hermer & Spelke, 1994; Hermer-Vazquez et al., 1999). In experiments using a task similar to that of Biegler and Morris (1993), in which subjects searched for a movable object that bore a constant geometric relation to a movable landmark, adults also used the geometrical relationship among the objects to locate the target (Hermer-Vazquez et al., 1999). Interestingly, adults' flexible performance in both these situations disappears when they are tested while performing an attention-demanding, verbal interference task: under conditions of interference, adults perform similarly to children and rats and reorient only by the shape of the surrounding layout (Hermer-Vazquez et al., 1999). Moreover, adults who are disoriented have been found to maintain accurate representations of the surface layout (e.g. an arrangement of room corners) but not of separated objects (e.g. a geometrically identical arrangement of chairs) (Wang & Spelke, 2000). These findings raise the question of whether adults' performance in the present situation also diminishes under conditions of interference.

Our findings have implications for theories of object and surface representation. They suggest that movable objects – even large ones that only are encountered in a single position – are encoded differently from non-movable extended surfaces – even surfaces that are freestanding and not connected to one another (see also Wang & Spelke, 2000). But what defines an object for children, and how do children determine which surfaces in the environment are part of the permanent, extended layout? For the past 150 years, intensive research has focused on the nature of visual surface representations (e.g. Helmholtz, 1867/1925). For nearly a century, moreover, research has focused on the nature of visual object representations (e.g. Wertheimer, 1923/1958). To our knowledge, however, few studies have asked how perceivers distinguish between these classes of entities (although see Epstein & Kanwisher, 1998). Research on navigation and reorientation suggests that this is an important distinction for humans and for other mammals. The perceptual basis of this distinction calls for further investigation.

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