A Modular Geometric Mechanism for Reorientation in Children

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Modular Geometric Mechanisms for Navigation in Disoriented Children

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Abstract

Although disoriented young children relocate objects in relation to the shape of the surrounding surface layout, cognitive accounts of this ability vary. The present paper tests three classes of theories of reorientation – snapshot theories centering on visual image-matching computations, adaptive combination theories by which diverse environmental cues to orientation are weighted according to their experienced reliability, and modular theories, whereby disoriented search is guided by multiple, distinct processes, including an encapsulated, geometry-based reorientation process. Six experiments test these theories by manipulating four properties of landmarks: their size, movability, dimensionality, and distance from layout boundaries. Their findings support a modular theory centering on two processes: a reorientation process based on the geometry of the bounded 3D surface layout, and a beacon-search process based on the local features of objects.

Keywords: reorientation; spatial navigation; geometry; modularity; image matching; beacon homing

Introduction

When an animal becomes disoriented, how does it regain its sense of direction? Research in developmental and comparative psychology, behavioral ecology, cognitive neuroscience, and neurobiology reveals an impressive sensitivity to surface layout geometry in guiding reorientation. In behavioral studies, both humans and a variety of nonhuman animals including monkeys, rats, chicks, pigeons, fish, and even ants (Wystrach & Beugnon, 2009), use the overall shape of their environment to reorient (for review, see Cheng & Newcombe, 2005). For example, when children as young as 18 months observe the hiding of a toy in one corner of an empty rectangular testing arena and then are disoriented, they concentrate their search at the arena's two geometrically correct corners, avoiding the remaining corners with inappropriate relations between the lengths and lateral positions of the walls that bound them (Hermer & Spelke, 1994, 1996; Learmonth, Nadel, & Newcombe, 2002; Learmonth, Newcombe, & Huttenlocher, 2001).

Children and other animals also use objects and non-geometric layout features such as wall coloring to guide their search under disorientation (e.g., Cheng, 1986; Hermer & Spelke, 1996), but their use of these landmarks is less consistent and reliable across species, environments, and tasks (Cheng & Newcombe, 2005; Cheng, 2008). When children are disoriented in a rectangular room with one uniquely colored wall, for example, they base their search on both the shape of the room and the position of the colored wall when the room is large (Learmonth et al., 2001; Learmonth et al., 2002), but only on the shape of the room when it is small (Hermer & Spelke, 1994, 1996; Learmonth et al., 2002).

Such studies of reorientation behavior have animated a large, ongoing debate over the specificity and organization of the mechanisms underlying spatial reorientation. The *geometric module* was first proposed by Cheng and Gallistel, following the observation that disoriented rats rely primarily on room shape to relocate hidden food, while often failing to use other available cues such as odors, 2D contrast patterns, and wall color (Cheng & Gallistel, 1984; Cheng, 1986). On this view, animals possess a core system that represents the shape of the environment in which they navigate, and that uses geometric congruence-finding computations to maintain or reestablish the animal's sense of orientation (Gallistel, 1990).

According to such modular views, disoriented search behavior depends on at least two independent processes, operating on distinct representations of the environment. The first process uses representations of nearby, visible objects or surface markings as direct cues to the locations of hidden objects; this use of objects and features as beacons does not involve the computation of one's position and heading, relative to other locations in the environment. The second process uses the global shape of the surrounding surface layout as a cue to the animal's position and heading; this use of environmental terrain excludes information about objects and surface markings and involves a geometric process of congruence finding between the current, perceived layout and the remembered layout prior to disorientation, according to their shape.

This modular theory accounts for disoriented children's and animals' use of landmarks by proposing that the two processes operate independently and in parallel. For example, toddlers' successful search in a large rectangular room with one red wall does not depend on a single process, whereby hidden object's position is specified by its orientation relative to the landmark (e.g., as “northwest of the red wall”). Instead, children use the room’s surface layout to reorient, thereby limiting their search to one of the two locations “northwest of the long wall,” and they independently use the red wall as a beacon, a direct marker that indicates whether the hidden object’s location is toward it or away from it (i.e., “near the red wall”). On this view, the computations involved in reorientation by surface layout are modular, but they do not overshadow all other spatial representations that influence the resulting search behavior of a disoriented child or animal.

The modular view gains support from both ecological and computational analyses of navigation. From an ecological standpoint, the extended 3D surface layouts that form an animal’s terrain are the most stable, reliable, distinctive cues in the natural environment. Surface features such as colors and 2D markings tend to change over time, whereas the global shape of the terrain tends to be invariant (Gallistel, 1990). From a computational perspective, objects in nature such as trees and rocks, and surface markings such as leaf striations, have many featural look-alikes that can only be distinguished by means of fine-grained, computationally expensive, point-by-point comparisons. Because surfaces tend to be smooth whereas objects introduce spatial discontinuities at their boundaries, the shape of a surface layout that excludes objects and their features typically can be described more economically than that of a layout that includes them (Gee, Chekhlov, Calway, & Mayol-Cuevas, 2008). Two of the greatest difficulties faced by robots programmed to navigate by visual images are (a) the error caused by misrecognition of a location when the robot encounters similar objects or displaced objects in different parts of the environment (Thrun, 2002), and (b) the computational explosion caused by the accumulation of representations of complex, cluttered environments **(**Silveira, Malis, & Rives, 2008**).** A reorientation system that focuses exclusively on representing the shape of the continuous surface layout minimizes both these problems.

Thus, one of the key concepts characterizing the modular process of reorientation is that it involves a computation that evolved to be specifically sensitive to 3D surface layouts. In accord with Fodor's (1983) original description of mental modules, this computation is posited to be automatic, specific, and encapsulated from other cognitive processes. Encapsulation is often misinterpreted to imply that a modular computation determines behavior regardless of other cognitive processes; however, encapsulation more accurately refers to the impenetrability of the computation itself, not of the behavioral outcome that it supports (see Fodor, 1983). The distinctive prediction of a modular theory, therefore, concerns the inflexibility of the reorientation process: while reorientation by 3D surface layouts should exhibit high sensitivity, it should be impervious to other functional cues. In particular, a modular geometry-based reorientation process should continue to respond to layout geometry when the navigating child or animal confronts an environment in which geometry is shown to be unreliable.

Several lines of evidence support the modular, two process theory of reorientation. First, controlled-rearing studies with both chicks and fish, performed by two different groups of researchers, have shown that reorientation by room shape does not require experience, supporting the view that reorientation is innately attuned to these environmental cues (Brown, Spetch, & Hurd, 2007; Chiandetti & Vallortigara, 2008). In contrast, use of landmark features is reliably heightened by prior navigation experience

(Brown et al., 2007), providing evidence that the process of navigating by landmarks and the process of navigating by geometry are differently affected by learning.

Second, behavioral studies of spatial learning by human adults provide evidence for distinct processes of encoding the geometry of the borders of an array, on one hand, and for encoding the position and identities of landmark objects (Doeller & Burgess, 2008). While adults navigated actively in a virtual environment containing both a border surface and a landmark object, they were required to encode the positions of specified target objects so as to relocate the objects on a subsequent test. Patterns of performance indicated that the adults automatically encoded the target position relative to the border surface, and that their encoding was resistant to interference from other associative processes in memory. Adults also encoded the target position relative to landmark object, but the latter encoding showed associative interference effects. These findings provide evidence that within a single array and task, landmark-related locations obey the laws of associative reinforcement, whereas boundary-related learning is automatic and incidental, as the modular, two-process view would predict. The modular theory also is supported by evidence for independent neural structures underlying the computation of surface layout geometry and object features, both in animals and in humans. Single-cell recording studies of rats' hippocampal *place cells*, which fire when an animal moves to a particular location in the environment (O'Keefe & Nadel, 1978), have shown that extended surfaces, such as the walls of the testing space, are crucial to the representation of location (O'Keefe & Burgess, 1996). Importantly, while changes in surface boundaries affect place cell activations, changes in texture and material do not (Lever, Wills, Cacucci, Burgess, & O'Keefe, 2002)). In addition, the activation of hippocampal place cells and *head-direction cells,* which fire when a rat is oriented a particular way with respect to the environment, are controlled by landmark objects placed at the periphery of the testing space, where they contribute to the shape of its borders, but not by objects placed in the center of the space (Cressant, Muller, & Poucet, 1997; Zugaro, Berthoz, & Wiener, 2001). Representation of geometric borders has recently been found in the entorhinal cortex of rats; these "border cells" are hypothesized to define the perimeter of the environment and serve as reference frames for encoding locations within that environment (Solstad, Boccara, Kropff, Moser, & Moser, 2008). In humans, moreover, functional neuroimaging studies have shown activation of the right posterior hippocampus for processing locations with respect to environmental boundaries and activation of the right dorsal striatum for landmark-related locations (Doeller, King, & Burgess, 2008).

Despite this evidence, two influential alternatives to the modular view have been proposed. On one view (Cheng, 2008; Sturzl, Cheung, Cheng, & Zeil,2008; Wystrach & Beugnon, 2009), reorientation depends on a coarse-grained view-matching system based on snapshot representations similar to those that guide oriented search by insects (Cartwright & Collett, 1982). According to *image matching theories*, an animal moves to reduce the discrepancy between a stored representation of the two-dimensional image evoked by a scene, on one hand, and the current retinal projection of that scene, on the other; retinal salience therefore determines what environmental features affect an animal's navigation. Computer simulations have demonstrated that search in a geometrically structured environment can result from such models of navigation, and that failure to reorient by wall color can result from the visual similarities of the edges of different colored walls against the simulated "sky" or background (Cheng, 2008; Sturzl et al., 2008). Image matching theories present a stark contrast to theories positing a geometric module, because they make no distinction between 2D, local surface features and 3D, global surface layouts. In particular, the shape of the surface layout plays no privileged role in reorientation apart from the salience of its projected image features in the retinal array.

The second family of alternatives to a modular geometric theory are *adaptive combination theories*, which hold that multiple types of cues can be used for reorientation, weighted according to their experienced validity (Newcombe & Ratliff, 2007). On such views, disoriented subjects' use of landmarks and featural information depends on a single computation for spatial reorientation, performed on all types of available cues (Learmonth et al., 2001; Cheng & Newcombe, 2005). According to these theories, small, movable objects are often ignored by disoriented subjects, because they have previously been experienced as unreliable cues to reorientation. Large landmarks in a large room, on the other hand, are distal, stable, and salient; children and animals learn that such landmarks are reliable cues for navigation and assign high weights for their use in the task of reorienting. Adaptive combination views, like image-matching views, grant no special status to 3D surface layouts other than the high weighting they gain from their salience, size, and stability, all of which make them reliable cues for experienced navigators.

Testing the views through studies of reorientation in children

Studies over the past 20 years have resulted in a wealth of evidence concerning the types of environmental cues that support reorientation by young children. These studies reveal that large, extended 3D surfaces guide children's reorientation whether or not they form a connected enclosure (Gouteux & Spelke, 2001) or surround the child (Huttenlocher & Vasilyeva, 2003). Furthermore, children use surface layout geometry to reorient not only in rectangular spaces but also in spaces that are asymmetric (Wang, Hermer, & Spelke, 1999), triangular (Lourenco & Huttenlocher, 2005), or (by 4 years of age) rhombic (Hupbach & Nadel, 2005).

As discussed above, disoriented children use landmarks in large rooms with one large distinctively colored wall (Learmonth et al., 2001; Learmonth et al., 2002; Hupbach & Nadel, 2005; Learmonth, Newcombe, Sheridan, & Jones, 2008). However, studies testing disoriented children's capacity to use featural information in the absence of informative room shape (in a circular enclosure) suggest that while children successfully encode and remember the object features as direct markers to location, they fail to use their relative positions to reorient by them (Gouteux & Spelke, 2001; Lee, Shusterman, & Spelke, 2006). Children also fail to reorient by the relative positions of freestanding objects with distinctive shapes and colors, or by 2D forms in geometrically distinctive arrays. For example, disoriented children search randomly in geometric arrays of identical objects in the middle of a circular enclosure, even when they are connected by 2D lines on the floor to form a triangle or rectangle (Gouteux & Spelke, 2001; Lee & Spelke, 2008).

In contrast, children's reorientation is affected by objects that are placed at the periphery of the room and therefore contribute to its overall shape. For example, children reorient by a geometric array of 3D objects when the objects are placed at the periphery of a circular enclosure (Garrad-Cole, Lew, Bremner, & Whitaker, 2001).

Similarly, while children fail to use a freestanding object on one side of a room to distinguish between geometrically identical corners (Hermer & Spelke, 1996), they succeed when there is a 3D bulge on one of the walls of the room (Wang et al., 1999). These findings are reminiscent of the findings, from neurophysiological studies of rats and from neuroimaging studies of adult humans, that navigation depends on an automatic encoding of information at the borders of the navigable space (e.g., Cressant et al., 1997; Doeller et al., 2008). Nevertheless, it is not clear whether these successes with objects at the walls of the enclosures indicate reorientation by landmarks or an incorporation of the 3D peripheral objects into the representation of the environmental shape itself.

Recently, Newcombe, Ratliff, Shallcross, and Twyman (in press) tested for direct evidence of 48-59 month old children's reorientation by a large landmark (a colorful blanket) on the edge of a circular enclosure. When three containers were placed in the enclosure to form an equilateral triangle, children had marginally higher success rates at the container that was positioned at a distinctive distance from the landmark (either closer or farther), indicating a possible use of the landmark. They reported above chance performance between the other two locations as well, but the effect was weak (44% success rate against a chance level of 33%) and possibly explained by the children's ability to eliminate the container that was closest to or farthest from the landmark (a strategy that would raise the level of chance responding to 50%). Newcombe et al (in press) also found that 48-59 month old children distinguished between two containers in the middle of a circular enclosure, with a colorful blanket hanging on one side of the room (64% accuracy, against 50% chance). Because the two containers were equidistant from the blanket, and only their relative positions to the blanket distinguished them, this is an important finding that directly challenges the claim that 2D landmark features are not used for reorientation. These findings conflict with the findings of an experiment with younger children (37-51 months old), who failed to use a red curtain on one side of a circular enclosure to successfully reorient and distinguish between object locations (Gouteux & Spelke, 2001).

Nevertheless, three features of these experiments complicate their interpretation. First, Newcombe et al.'s (in press) experiments tested children who were considerably older than the children in the previous research. Some of these children may have learned the relevant spatial words such as *left/right* that would allow them to go beyond the limitations of a purported core capacity of reorientation (Hermer-Vazquez, Moffet, & Munkholm, 2001). To test for this possibility, children's *left/right* word knowledge should be assessed in studies using this age range. Second, because the experiments did not check for disorientation on a trial by trial basis, successful search in this task may be driven by those trials in which children were not sufficiently disoriented. In experiments with more than one "correct" answer, such as the two geometrically correct corners in a rectangular room, disorientation can be checked internally within the data by making sure children search at the correct location no more often than they search its geometric equivalent. In arrays with one correct answer, however, it is crucial to ensure that children's path integration system is completely unavailable by confirming that children are truly disoriented on every trial. Third, the above experiments used 3D objects to create the 2D color cues. It is possible that the thickness of the blanket or the contours formed by the hanging fabric may have been enough to be encoded as 3D bumps on the surface, thus making the blanket a 3D surface cue rather than simply a featural landmark cue. Given the questions concerning the methods of the research discussed above, and the important discrepancies between their findings and those of the past literature, further experiments are needed to pinpoint the role of 2D color cues in guiding children's reorientation.

Suggestive evidence against adaptive combination theories comes from a recent study by Lee and Spelke (2008). Children, whose disorientation was confirmed on every trial, successfully reoriented by a rectangular arena consisting of 30-cm-high walls that they could see beyond and step over, as accurately as they did in an arena with 1-m-high walls that obstructed both their vision and locomotion. In contrast to their success with the layout of wall-like surfaces, children did not reorient using a rectangular array of four 1.8-m-high columns or a 2D rectangular outline form on the floor. Importantly, the children in the column condition and the 2D form condition never failed to look in one of the relevant hiding places (a column, or a 2D corner), showing that they both attended to and encoded these landmarks as direct cues to location. These findings cast doubt on adaptive combination views in three ways. First, the direct functional relevance of high walls that block both vision and navigation did not cause children to rely more heavily on them than on the lower walls that children could see and step over. Second, the large size and apparent stability of the columns nevertheless did not lead children to use their relative positions for reorientation. Finally, the 2D rectangle was not used for reorientation, despite the fact that the round room was devoid of any other competing cues such as a geometrically distinct room shape. In these experiments, therefore, reorientation by surfaces cannot likely be attributed to their functional relevance to navigation, according to their size, salience, and functions as barriers to vision or locomotion.

What properties of wall-like surfaces cause children to use their layout and their relative positions for reorientation? Why, moreover, do children notice and remember columns and 2D forms but fail to reorient by them? The three theoretical views presented above provide different answers to these questions. Image-matching views attribute children's success with wall-like surfaces, as opposed to columns, objects and 2D forms, to the visual salience of the 2D retinal projections from these features of the environment. While the total surface area of the columns tested by Lee and Spelke (2008) was comparable to that of the 30-cm-high walls, the projections of the flat surfaces of the walls, at the child's eye height, produced regions of greater area than those of the cylindrical columns that were 1.8 m tall but only 10 cm wide. Thus, a snapshot matching process may have succeeded better with the continuous surface array.

As noted, adaptive combination views cannot easily explain children's equal performance with tall and short borders of an array, or their failure to reorient by a distinctive array of freestanding columns or surface markings. Nevertheless, walls of variable height, large columns and 2D markings may be rare in the environments that children typically experience, and so children may have failed to learn to use them to modulate their navigation strategies. More conclusive evidence against adaptive combination theories, therefore, would come from studies in which children's performance with the very same landmark objects was modulated by changes in the objects' positions that affect either their 2D image projections (as predicted by image-matching theories) or 3D surface geometry (as predicted by the modular geometric process theory).

Finally, the modular geometric process view explains children's disoriented behavior in terms of distinct processes for navigating by 3D surface layouts and by other cues such as object features, columns, or 2D patterns. On this account, the 3D borders of the surface layout, large and small, distal and proximal, stable and unstable, provide the valid inputs to the modular computation of reorientation. At the same time, objects and featural cues are used as beacons, independently of the surface layout computation for reorientation.

The three theoretical positions described above therefore make contrasting testable predictions concerning the types of arrays and events that will influence children's reorientation. The present study aims to test these predictions by investigating the effects of landmark size, salience, stability, dimensionality, and continuity to the larger layout on the navigation patterns of disoriented children.

Materials and Methods

Overview. Each experiment presented children with two featurally identical landmarks at which an object could be hidden on one side of an otherwise empty circular room. The two landmarks were placed a 90 degree arc apart and oriented perpendicular to the radius of the circular room such that they faced the center of the room. In Experiment 1, the landmarks were two large, 3D, stationary columns, positioned so that all three theories would predict successful reorientation. Experiments 2-6 then attempted to identify the crucial characteristics of the layout that cause children to include or exclude particular landmarks in the disoriented spatial representation. Experiment 2 manipulated the size and salience of the columns by replacing the columns with small boxes; Experiment 3 and 4 manipulated the stability and mobility of the columns by moving them between or within trials; Experiment 5 manipulated the continuity of the columns to the walls of the room; and Experiment 6 manipulated the dimensionality of the columns by replacing the solid 3D columns with 2D strips of the same size.

Testing room. All experiments were conducted within a circular testing room, consisting of twelve curved wall panels, soundproof walls, a solid gray floor, and symmetrical lights mounted on the ceiling. One of the twelve wall panels functioned as the door to the room; from inside the room, the door panel was indistinguishable from the other eleven wall panels. A hidden camera, mounted at the center of the ceiling, provided a video feed to the adjacent room where parents and coders watched the experiment.

Subjects. Subjects were 3 year old children who were recruited from the greater Boston area to come into the lab to participate in a study. Afterwards, their parents received travel cost reimbursements, as well as toys for the child to take home.

Design and Procedures. All experiments implemented a disoriented object search task. The experimenter showed the child an object (typically a sticker) and placed it in one of two possible hiding locations. The child was then blindfolded and turned around in place until disoriented (typically about three or four rotations). Disorientation was checked by asking the child to point to the door while blindfolded; if he/she pointed to the door correctly, the child was turned one or two more times and asked to point to the door again. After disorientation was confirmed, the experimenter stood behind the child and faced the child towards one of four predetermined directions. Finally, the blindfold was removed, the child was encouraged to find the hidden object, and his or her first choice was recorded. Four such search trials were administered with the facing directions varied across trials and the order counterbalanced across subjects. The hiding location was held constant across all trials for a given subject, but varied across subjects. Following the search trials, children were tested on their comprehension of the words *left* and *right* through a set of six randomly ordered questions on their left/right body parts (3 question on *left* and 3 on *right*: e.g., "Can you raise your right hand?").

Experiment 1

In this experiment, children were presented with a white circular room with two large, dark, featurally indistinguishable columns placed against its borders, at positions that were 90 degrees apart (Figure 1). On each trial, an object was hidden in the pocket of one of the columns, the child was disoriented, and then the child was encouraged to find the object. The experiment therefore tested whether children would reorient by the columns and confine their search to the correct column.

Methods. Two square columns were placed against the wall on one side of the circular room. The columns were built out of thick foam boards and measured 38 cm on each side and 1.45 m in height. They were covered with blue fabric on the sides and the front, and were white on the back. A flat square pocket (10 cm on each side) was attached to the front of each column and served as hiding places for the stickers. The columns were placed directly against the curved wall, 90 degrees apart, such that they were oriented to face toward the center of the room.

Subjects were 7 boys and 9 girls, between 36 and 46 months old (*M*= 39.6 months). Two additional children's data were excluded from the analyses because they refused to follow instructions and did not cover their eyes while turning.

Results. On every trial children directly headed for and searched at one of the two columns without searching any other part of the room. Children tended to searched in the correct location (66% correct search, chance = 50%, Cohen's $d = 0.71$, $t(15) = 2.83$, $p = 0.013$, two-tailed). Performance was not correlated with the number of times children turned during the disorientation procedure (Pearson's $r = 0.05$, n.s.) and did not improve from the first to the last trial ($t(15) < 1$, n.s.). The *left/right* language test showed that, as a group, the children were at chance ($M = 56\%$, $SD = 0.18$; compared to 50% chance, $t = 1.38$, n.s.). Furthermore, a particular child's performance on the search trials was not correlated with his/her score on the *left/right* language test (Pearson's $r = 0.09$, n.s.). Finally, we found no effect of sex ($t(14) < 1$, n.s.).

Discussion. Consistent with the findings of past research, the present experiment provides evidence that children reorient by two large, stable landmarks placed against one side of a large circular room. This finding is consistent with all three theories of reorientation, but the theories offer different explanations of this ability. Do children reorient by the two columns because they have learned that large and distal landmarks are stable and reliable? Do children reorient by the columns because they are included in the representation of the overall surface layout of the room? Or do children simply use the columns because they give rise to large and salient retinal projections? Experiment 2 began to address these questions by manipulating the size of the layout objects.

Experiment 2

Experiment 2 tested the importance of the size and salience of the layout objects to disoriented children's ability to use their spatial arrangement, by replacing the large and dark columns of Experiment 1 with small boxes of the same color as the surrounding walls (white). The adaptive combination theory makes a strong prediction of failure in this situation, as the theory claims that children learn that small objects are movable and, therefore, unreliable cues to location (Newcombe & Ratliff, 2007). The visual snapshot account makes a weak prediction of failure in this case, given that the small boxes of the same color as the walls of the room may not be salient enough to be included in the input to a coarse-grained visual image matching system. In contrast to the two above theories, the modular environmental layout account predicts success even with small objects when the objects are placed at the borders of the array, as they yield 3D surface contour information for the geometric reorientation system.

Methods. The methods for Experiment 2 were identical to Experiment 1 except for the size and color of the layout objects: the large blue columns were replaced with small white boxes (30 cm by 15 cm by 15 cm) (see Figure 1). The flat pockets on one face of the boxes were the same size and color as in the previous conditions. Subjects were 8 girls and 8 boys between 36 and 45 months of age (M = 39.6 months).

Results. On every trial children directly headed for and searched at one of the two boxes without searching any other part of the room. Children tended to search in the correct location (67% correct, chance = 50%, Cohen's d = 0.98, $t(15)$ = 3.91, p = 0.001, two-tailed). Again, performance did not depend on the number of turns (Pearson's r = 0.16, n.s.) and did not improve from the first to the last trial ($t(15) < 1$, n.s.). Children performed at chance on the *left/right* language test (*M* = 55%, *SD*= 0.24; compared to 50% chance, $t(15) < 1$, n.s.), and a particular child's performance on the search trials was not correlated with his/her score on the *left/right* language test (Pearson's $r = 0.10$, n.s.). Finally, we found no effect of sex ($t(14) < 1$, n.s.). Performance in this experiment did not differ from performance in Experiment 1, with stationary columns against the wall, $t(30) < 1$, n.s.

Discussion. Despite the fact that the layout objects on the wall were small and subtle, disoriented children used their relative positions to differentiate the two boxes and search the correct location more often than the incorrect one.

What explains disoriented children's ability to use the layout of the columns and boxes in Experiments 1 and 2? According to the adaptive combination theory, the stability and permanence of an environmental component affect the degree to which children use their spatial arrangement to reorient. While the boxes in Experiment 2 were small, they were nevertheless stable – children never saw them move. It is possible that children, therefore, encoded them as attached to the wall and as permanent features of the room. Experiments 3 and 4 test the claim that experiencing layout objects as movable and unstable decreases children's dependence on them for navigation.

Experiment 3

Experiment 3 investigated the search patterns of disoriented children using the same array of columns as in Experiment 1. In contrast to Experiment 1, however, the stability of the columns was compromised by moving them to new locations against the wall before each trial. At the start of each reorientation trial, the two columns appeared in the center of the round room. Then the experimenter lifted each column in turn and placed it against the wall, so as to form the same geometric configuration as in Experiment 1. To further reduce the perceived stability of the columns, their absolute positions against the wall were rotated 90 degrees between successive trials, although their relative positions were invariant. Research on rat place learning suggests that landmark stability affects rats' use of it as an indirect cue to a goal location (Biegler & Morris, 1996). Will the perceived movement of the columns diminish children's spontaneous tendency to reorient by them?

According to the adaptive combination view, children should not rely on unstable, movable objects for reorientation; that view therefore predicts that the motion of the columns will reduce children's search in relation to them. In contrast, the snapshot view and the modular two-process view both predict success, although for different reasons. According to the snapshot view, large, salient columns should have the same effect on the image matching process that is applied to a retinal array, regardless of their stability. According to the modular view, the mechanisms by which an animal reorients have evolved to be sensitive to the surface layout because of their stability (and therefore, their ecological validity) in ancestral environments. Nevertheless, the encapsulated nature of the computation should render the child incapable of strategically suspending this analysis in the face of information that a part of the layout that typically is stable has in fact ceased to be so.

Methods. The methods for Experiment 3 were identical to Experiment 1 except for the movement of the columns before each trial: The columns started out placed in the middle of the room. When the experimenter brought the child inside the circular room, she moved the columns to one side of the room, and placed them against the wall in one of four possible positions before starting the first hiding event. After the disorientation and search trial, the experimenter moved the columns one by one to a new position in the room against the wall, before beginning the next hiding event. The left/right relation of the two columns was held constant (the left column was still the left column after the columns were moved to new positions), and the distance between the two columns was the same as in Experiment 1. Because the positions of the columns was varied across trials, the direction in which the child faced after disorientation was kept constant, such that for each search trial the relative position of the columns to the child (at the time the child opened his/her eyes) was varied and therefore identical to the other experiments. The order of the positions was varied and counterbalanced across subjects. Subjects were 9 boys and 7 girls, between 36 and 45 months old (M = 39.4 months).

Results. On every trial, children directly headed for and searched one of the two columns without searching any other part of the room. Children searched in the correct location reliably (69% correct, chance = 50%, Cohen's d = 0.88, two-tailed $t(15) = 3.50$, $p = 0.003$). Search performance was not related to the number of turns during disorientation (Pearson's r = 0.04, n.s.); moreover, children's accuracy on their last trial was not significantly different from their first ($t(15) < 1$, n.s.). As a group, the children again were at chance on the *left/right* language test (M = 52%, SD = 0.20; compared to 50% chance, $t(15) < 1$, n.s.), and performance on this test was not correlated with search performance (Pearson's r = 0.42, n.s.). We found no effect of sex ($t(14) = 1.72$, n.s.).

Discussion. Despite clear evidence that the columns were movable and an impermanent part of the spatial layout, children performed as accurately as they did in

Experiment 1. These results suggest that children do not adjust their dependence on layout features in the face of evidence for their impermanence and instability. However, it is possible that the methods used in this particular experiment failed to compromise layout stability effectively. Specifically, the movement of the columns always occurred before a particular hiding-finding trial, never during the trial. It is possible that children refreshed their spatial representation of the layout between trials and believed the layout to be stable within each trial of the task. Experiment 4 addressed this possibility by providing children with evidence of the columns' mobility within trials, rather than between them.

Experiment 4

Experiment 4 differed from Experiment 3 in that the movement of the column was introduced at a more critical point in the task: after the object was hidden in one of the columns and just before the child was disoriented.

Methods. The methods were identical to Experiment 1, except for the introduction of a single "column shaking" step between the hiding and disorientation procedures – once the sticker was hidden in one of the columns, the experimenter picked up the column and while shaking it said, "Now, we are going to pick up the box and shake it! See? It can move around!" To avoid introducing long time delays or difficulties in tracking the correct column, the columns were not carried to new positions in the room and only the correct column was shaken – following the shaking procedure, the column was placed back in its original place, the child brought to the center of the room to be disoriented. Subjects were 9 girls and 7 boys between 36 and 43 months of age ($M = 39.9$ months).

Results. On every trial children directly headed for and searched at one of the two columns without searching any other part of the room. Children searched in the correct location successfully (75% correct, chance = 50%, Cohen's $d = 1.22$, two-tailed $t(15) = 4.90$, $p < 0.001$). Performance was unrelated to the number of turns during disorientation (Pearson's $r = 0.12$, n.s.) and did not improve from the first to the last trial ($t(15) < 1$, n.s.). Children were at chance on the *left/right* language test ($M = 54\%$, $SD = 0.22$; compared to 50% chance, $t(15) < 1$, n.s.), and performance on that test was not associated with search accuracy (Pearson's $r = 0.19$, n.s.). We found no effect of sex ($t(14) < 1.3$, n.s.). Performance in the two stationary conditions (Experiments 1 and 2) did not differ from performance in the two movement conditions (Experiments 3 and 4), (67% vs. 72%, $t(62) = 1.08$, n.s.).

Discussion. The results of Experiments 3 and 4 show that evidence of impermanence and instability do not influence whether an object is used as a part of the surface layout representation for reorientation, as adaptive combination theories would predict. Children's tendency to search in relation to the columns was not diminished by evidence for their mobility, either overall or progressively over the course of the experiment. These findings suggest that reorientation performance is quite resistant to evidence that the borders of the layout are not stable.

This resistance is consistent both with the snapshot theory (because momentary snapshots contain no information about the history of an array) and with the two-process modular theory. The modular view interprets these results as evidence for an automatic, encapsulated representation of surface layout whose operation cannot be adjusted strategically in the face of information that the large-scale layout cannot be trusted. While the stability of the surface layout may have played a role in the evolution of sensitivity to surface layouts, observation of mobility in real time does not change the way reorientation is computed. Therefore, children relied on the movable columns as though they were a part of the surface layout in the same way they did in Experiment 1. Nevertheless, the snapshot view provides an equally plausible account of performance in Experiments 1, 3 & 4. Consequently, the next two experiments contrasted these two views directly.

Experiment 5

Experiment 5 tested the effect of dimensionality on reorientation by presenting children with two 2D, dark rectangular strips on the wall with the same dimensions as the columns used in Experiments 4 and 5. According to the snapshot view, large landmarks will be used for reorientation, whether or not they are 3D or 2D, because only their salience in the retinal projection can influence the image comparison process that guides navigation. In contrast, the two-process modular view predicts that children will use 2D surface markings as beacons by which they can localize an object, but not as part of the geometry of the surface layout by which they reorient. On this view, therefore, disoriented children should confine their search to the two strips but choose at random between them.

This study also offers a conceptual replication of the research by Newcombe et al (in press). Recall that in their studies, disoriented children used the position of a single landmark (blanket) on the wall of a circular enclosure to guide their search for a hidden object located at a distance from that strip. Because Newcombe et al's (in press) findings were open to alternative interpretations, however, this conceptual replication seemed warranted. Reorientation by large, 2D markings on the border of the array is predicted by both the adaptive combination view and the snapshot view.

Methods. Subjects were 9 boys and 7 girls, between 36 and 45 months old (*M* = 39.9 months). One additional child participated whose data were not included in the analyses because he refused to follow the blindfolded disorientation procedures. Experiment 5 was identical to Experiment 1, except that the 3D columns were replaced by 2D strips of equal width and height as the 3D columns (38 cm by 145 cm), pasted on the wall of the room (see Figure 1).

Results. On every trial children directly headed for and searched one of the two strips without searching any other part of the room. Children nevertheless searched the correct strip only 47% of the time (chance = 50%, Cohen's $d = 0.10$, $t(15) = 0.42$, $p = 0.68$). Search performance was unrelated to the number of turns during disorientation (Pearson's $r = 0.07$, n.s.) and did not improve from the first to the last trial ($t(15) < 1$, n.s.). Children were at chance on the *left/right* language test (M= 60%, $SD = 0.32$; compared to 50% chance, $t(15) = 1.29$, n.s.), and performance on that test was not correlated with search performance (Pearson's $r = 0.11$, n.s.). Finally, we found no effect of sex ($t(14) < 1$, n.s.). Comparing with the conditions in which the columns were 3D and stationary (Experiments 1 and 2), children's performance was significantly worse using the 2D strips in the present experiment (67% vs. 49%, Cohen's $d = 0.79$, two-tailed $t(46) = 2.69$, $p = 0.01$).

Discussion. On every trial, children searched directly in one of the two 2D strips, showing that they detected the strips, remembered that the object was hidden at one of them, and used one or the other strip as a beacon to guide their search. Despite this ability, children failed to reorient by the strips. These results provide further evidence that children reorient by 3D surfaces but not by 2D surface markings, contrary to image matching views and in accord with the modular reorientation view.

The findings of this experiment accord with those of Gouteux & Spelke (2001), in which children failed to reorient by a single large 2D patch on a circular enclosure. They fail to accord with the findings of Newcombe et al. (in press), in which children did appear to reorient by such a landmark. Because Newcombe et al. (in press) tested an older group of children, failed to check for their knowledge of *left/right* spatial language, and did not confirm children's disorientation on every trial, future experiments could test these potential reasons for the differing findings.

While it seems that the physical properties of mobility and distance from the observer are not the determining factors for reorientation in this task, it is still unclear why children succeeded in Experiments 1-4, given that they failed to use arrays of freestanding columns and objects in the middle of the room in prior experiments (Gouteux & Spelke, 2001; Lee et al., 2006; Lee & Spelke, 2008). Are objects at the borders of the room different from those in the middle of the room, because objects that are continuous with the walls of the room change the room's perceived shape? If that is indeed the case, then the same 3D columns that successfully guided children's reorientation in Experiments 1, 3, and 4 should not be used if they are offset from the walls of the room, such that the real and perceived shape of the room is circular and uninformative for a geometric reorientation process. In contrast, columns that are offset from the walls will be represented more prominently in the retinal projection of the room than are columns at the borders of the room, because of their lesser distance and greater image size. Image-matching views and geometric modular views therefore make opposite predictions concerning children's reorientation by freestanding columns.

Experiment 6

In the final experiment, we placed the 3D columns from Exp 1, 3 & 4 in two positions that were similar to those of Experiment 1 but that were offset from the circular wall of the room. Various precautions were taken to prevent possible confusion by the children as to which side of the columns they were on following disorientation. The front and sides of each column were of a different color and texture from the back and the hiding pocket was only on the front side. Furthermore, the placement of the columns in the circular space was clearly asymmetrical, and they were placed perpendicular to the radius of the circular room such that they were oriented to face the center of the room. To show children that the columns were separated from the walls without giving verbal cues, children were walked once along the periphery of the room at the beginning of the session. Thereafter, all testing occurred with the child in the center of the room, viewing the wall and the columns from the same perspective as in the past experiments.

Methods. Subjects were 7 boys and 9 girls, between 36 and 47 months old (M = 42.4 months). One additional child’s data were excluded from the analyses because he refused to keep his eyes covered while turning. Experiment 6 was identical to Experiment 1 except that the columns were placed 25 cm away from the wall, which was barely far enough from the wall so that the experimenter could walk behind them without touching them (see Figure 1). The front sides of the columns were of a different color and texture from the back and the hiding pockets were only on the front side of the columns. Before starting the game, the experimenter walked the child once along the edge of the room.

Results. On every trial, children directly headed for and searched on the front side of one of the two columns without searching any other part of the room. Nevertheless, children searched the two columns at random (50% correct, chance = 50%, Cohen's $d = 0$, $t(15) = 0.00$, $p = 1.00$. Search performance was unrelated to the number of turns during disorientation (Pearson's $r = 0.01$, n.s.) and did not improve from the first to the last trial ($t(15) < 1$, n.s.). Children performed at chance on the *left/right* language test ($M = 58\%$, $SD = 0.17$; compared to 50% chance, $t(15) = 1.94$, n.s.), performance on that test was not correlated with search performance (Pearson's $r = 0.26$, n.s.), and we found no effect of sex ($t(14) = 1.05$, n.s.). Comparing against the two conditions in which columns or objects were stationary and against the wall (Experiments 1 and 2), we find that the present manipulation of setting the columns off of the wall resulted in significantly lower accuracy (67% vs. 50%, Cohen's $d = 0.74$, two-tailed $t(46) = 2.51$, $p = 0.016$).

Discussion. Children successfully detected the columns and remembered that a sticker was hidden in one of them. Nevertheless, children failed to reorient using an array of two large, stable freestanding columns within the large circular room. These results are in accord with the modular account of reorientation, which proposes that continuity of objects with the rest of the larger surface layout allows objects to be incorporated into the geometric representation of the borders of the navigable array.

The present findings are difficult to reconcile with either the snapshot view or the adaptive combination view. When the columns are moved from the walls of the display (Experiments 1, 3 & 4) toward the center of the display, their projections on the retinal snapshot increase in size. Depending on the detailed nature of the image-comparison process, this size difference should either enhance image comparison and reorientation (if the resolution of the snapshot is extremely poor) or should fail to affect it (if resolution is sufficiently high: see Sturzl et al., 2008). In neither case, however, would a 2D image-matching process account for the present failure of children to reorient by the freestanding columns. We conclude that children's reorientation depends not on processes for matching unanalyzed retinal projections but on processes for establishing geometric congruence between the perceived and the remembered borders of the 3D spatial layout.

The present findings present further problems for the adaptive combination view. To be sure, proponents of that view can posit that more distant objects are more reliable cues to reorientation than more proximal ones. This assumption, however, cannot explain both the contrast between Experiments 1 and 6 (in which only the more distal landmarks were used) and that between Experiments 1 and 5 (in which only the more proximal landmarks were used).

General Discussion

One of the most lively debates in psychology stems from the idea that the mind, like the body, consists of specialized parts that are functional adaptations, evolved to solve specific tasks by processing only a subset of the available environmental information. In the present study, we tested for such a cognitive module for the task of reorientation.

Through a series of six experiments, we demonstrated that children use surface layout geometry for reorientation regardless of whether the surfaces are small or large, stable or movable, salient or subtle. Nevertheless, children's reorientation showed marked signature limits: they successfully reoriented only in relation to 3D objects that were continuous with the walls of the room. These results suggest that the crucial factor that determines whether children will use a landmark object to reorient is not its size, distance, or stability, but its ability to alter the 3D shape of the borders of the extended surface layout.

Children's pattern of performance in these experiments supports the claim that reorientation is specialized to use the 3D surface layout representation that excludes information on 2D features, freestanding objects, and immediate functional behavior or strategic relevance of the layout object. We interpret these results to be signatures of a specialized cognitive computation selected for the use of computationally efficient, ecologically reliable cues to reorientation: the shape of the surrounding landscape. The successes and failures demonstrated by the children demonstrate both the degree of specificity and inflexibility of these computations.

The present findings accord with neurophysiological research on animals. Just as neurons in the rat hippocampus respond specifically to the layout of extended surfaces that forms the walls or borders of the environment (O'Keefe & Nadel, 1978; O'Keefe & Burgess, 1996; Cressant et al., 1997; Zugaro et al., 2001), children's disoriented search behavior depended specifically on the columns that were a part of the walls of the testing room. Furthermore, just as rat place cells fire in accord with the shape of the 3D environment over other properties of the walls such as texture, color, or material (Lever et al., 2002), children's disoriented search behavior did not rely on spatial relationships between two dark 2D strips.

The present findings are at odds with the findings of studies that show rats' place and head-direction cells responding to cue cards at one end of the testing space (Muller & Kubie, 1987; Taube, Muller, & Ranck, 1990). Nevertheless, there are two important differences between the 2D strips used in the present study and the cue card used in past studies of rats. First, cue cards typically are objects, albeit thin ones, whose presence subtly perturbs the symmetry of the 3D layout. As in Experiment 2 of the present study with children, rats may be sensitive to even slight 3D perturbations in a room shape. Second, the present study required a representation of the correct location using relative spatial position between two objects, not one. An interesting comparison to address the above questions would be to test rats using a scaled down version of the current apparatus.

The convergence between humans and other animals provide further reason to view disoriented spatial navigation as implicating modular processes for environmental surface layout representation. Although the snapshot view can account for some aspects of insect navigation, it fails to explain striking features of navigation in rats. In particular, place cell firing in rats is unaffected by plunging the animals into darkness so that no visual matching process could guide them (Quirk, Muller, & Kubie, 1990). And although the adaptive combination view predicts flexibility in cue use, the hippocampal studies show persistent reliance on the shape of the surrounding layout, impervious to large changes in other visible properties of the layout such as the color, texture, and composition of its surfaces (Lever et al., 2002).

In studies of the specificity of cognitive mechanisms, we must recognize that two processes that overlap in time are not necessarily interdependent. Underlying the search behavior of a disoriented child or animal, we propose, are several independent computations: a geometric-congruence computation performed on the 3D surface layout representation of the environment, and a beacon-homing computation performed on landmark objects. Every experiment reported in this paper shows the operation of both these systems. In every study, children moved directly and efficiently to one of the two distinctive landmarks, showing an adept ability to use landmarks to guide their search for an object and a robust use of beacon homing for navigation. Nevertheless, big differences were found across the studies in children's ability to select from among the two available beacons. Here, children's successes and failures accorded with the predictions of the geometric module hypothesis. Nevertheless, further research is needed across the many areas of cognitive science to clarify exactly *how* an animal distinguishes and represents the shape of its environment. The present methods may be useful for this enterprise.

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Figures

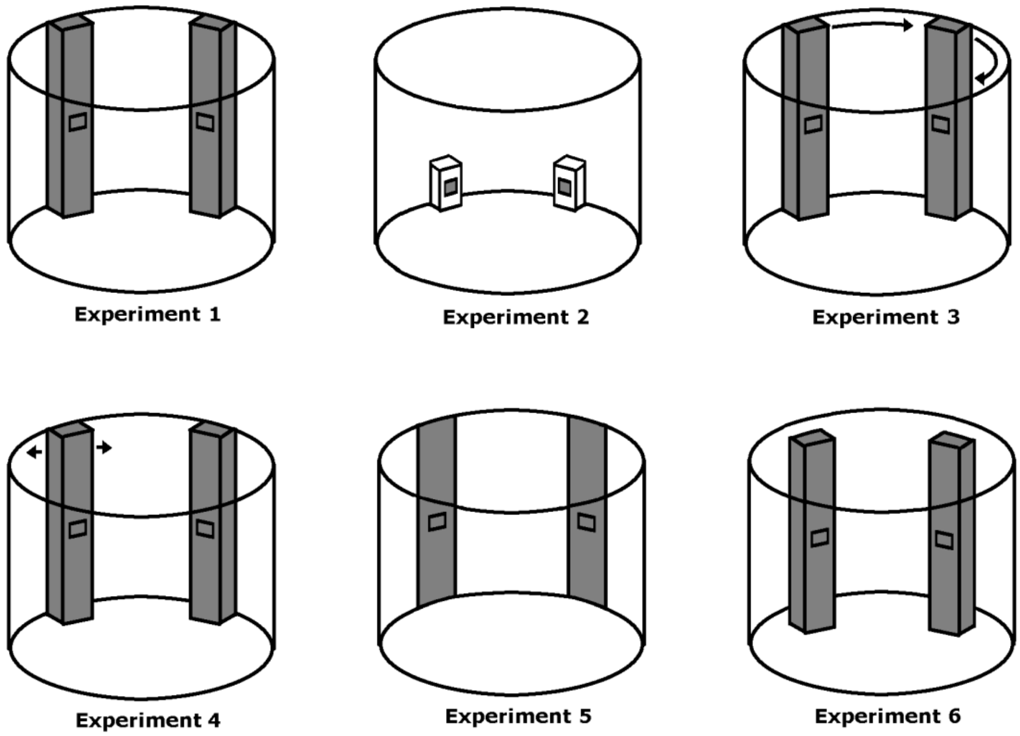

Figure 1. Schematic depictions of the experimental setup. In all experiments, the two landmarks were separated by a 90-degree arc. In Experiment 3, the columns were moved to a new location between trials but maintained the same relative positions for all trials. Arrows indicate the motion of the column containing the object in Experiment 4; for half the children, the opposite column contained the landmark and was moved.

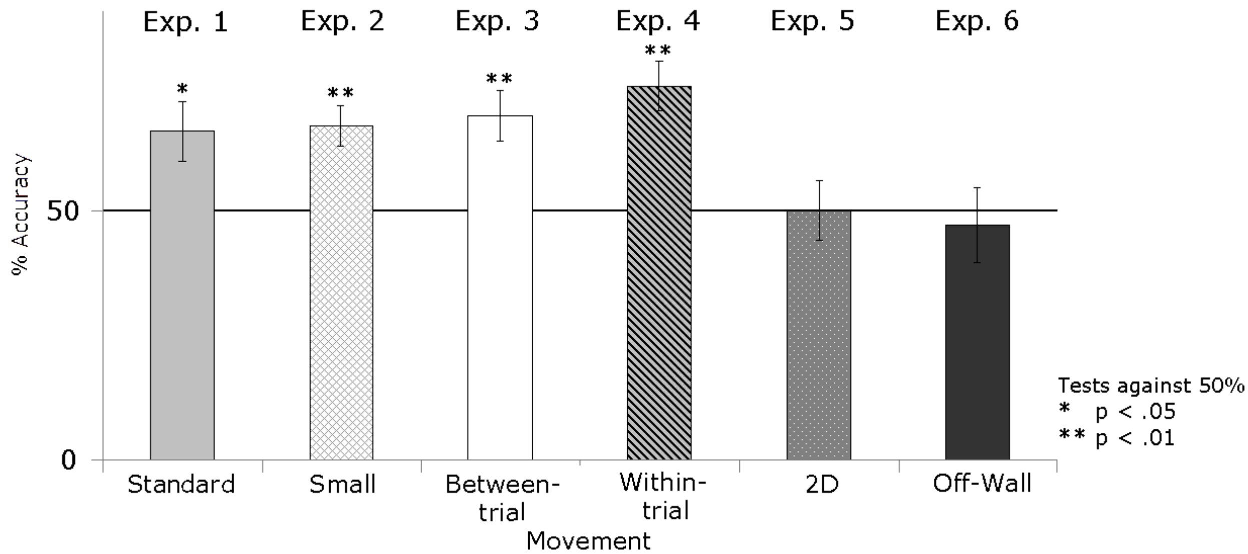

Figure 2. Children's accuracy in each experiment, with two-tailed t-tests against a chance level of 50%; significant comparisons are marked with asterisks. The first study ("Standard") used large 3D stationary columns against the walls: each of the other studies changed one aspect of this display; labels indicate the nonstandard aspect.