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Using geometry to specify location: implications for spatial coding in children and nonhuman animals

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Abstract The study of spatial cognition has benefited greatly from a technique known as the disorientation procedure. This procedure was originally used with rats to show that they relied on the geometry of an enclosed space to locate a target hidden in that space. Disorientation has since been used with a variety of mobile animals, including human children, to examine the coding of geometric information. Here, we focus mostly on our recent work with young children. We examine a set of issues concerning reorientation—namely, the nature of geometric coding, the processes invoked by disorientation, and the developmental origins of using geometric information to determine location. We have employed a variety of methods to examine these issues; the methods include analyzing search behaviors, using spaces of different shapes, varying viewing position, and comparing different disorientation procedures. The implications for how children and nonhuman animals code geometric information are discussed.

Introduction

The ability to reason about space is critically important for mobile organisms. They must be able to locate target places and objects such as food, shelter, and conspecifics. In many cases, finding such targets is necessary to ensure survival. Given this adaptive importance, it is not surprising that several species of animals can code location information in a variety of ways. Yet determining how this information is used for finding desired targets poses a challenging empirical problem since, in particular situations, there may be more than one effective strategy. The challenge for cognitive scientists is further complicated by the fact that even adult humans may not have explicit knowledge of the processes they use to determine location. Fortunately, the study of spatial cognition has benefited greatly from recent methodological advances. Innovative measurement techniques that serve to rule out particular strategies, isolating others, can profoundly affect our understanding of the mechanisms that underlie location coding.

The present paper focuses on one influential technique—the disorientation procedure. This procedure was originally developed for use with rats to examine whether they relied on landmarks or the geometric properties of an enclosed space to locate a hidden target (Cheng, 1986; Cheng & Gallistel, 1984; Margules & Gallistel, 1988). It involved moving the rats around in a dark box (or on a platform) to prevent them from keeping track of their changing relation to the target. By preventing tracking, the rats would have to code the target's position relative to the spatial environment (i.e., landmarks and/or geometry). The possibility that they simply used information about their own position, updating their relation to the target as they moved, was ruled out with this procedure.

Disorientation tasks have since been used with a broad range of mobile animals, including pigeons (Kelly & Spetch, 2001; Kelly, Spetch, & Heth, 1998), rhesus monkeys (Gouteux, Thinus-Blanc, & Vauclair, 2001a), fish (Sovrano, Bisazza, & Vallortigara, 2002;

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Vargas, Lopez, Salas, & Thinus-Blanc, 2004), and human children (e.g., Gouteux & Spelke, 2001; Hermer & Spelke, 1994, 1996; Wang, Hermer, & Spelke, 1999). The present paper is concerned mostly with recent research in young children, mostly from our lab. We review studies, which involve disorientation under a variety of conditions, to examine questions concerning how children code and use location information.

By way of introduction, we present background on different ways to code location. Then, we discuss briefly the issue of geometric modularity, which has received considerable attention in the disorientation literature; this is the view that only geometric information is used for reorientation (e.g., Cheng, 1986; Hermer & Spelke, 1996; Wang & Spelke, 2002; cf. Cheng, 2005; Newcombe, 2002a). Our work, however, has focused on other issues such as the nature of geometric coding, the mechanisms invoked by disorientation, and the developmental origins of using geometric information to determine location. This work has been conducted in young children, but there are clearly implications for understanding spatial processing in other organisms.

Coding location information

For mobile organisms, it is critical to perceive location information across a variety of transformations such as changes in viewing position. When these changes are observable and can be tracked, there are alternative ways to maintain location. One way, often referred to as ego-centered coding, involves specifying a target's location in terms of its relation to the viewer him- or herself. If viewers change position, they can compensate for their translatory and/or rotational movements by calculating the distance and angular variation (direction) of these movements—a process known as dead reckoning or path integration (e.g., Gallistel, 1990; Newcombe & Huttenlocher, 2000; Rieser, Pick, Ashmead, & Garing, 1995). While the mechanisms involved in compensating for positional change are complex, they may be automatic, employed by a wide range of animal species (e.g., Cheng, 1988; Gallistel & Cramer, 1996) and appearing early in development, at least for humans (e.g., Huttenlocher, Newcombe, & Sandberg, 1994; Landau & Spelke, 1988; Newcombe, Huttenlocher, Drummey, & Wiley, 1998).

Another way to maintain location information, often called environment-centered coding, involves specifying the target's relation to the surrounding spatial environment in terms of its distance and direction from particular environmental features (e.g., Gallistel, 1990; Newcombe, 2002b). These features could involve geometric information, landmark cues, or both. Information that is geometric includes extent-based properties such as shape, distance/length, and angle. Landmark cues, in contrast, involve perceptual properties such as color and odor (e.g., Cheng, 2005; Gallistel, 1990; Newcombe, 2006). As indicated above, when organisms can keep track of the changes in their position, they can rely on either ego- or environment-centered information to specify location. However, when tracking is more difficult or impossible (i.e., when organisms become disoriented), some information from the spatial environment *must* be coded to determine the location of a target.

Using disorientation to examine geometric coding

In a seminal study, Cheng (1986; also, Cheng & Gallistel, 1984) showed that when rats were prevented from keeping track of their movements, they used the geometry of an enclosed rectangular space, but not available landmark cues, to locate a hidden target (food). In this task, rats were trained to go to the corner of a rectangular chamber containing buried food. Then, they were moved around in a dark box or fully disoriented by being rotated on a platform (see Margules & Gallistel, 1988). Following the disorientation procedure, the rats were returned to the rectangular chamber where they were allowed to search for the hidden food. They searched mostly at the geometrically appropriate corners (e.g., the ones with the longer wall to the left of the shorter wall), whether or not landmarks (e.g., a different colored wall) were available to disambiguate the target corner from its geometric equivalent (e.g., the corner with the longer *black* wall to the left of the shorter *white* wall versus the corner with the longer *white* wall to the left of the shorter *white* wall).

Hermer and Spelke (1994, 1996) subsequently adapted the disorientation task for use with human children (18–24 months). Children were tested in a rectangular room (4 × 6 ft) with four identical containers, one in each corner. As in the version with rats, children first were shown which corner contained the hidden object (toy). Children then were disoriented—i.e., the parent picked up the child, covered the child's eyes, and spun around several times. After being disoriented, children were placed in front of one of the room's walls (a different wall on each trial) and allowed to search for the hidden toy. Like rats, children searched at the two geometrically appropriate corners significantly more often than chance, whether or not landmarks were present.

The finding that rats and children did not use landmarks to distinguish between the target corner and the geometrically equivalent corner led investigators to posit the existence of a "geometric module" (Cheng, 1986; Gallistel, 1990; Hermer & Spelke, 1996; Wang & Spelke, 2002). The idea is that the processing of geometric information is task-specific and encapsulated, preventing the use of non-geometric cues (landmarks) for reorientation. However, there is accumulating evidence that children and nonhuman animals *do* code landmark information on disorientation tasks under certain conditions. For example, Learmonth and colleagues (Learmonth, Newcombe, & Huttenlocher, 2001; Learmonth, Nadel, & Newcombe, 2002) showed that room size affected the coding of landmarks. Although children did not use landmark information in a relatively small room (4 × 6 ft) like the one used by Hermer and Spelke, they did use this information to restrict search to the target corner in a larger room (8 × 12 ft).

Similar contextual effects have been shown with nonhuman animals. For example, while rhesus monkeys use "big" landmarks to distinguish between geometrically equivalent corners, they are less likely to use smaller ones (Gouteux et al., 2001a). Another example comes from work with pigeons showing that the coding of landmark information may depend on training; for example, pigeons exposed to landmarks from the start of the task continued to rely on this information even when the landmarks were moved to a position that put them in conflict with the geometric information (Kelly et al., 1998). In a review of the existing work, Cheng and Newcombe (2005; see also, Cheng, 2005; Newcombe, 2006) concluded that while geometry is prepotent in many cases, landmarks also are incorporated into the coding of enclosed spaces.

Studying geometric coding: important issues

While it is currently undisputed that mobile organisms are able to use geometric information to locate target objects and that, under certain conditions, this information is given more weight than landmark cues, the nature of this ability remains poorly understood. Several important questions have not been investigated empirically. One of these questions concerns which aspects of geometry are actually coded. In particular, it is not known whether viewers code global parameters such as the entire shape of an enclosed space, or whether they code more local parameters such as the portion of the space containing the target object. In the following section, we present research on young children showing that when the task involves finding an object hidden in an enclosed space following disorientation, children code information about the entire space (Huttenlocher & Vasilyeva, 2003; Huttenlocher, Lourenco, & Vasilyeva, 2006; see also, Lourenco, Huttenlocher, & Vasilyeva, 2005b). We also discuss recent work with nonhuman animals examining which geometric cues are relevant for reorientation (e.g., Cheng & Gallistel, 2005; Tommasi, 2005).

A related issue concerns the role of viewing perspective on object location tasks. While current conceptualizations of geometric (environment-centered) coding do not specify information about the viewer (ego), there is reason to believe that such information may be important to the task of locating a hidden object, even under disorientation. After all, the goal of the disoriented viewer is to find the hidden object, and, ultimately, this requires knowing its position relative to the viewer. Below, we present evidence that children code information about their own position relative to enclosed spaces, which may be critically important to the object location task by allowing them to infer their relation to the target object (Lourenco et al., 2005b; see also, Huttenlocher et al., 2006).

Another important issue concerns the nature of the disorientation procedure itself. While most disorientation studies have used the technique of rotating the viewer, it has been tacitly assumed that the procedure would have the same effect if instead the spatial array were rotated (with eyes covered). This would seem to be a reasonable assumption since both tasks prevent tracking of the viewer's relation to the target. However, given that the processes invoked by disorientation are poorly understood, such an assumption may actually be unwarranted. Recently, we compared the effects of two disorientation procedures—one involving viewer movement, the other involving space movement—on children's ability to locate a hidden object. Below, we present evidence showing that how disoriented viewers approach the problem of object-finding is highly influenced by the kind of transformation causing the disorientation (Lourenco & Huttenlocher, 2006).

Finally, questions concerning the developmental origins of geometric coding have received little attention. While many studies have shown that the ability to use geometric information for determining location is present by 18–24 months, there is reason to believe that this ability may be present earlier in life, perhaps even in infancy. The fact that several species of animals are sensitive to geometry suggests the possibility of hardwired adaptive mechanisms. Alternatively, it is possible that certain experiences common to these species (e.g., locomotion) are involved in the development of this ability. Below, we present recent data from our work with pre-crawling infants showing that under some conditions, they can already use geometric information to locate a target (Lourenco, Huttenlocher, & Fabian, 2005a).

Studies from our lab have begun to explore the issues described above. We have devised a variety of methods to examine how young children (18–24 month age range) represent location when it is not possible to keep track of a target's position relative to oneself (i.e., on disorientation tasks). These methods include analyzing children's search behaviors, using spaces of different shapes, and varying the position of the child at various points throughout the task. As indicated above, we also have used different procedures for invoking disorientation and, more recently, have used a paradigm appropriate for examining geometric coding in young infants (5.5 months of age).

How is geometry coded?

To find an object hidden in an enclosed space, with no available landmarks, disoriented viewers must code geometric information about the space. But there is more than one possible way to do so. One way would be to focus on the critical portion of the space, namely, just the target corner containing the hidden object. The relevant information could involve the relative side lengths of the conjoining walls or the angular size of the target corner. Notably, this kind of "local" spatial coding is constrained by the initial viewing position. Take, for example, the relative side lengths of the target corner in a rectangular space. The relation here is specified by where the viewer stands. If the viewer stood outside the space, rather than inside, the relative positions of the long and short walls for the corner would be reversed (see Fig. 1). This also is the case for information about angular size. For a viewer who stands inside the space, the target corner appears as an angle of 90°; from outside, it appears as a 270° angle (see Fig. 1). If children coded such local information, which is dependent on the initial viewing position, they would have to survey the various parts of the space after disorientation to recover their original viewpoint.

Another way to represent the location of a target in an enclosed space would involve using geometric parameters that are more "global" than those described above. Global parameters could involve the shape of the space so that the location of the target object would be coded relative to the entire space. Because shape information involves the relations among the space's constituent parts, this information is not dependent on a particular viewpoint. That is, an enclosed space shaped as a rectangle would likely be represented as rectangular regardless of where the viewer stood. Thus, if viewers coded the entire shape of the space, they would be able to infer their relation to a geometrically appropriate corner from different viewpoints. More importantly, they would not have to survey the space for their original viewpoint to locate the target, as is the case when more local parameters are coded.

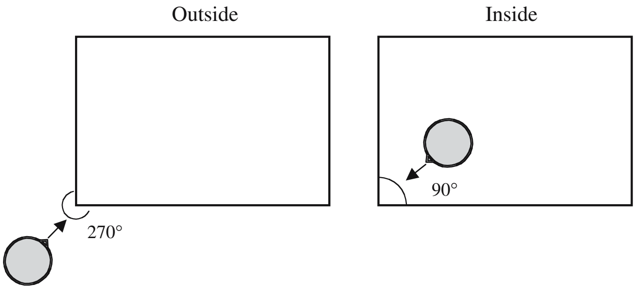

Fig. 1 The appearance of a target corner in a rectangular space from different positions—outside and inside. From outside, the shorter wall is to the left of the longer wall and the angular size of the corner is 270°. From inside, the longer wall is to the left of the shorter wall and the corner is a 90° angle

Search behaviors

While previous studies involving disorientation have focused on performance accuracy, Huttenlocher and Vasilyeva (2003) noted that further insight could be gained about children's spatial coding by examining how they searched for a hidden object. More recently, Tommasi (2005) made a similar suggestion; he proposed that examining animals' visual behavior patterns, such as the time spent scanning the space, could help to resolve questions of which geometric parameters are coded on these tasks.

In our experiments, children were videotaped (with an overhead camera) throughout the task and their search behaviors following disorientation were analyzed (Huttenlocher & Vasilyeva, 2003; Huttenlocher et al., 2006). Specifically, we examined whether children surveyed the various parts (e.g., corners) of the space, or if they went directly to a particular corner without surveying the space (i.e., beeline). Children were classified as having displayed surveying behaviors if they looked or moved around the space (e.g., turning their heads, torsos, or whole bodies) prior to searching for the object. Although it was not always possible to make a classification because children were occluded in the video or their movements were too subtle, it was clear that they made a beeline to a particular corner (no surveying) on the majority of trials—ranging from 67 to 91% of the trials, depending on the condition.

Importantly, the finding that children tended to go directly to a particular corner did not reflect a failure of the disorientation procedure. That is, in a rectangular space, children were not always going to the target corner; they also searched at the geometrically equivalent corner. Furthermore, the performance of children who displayed surveying behaviors did not differ from the performance of those who did not display these behaviors; this is important because coding information that is more specific to the target corner vs. the entire space does not predict differences in performance on this task, it only predicts differences in *how* children should search for the hidden object.

That children are not likely to survey the space following disorientation applies to enclosed spaces of different shapes (rectangle and isosceles triangle); it also applies to different positions, as long as the viewer's position relative to the space is held constant throughout the task (i.e., children remain inside or outside the space). Thus, in most cases, children can infer their relation to a geometrically appropriate corner, regardless of which wall they face following disorientation. As indicated above, these results suggest that children use more global geometric parameters to determine the location of a target. Indeed, we have proposed that children may code information about the entire space on these tasks (Huttenlocher & Vasilyeva, 2003; Huttenlocher et al., 2006; see also, Lourenco et al., 2005b).

Different shaped spaces

In addition to analyzing search behaviors, we have tested children with spaces of different shapes to examine questions concerning the nature of geometric coding. The initial disorientation studies involved rectangular-shaped spaces (e.g., Hermer & Spelke, 1996; Learmonth et al., 2001). Yet the use of a rectangle presents certain limitations since only one kind of geometric parameter is available. In particular, the corners of a rectangular space can only be distinguished on the basis of relative side lengths; other parameters, such as angular size, are not informative since all the corners are identical in the size of the angle. In contrast, information about angular size can be useful in spaces of other shapes such as an isosceles triangle or a rhombus.

In our studies, we have used spaces shaped like isosceles triangles (in addition to rectangles). In an isosceles triangle, the corners can be distinguished on the basis of side lengths and/or angle. Two of the corners are like those of a rectangle, distinguishable in terms of their relative side lengths (i.e., one corner has the longer wall to the left of the shorter wall, and the other corner has the longer wall to the right of the shorter wall), but not by the size of their angles (both are identical). However, one of the corners is "unique" with respect to these parameters; this corner can be distinguished from the other two in terms of side lengths (both sides are equal) and angular size (the smallest angle). By using an isosceles triangle, we could examine exactly what geometric information children used to locate a target object.

There are different ways that children could represent the location of an object hidden at one of the corners of an isosceles triangle. One way would involve coding relative side lengths *and* angular size. If children used both kinds of information, their performance would be above chance, regardless of which corner served as the hiding location. More importantly, though, they should be significantly better at the unique corner since it differs on both dimensions. Another way to determine the target's location would be to use angular size alone. In this case, children would only perform above chance if the object was hidden at the unique corner; the other two corners would be indistinguishable since they are identical in angular size. Yet another way to approach the object location problem with an isosceles triangle would involve coding information about relative side lengths. In this case, performance would be above chance at all of the corners and would not vary by corner since each is distinguishable on the basis of this information. Note that this approach would be consistent with the view that children code the shape of a space because information about relative side lengths can be used to specify shape.

We have shown that with isosceles triangles, children perform significantly above chance at each of the corners, whether they are tested from inside or outside the space (Huttenlocher & Vasilyeva, 2003; see also, viewer-movement groups in Lourenco & Huttenlocher, 2006). But more important, task difficulty does not vary as a function of hiding corner; in particular, performance was not better at the unique corner, nor was it at chance for the other two corners. Using a rhombic-shaped space, Hupbach and Nadel (2005) showed that even when angular size was the only information available to distinguish between the corners, it was not until 4 years of age that children coded angle on this task. These findings make a great deal of sense since, as indicated above, information about relative side lengths (but not angle) can be used to specify the shape of a spatial layout.

Questions concerning the nature of geometric coding are currently receiving attention in the nonhuman animal literature as well. Two recent studies, one with rats (Pearce, Good, Jones, & McGregor, 2004) and one with chicks (Tommasi & Polli, 2004), examined whether these animals coded global information about the entire shape of a space or whether they coded local information more specific to the target corner. In these studies, animals were trained to go to a particular corner in one space (e.g., parallelogram-shaped space) and then were moved to the test space, differing in overall (Euclidean) shape (e.g., rhombus), where their choice of corner was observed. Because the animals made nonrandom choices in the test space, the authors concluded that they had not coded the shape of the training space. Instead, it was proposed that the animals relied on more local cues such as the angular size of the target corner.

Cheng and Gallistel (2005) and Cheng (2005) proposed an alternative explanation to account for the finding that animals searched consistently at particular corners when moved to a different-shaped test space. They suggested that the animals coded the first (major) principal axis, which passes through the centroid (i.e., center of mass) of the space, running its length. Because this axis captures global information about a spatial layout without specifying the Euclidean shape, organisms would be able to match location information from two spaces incongruent in shape. While our studies with young children cannot distinguish between different kinds of "global" coding—shape versus axes—this is clearly an area for future research with several important questions that should be addressed. One question concerns computation. For example, how would viewers compute the appropriate axes? While the principal axis for a rectangle may be obvious, it is not easily known for other shapes like parallelograms (see Fig. 2). Perhaps even more important is whether such axes are actually computed in three-dimensional navigable spaces, and, if so, whether these are the same principles underlying the computation of axes for two-dimensional shapes (cf. Tommasi, 2005).

Viewing position (inside vs. outside)

As indicated above, disoriented people and animals can use environment-centered (geometric) representations to locate a target object. These representations specify a target object's relation to the spatial environment; they are not thought to specify information about the viewer, either in relation to the object or to the space (e.g., Gallistel, 1990). Yet the relation of the viewer to the object must be known since the goal of the disorientation task is for the viewer to find the hidden object, which involves approaching the corner and retrieving that object. In other words, there must ultimately be a link between the viewer and the target object. Because the disorientation procedure disrupts this link by preventing the viewer from directly tracking his/her changing relation to the target, the viewer has to infer this relation. We hypothesized that such an inference could be made if children coded information about their own position in relation to the enclosed space, since the target's position is also specified in relation to the space.

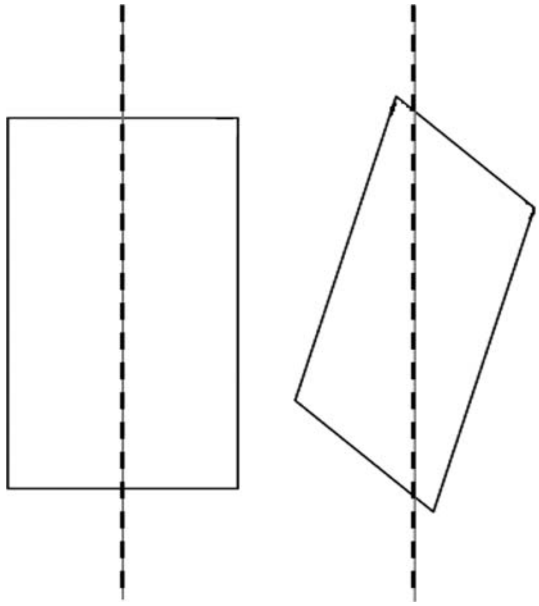

Fig. 2 The principal axes for two different shapes—rectangle and parallelogram

In a series of studies, we examined whether children actually coded information about their position on disorientation tasks by testing them from inside or outside various spaces. The idea is that if information about the viewer is not coded, this manipulation should not affect performance. In these experiments, we used enclosed spaces with short walls (e.g., 18 in high) so that when children stood outside the space they could see and reach into the containers at each of the corners. These testing spaces were surrounded by a round fabric enclosure (13 ft. in diameter, 7.5 ft high) to prevent the use of other cues from the larger room.

In some of our experiments, viewing position relative to the space was held constant so that children remained either inside or outside a space throughout the task (Huttenlocher & Vasilyeva, 2003; see also, control groups in Lourenco et al., 2005b; viewer-movement disorientation groups in Lourenco & Huttenlocher, 2006). The inside and outside conditions were identical except that, in the outside version, the disorientation procedure involved the parent holding the child, whose eyes were covered, and walking around the space (rather than spinning around in one place as in the inside version). In another study, we made viewing position more variable so that children were moved (i.e., "translated") into or out of the space during the task (Lourenco et al., 2005b). Specifically, children either stood inside the space during the hiding phase and outside during the search phase, or they stood outside during hiding and inside during search. Importantly, the order of translation and disorientation was also varied—i.e., the disorientation procedure was administered either before or after children underwent translational movement. These conditions were identical except for the translation–disorientation order; hence, any differences in performance would be due to the order of these transformations.

Consider first the conditions in which children remained inside or outside the space (i.e., no translation). Although performance was above chance for both positions, the difficulty of the task depended on where children were tested. Specifically, children in the inside version performed better than children in the outside version, regardless of the shape of the space (rectangle or isosceles triangle). These findings showed that children did not code the target's location exclusively in terms of its relation to the enclosed space; if they had, performance would not have varied as a function of the viewer's position. Instead, these findings show that children incorporate information about their own position (inside vs. outside) into the coding of enclosed spaces.

Consider next the conditions in which children were translated into or out of the space during the task. It is possible that when viewing position is made more variable, children would not code information about their own position. Instead, they might just rely on information about the spatial environment (i.e., the shape of the enclosed space) to locate the hidden object. If children approached the location problem in this way, their performance should be unaffected by translational movement since information about their own position is not included (and thus need not be updated). In contrast, if children continued to rely on their relation to the enclosed space (as being inside or outside), their performance might be affected by the order of transformations. The reason is that with a task involving translational movement, children would have to update information about their position, and, as explained below, this may be easier to do if translation precedes disorientation than if disorientation precedes translation.

Consistent with children having coded information about their position relative to the space, we found that performance depended on the order of transformations. When translation preceded disorientation, performance was comparable to when there was no translational movement; children searched mostly at the geometrically appropriate corners. Furthermore, children who searched for the hidden object from inside, having been moved into the space, performed somewhat better than children who searched for the object from outside, having been moved out of the space. In contrast, when disorientation preceded translation, performance was much worse; indeed, children searched randomly (i.e., chance level) at each of the corners, either when outside or inside the space. This effect of translation–disorientation order is important for showing that performance differences on inside and outside versions of the task are not simply due to children being unable to deal with different perspectives on a space since performance was only affected by translational movement if they were disoriented before being moved into or out of the space.

Having shown that performance depends on the viewer's position relative to an enclosed space, consider why the outside version of the task might be more difficult than the inside version. The difference might reflect variation in the distinctiveness of the critical components of the space (i.e., the corners). For a viewer who stands outside a space, all of the potential hiding corners lie in front of the viewer (see Fig. 3). Since the corners' positions relative to the viewer are highly similar, they are more likely to be confused with one another. In contrast, for a viewer who stands inside the space, the corners are not all in the frontal plane—they are either in front, behind, to the left, or to the right (see Fig. 3). Thus, from inside, the corners relative to the viewer are more differentiated, making them

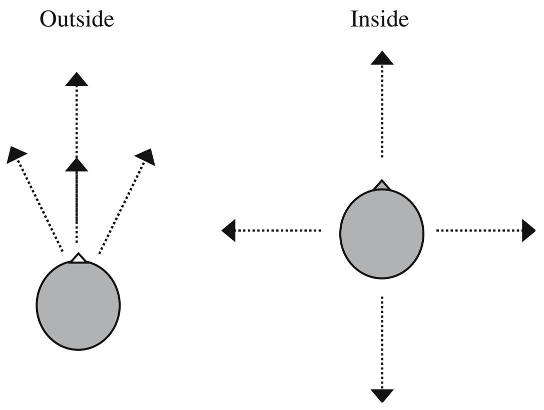

Fig. 3 All illustration of outside and inside perspectives on an enclosed space

less confusable and perhaps leading to better performance on this version of the task.

Let us now return to the issue of why the viewer's position might be coded on disorientation tasks. Above, we suggested that it might serve an important function—that it could allow disoriented viewers to infer a link between themselves and the target object. Our findings suggest that this inference may be relatively easy to make in some cases, such as when the viewer and the target object bear a common relation to the space. This is the case when the viewer remains inside or outside the space throughout the task. However, when the task involves translational movement so that viewing position is more variable, children have to establish a relation to the space before an inference can be made. When translation precedes disorientation, they can do this by keeping track of their movements relative to the target object and then updating their own position relative to the space as they are translated. However, when disorientation precedes translation, viewers cannot keep track of the target's position during translation (because they have just been disoriented) and it is more difficult to update information about their own position during translation (because they have just been disoriented). Hence, when disorientation occurs first, children have to rely on information about the target's location that they coded from a different perspective, one that does not match how they see the space after translation, which may make this version of the task much more difficult.

Taken together, our findings have important implications for how to conceptualize "environment-centered" coding. As indicated above, current conceptualizations do not specify information about the viewer ("ego"). Yet information about the viewer's position may be necessary to support the task of retrieving a target object. Indeed, it may provide a link (albeit an indirect one) between the viewer and the target. The idea is that the viewer's relation to the target object is mediated by his/her relation to the spatial environment. The environment could involve an enclosed space (as in our tasks) or other features such as landmarks. As with enclosed spaces, coding an organism's relation to a landmark could allow one's relation to the target to be inferred. Consider an example from the animal literature. Cheng (1988, 1989) provided evidence that pigeons learn to find a hidden target (e.g., grain buried in sand) by coding two kinds of information—the target's relation to nearby landmarks (i.e., landmark-to-target vectors) and the pigeon's own relation to these landmarks (i.e., self-to-landmark vectors). By coding both kinds of relations, the animals are able to compute (implicitly) the distance and direction they need to move to retrieve the target (i.e., self-to-target vectors).

The disorientation procedure

While the use of the disorientation procedure has profoundly influenced current views of spatial coding in mobile organisms, the nature of the procedure itself remains poorly understood. As indicated above, studies using disorientation have generally adopted the procedure of rotating the viewer (e.g., Hermer & Spelke, 1996; Huttenlocher & Vasilyeva, 2003; Learmonth et al., 2001, 2002; Lourenco et al., 2005b; Wang et al., 1999). However, other studies with children and nonhuman animals have used an alternative method of rotating the space (children: Gouteux, Vauclair, & Thinus-Blanc, 2001b; Hupbach & Nadel, 2005; chickadees: Gray, Bloomfield, Ferrey, Spetch, & Sturdy, 2005); the assumption being that as long as the rotations cannot be tracked, the task of locating a target object should be equivalent in both cases.

The fact that both disorientation tasks require that viewers use information about the spatial environment (enclosed space) to locate the target object may justify the assumption of task equivalence. But it does not guarantee psychological equivalence. Indeed, several studies have shown that determining a target object's position in an array of several objects is affected by whether the task involves movement of the viewer versus of the array. In general, children and adults are better at locating targets following their own movements than following movements of an array (e.g., Huttenlocher & Presson, 1979; Presson, 1982; Simons & Wang, 1998; Wraga, Creem, & Proffitt, 2000, 2004). This dissociation makes sense since viewer movement tasks require keeping track of only one item (i.e., the self), whereas space movement tasks generally involve maintaining the relations among several items (Huttenlocher & Newcombe, 1984; Huttenlocher & Presson, 1973, 1979; Presson, 1982).

Recently, we examined whether determining location following disorientation also depends on whether the viewer or the space is rotated (Lourenco & Huttenlocher, 2006). We tested young children in either a viewer- or a space-movement disorientation task with an enclosed space shaped like an isosceles triangle (4.3 × 3 × 4.3 ft). The tasks were identical except for the disorientation procedure, which involved rotating either the viewer or the triangular space several times. In both cases, children's eyes were covered to prevent them from keeping track of the hidden object. The triangular space in this experiment was bottomless with shelves affixed to each of the corners; the identical containers, which served as potential hiding places, were placed on the shelves. Attached to the underside of the triangular structure were wheels with brakes so that it could be moved and would remain stationary when in the appropriate position. As in our other studies, there was a round enclosure surrounding the triangular space so that no other cues could be used to locate the hidden object.

As indicated above, it has been tacitly assumed that both methods of disorientation are psychologically equivalent, invoking the same processes for determining location. On this view, performance on our two tasks, which involved the same space, should not differ. Yet we found significant differences. Specifically, there was an interaction between the disorientation procedure used and the corner that served as the hiding location. In the viewer-movement version, children performed above chance regardless of the hiding corner. However, in the space-movement version, children could only locate the object when it was hidden at the unique corner (and did so as accurately as their viewer-movement counterparts); with the non-unique corners, performance did not differ from chance. Importantly, then, any explanations of these findings must account for the interaction between disorientation procedure and hiding corner, not just the overall worse performance on the space-movement task.

While both disorientation procedures prevented viewers from tracking their changing relation to the hidden object (so that geometric information would have to be used to find the object), it was clear that the nature of the problem changed on the two tasks. Take the task involving rotation of the space. Following disorientation, children were confronted with the unusual situation of seeing the triangular space in a different position when they had not themselves been moved. This situation clearly contrasts with the one involving viewer movement where the change in the viewer's perspective is consistent with the child having been rotated. Indeed, mobile organisms normally experience such changes in this way; viewers, not large spaces, move to different positions, thereby altering their relations to objects and places in the environment.

Consider, then, how children might have approached the problem of object location in the space-movement task. It is possible that to deal with the unexpected change in perspective, children attempted to establish their original relation to the space, perhaps by mentally re-aligning the space with themselves. The transformation in this task would be like visualizing an object undergoing rotational movement. While it has been shown that mental transformations are generally difficult for young children, it also has been shown that certain conditions can facilitate the transformation of spatial arrays. For example, children are better at mentally rotating objects with distinctive cues (Rosser, Ensing, & Mazzeo, 1985; Rosser, Ensing, Gilder, & Lane, 1984). And we found a similar benefit with the unique corner in our space shaped like an isosceles triangle.

Another way to facilitate performance on tasks involving movements of an array would be to focus on one of the items, rather than the entire array (Huttenlocher & Presson, 1979; Presson, 1982; see also, Hermer & Spelke, 1996). This strategy can be used when the task requires knowing the location of only the target item. Children in our task might have used a similar strategy. That is, they could have focused on the critical part of the space—the hiding corner. On this strategy, transformations of the critical information would be easier with the unique corner because the sides are equal in length, making it unnecessary to maintain the left–right relations of the sides. (This corner also is unique with respect to angular size but, as indicated above, the existing evidence suggests that young children may not code such information, especially if they can use information about side lengths.)

It is important to note that in the space-movement disorientation task, but not the viewer-movement version, accuracy increased over the test trials, indicating that children's transformations of the critical information improved with experience. This finding is consistent with research showing that practice leads to better performance on more traditional mental rotation tasks, even when no explicit instruction is provided (e.g., Levine, Huttenlocher, Taylor, & Langrock, 1999; Platt & Cohen, 1981). Because the improvement occurred in the context of a corner by task interaction, it is not likely that children simply learned that their perspective could change when they remained stationary; if they had, they would have done well at all of the corners, as in the viewer-movement task.

Let us now consider how children might have approached the object location problem on the viewer-movement task. Unlike the space-movement version, the change in the viewer's perspective was not an unusual situation; it was entirely consistent with children having themselves been rotated. Accordingly, children would not have to adjust their relation to the triangular space (cf. Huttenlocher & Presson, 1979), which explains why they could find the object regardless of which corner served as the hiding location. As in previous studies, our results show that when the task involves a viewer-movement disorientation procedure, children can easily use information about the shape of the space to locate a target object.

Having shown a dissociation between viewer- and space-movement disorientation procedures, consider the findings from two other studies. In a study with children, Gouteux et al. (2001b) showed that 3-year-olds did not use the geometry of a small rectangular box to locate a hidden object, searching randomly at all four corners. They argued that small (non-navigable) spaces are represented differently than larger (navigable) spaces. However, children may have found this task difficult because it involved movement of the rectangular space, which may require establishing the child's original relation to the space. Indeed, using a viewer-movement disorientation procedure, it has been shown that younger children (21–24 months) can code the shape of enclosed spaces comparable in size to that used by Gouteux and colleagues (see Huttenlocher & Vasilyeva, 2003). More recently, Gray et al. (2005) found that although wild-caught mountain chickadees used landmark cues to find a target, they did not always use geometric information. The reason, they argued, is that wild animals lack experience with enclosed spaces. However, they too disoriented the animals by rotating the space, which may have affected how the animals approached the location problem.

Origins of geometric coding

Several of the studies discussed thus far have shown that by 18–24 months of age humans can use geometric information for the purpose of determining location. Yet questions concerning the developmental origins of this ability remain unresolved. While there is reason to believe that the ability to code geometry may be innately specified, it also is reasonable to expect that certain experiences may be important to its development. The fact that several animal species can code the shape of enclosed spaces suggests the possibility of hard-wired adaptive mechanisms. However, cross-species convergence can arise from common environmental experiences serving to tune similar starting-point mechanisms. One important experience could be independent locomotion.

While it has been shown that locomotory experience can affect how one reasons about location (e.g., Bai & Bertenthal, 1992), there also is evidence that young, pre-crawling infants are sensitive to particular kinds of geometric information. For example, infants can discriminate between two different-shaped forms (e.g., rectangle vs. square) even when the orientations of these forms vary (e.g., Schwartz & Day, 1979; Slater, Morison, Town, & Rose, 1985). Infants also are sensitive to angular relations, at least when the connecting line segments are equal in length (e.g., Cohen & Younger, 1984; Slater, Mattock, Brown, & Bremner, 1991).

Despite the evidence showing an early sensitivity to certain geometric cues, it is not known whether infants can use such cues to determine the location of a target. Using a habituation paradigm, we examined this issue in pre-crawling 5.5-month-olds. Infants were shown (on a computer screen) a two-dimensional isosceles triangle with a red dot at one of the corners. The dot remained in the same corner during the habituation phase, but alternated between this corner and a different corner during the test phase. Importantly, the triangle always appeared in a different orientation. In one of the experiments, the orientations (eight in total) were highly variable, randomly sampled across 360° (see Fig. 4). In other experiments, the set of possible orientations (eight in total) was less variable, i.e., restricted to within 180° either along the horizontal or vertical axis.

We found that infants' ability to distinguish between two locations depended on the range of possible orientations—that is, how much the triangle appeared to rotate. When the rotation was highly variable, infants could only distinguish between two locations if one of them was at the unique corner. This result is similar to the one reported above with older children in a space-movement disorientation task, indicating that what may account for this effect is not that there was a triangular layout displayed on a vertical surface, but rather that it appeared to rotate (cf. Kelly & Spetch, 2004a, b). Importantly, we also found that when infants were presented with less

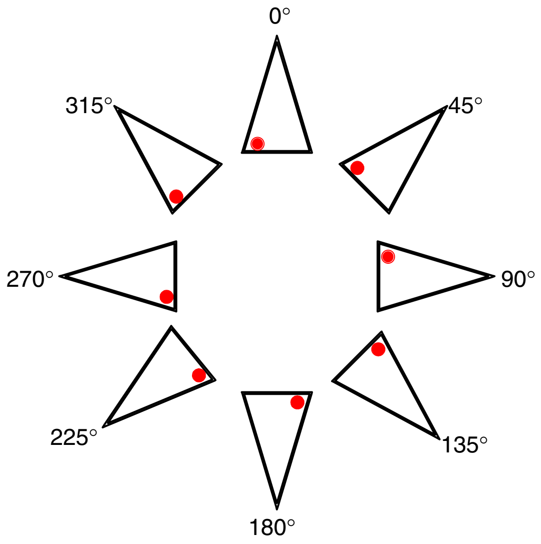

Fig. 4 The set of possible orientations used by Lourenco, Huttenlocher, and Fabian (2005a) in the experiment involving highly variable orientations (sampled across 360°). This example shows the (*red*) target dot at one of the non-unique corners

variable orientations, they could also discriminate between locations at the non-unique corners. Thus, it seems that at an early age, prior to independent locomotory experience, humans can use geometric information for the purpose of locating a target.

The fact that performance depended on the range of apparent rotational change is critical for understanding which geometric parameters are coded on this task. One possibility is that infants coded the invariant properties of the layout (cf. Biederman, 1987; Biederman & Bar, 1999; Jacobs, 2003). These are the properties that do not depend on the orientation of the triangle—namely, the size of the angles and the lengths of the sides. If infants coded just these properties, they would have little difficulty distinguishing between the unique corner and the non-unique corners, but they would find it impossible to distinguish between the non-unique corners (since these are identical in angular size and have unequal-lengthened sides). The fact that infants did discriminate between the non-unique corners when there was less apparent rotational change suggests that they coded more global geometric information. Unlike the invariant cues, however, this information does depend on the orientation of the spatial layout (cf. Diwadkar & McNamara, 1997). As a result, determining the location of the target on this task would require compensating for changes in the triangle's orientation, which may be easier to do when there is less change.

Conclusions

It was once believed that young children could only code location in an ego-centered way (e.g., Piaget & Inhelder, 1967). On this view, distance and length information were coded in terms of reach rather than as features of stimuli; furthermore, this information was specific to an initial viewing position, which could not be updated to compensate for changes in viewpoint. Yet more recent research, some from our lab, has provided evidence to challenge earlier views.

Perhaps the strongest challenge has come from work using the disorientation procedure. As indicated above, this procedure ensures that viewers code the target object in terms of its relation to the spatial environment. That young children and nonhuman animals can use environment-centered information, such as the geometry of enclosed spaces, to locate target objects is undisputed. Nevertheless, there are issues concerning the nature of geometric coding that require conceptual clarification. It is thus of critical importance to employ experimental techniques that are unambiguous about the processes organisms use to determine location.

In the present paper, we discussed a variety of methods used in examining how geometric information is coded and processed by young children. By analyzing search behaviors and using different-shaped spaces, we showed that young children code information about the entire spatial layout; they do not seem to focus on just the corner containing the target object. Using different disorientation procedures, we also showed that how this information is processed depends on how the viewer's perspective is changed, with some procedures invoking particular mental transformations. And, by varying the viewer's position, we found that children also code information about the ego on these tasks; in particular, they seem to incorporate information about their position in relation to the enclosed space (inside vs. outside), which may allow them to infer their relation to the target object.

The fact that young children and non-human animals show similar patterns of response on disorientation tasks suggests that the mechanisms underlying location coding may have arisen in the course of evolution, forming part of the basic cognitive scheme available at the start of life. Such a scheme may reflect the adaptive importance of being able to specify location as accurately as possible. While the present paper focused on coding information directly from the spatial environment, it should be noted that there are other ways to represent the location of objects and places. This information could be presented in the form of symbolic representations such as maps, models, or spatial language. Such symbolic processing is unique to humans, but it may rest on the more fundamental abilities described in this paper.

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References

Bai, D. L., & Bertenthal, B. I. (1992). Locomotor status and the development of spatial search skills. *Child Development, 63,* 215–226.

Biederman, I. (1987). Recognition-by-components: A theory of human image understanding. *Psychological Review, 94,* 115–147.

Biederman, I., & Bar, M. (1999). One-shot viewpoint invariance in matching novel objects. *Vision Research, 39,* 2885–2899.

Cheng, K. (1986). A purely geometric module in the rat's spatial representation. *Cognition, 23,* 149–178.

Cheng, K. (1988). Some psychophysics of the pigeon's use of landmarks. *Journal of Comparative Physiology A, 162,* 815–826.

Cheng, K. (1989). The vector sum model of pigeon landmark use. *Journal of Experimental Psychology: Animal Behavior and Processes, 15,* 366–375.

Cheng, K. (2005). Reflections on geometry and navigation. *Connection Science, 17,* 5–21.

Cheng, K., & Gallistel, C. R. (1984). Testing the geometric power of an animal's spatialrepresentation. In H.L. Roitblat, T.G. Bever, & H.S. Terrace (Eds.). *Animal cognition: Proceedings of the Harry Frank Guggenheim Conference, June 2-4, 1982* (pp. 409–423). Hillsdale, NJ: Erlbaum.

Cheng, K., & Gallistel, C. R. (2005). Shape parameters explain data form spatial transformations: Comment on Pearce et al. (2004) and Tommasi & Polli (2004) *Journal of Experimental Psychology: Animal Behavior Processes, 31,* 254–259.

Cheng, K., & Newcombe, N. S. (2005). Is there a geometric module for spatial orientation?Squaring theory and evidence. *Psychonomic Bulletin & Review, 12,* 1–23.

Cohen, L. B., & Younger, B. A. (1984). Infant Perception of Angular Relations. *Infant Behavior and Development, 7,* 37–47.

Diwadkar, V. A., & McNamara, T. P. (1997). Viewpoint dependence in scene recognition. *Psychological Science, 8,* 302–307.

Gallistel, C. R. (1990). *The organization of learning*. Cambridge, MA: MIT Press.

Gallistel, C. R., & Cramer, A. E. (1996). Computations of metric maps in mammals: Getting oriented and choosing a multi-destination route. *The Journal of Experimental Biology, 199,* 211–217.

Gouteux, S., & Spelke, E. S. (2001). Children's use of geometry and landmarks to reorient in an open space. *Cognition, 81,* 119–148.

Gouteux, S., Thinus-Blanc, C., & Vauclair, J. (2001a). Rhesus monkeys use geometric and nongeometric information during a reorientation task. *Journal of Experimental Psychology: General, 130,* 505–519.

Gouteux, S., Vauclair, J., & Thinus-Blanc, C. (2001b). Reorientation in a small-scaleenvironment by 3-, 4-, and 5-year-old children. *Cognitive Development, 16,* 853–869.

Gray, E. R., Bloomfield, L. L., Ferrey, A., Spetch, M. L., & Sturdy, C. B. (2005). Spatial encoding in mountain chickadees: Features overshadow geometry. *Biology Letters, 1,* 314–317.

Hermer, L., & Spelke, E. (1994). A geometric process for spatial reorientation in young children. *Nature, 370,* 57–59.

Hermer, L., & Spelke, E. (1996). Modularity and development: A case of spatial reorientation. *Cognition, 61,* 195–232.

Hupbach, A., & Nadel, L. (2005). Reorientation in a rhombic environment: No evidence for an encapsulated geometric model. *Cognitive Development, 20,* 279–302.

Huttenlocher, J., & Presson, C. C. (1973). Mental rotation and the perspective problem. *Cognitive Psychology*, 4, 277–299.

Huttenlocher, J., & Presson, C. C. (1979). The coding and transformation of spatial information. *Cognitive Psychology, 11,* 375–394.

Huttenlocher, J., & Newcombe, N. (1984). The child's representations of information aboutlocation. In C. Sophian (Ed.), *Origins of cognitive skills* (pp. 81–111). Hillsdale, NJ: Erlbaum.

Huttenlocher, J., Newcombe, N., & Sandberg, E. (1994). The coding of spatial location in young children. *Cognitive Psychology, 27,* 115–147.

Huttenlocher, J., & Vasilyeva, M. (2003). How toddlers represent enclosed spaces. *Cognitive Science, 27,* 749–766.

Huttenlocher, J., Lourenco, S. F., & Vasilyeva, M. (2006). Perspectives on spatial development. In L. B. Smith, M. Gasser, & K. Mix (Eds.). *The spatial foundations of cognition and language.* Oxford University Press, New York (in press).

Jacobs, D. W. (2003). What makes viewpoint-invariant properties perceptually salient? *Journal of Optical Society of America, 20,* 1304–1320.

Kelly, D. M., & Spetch, M. L. (2001). Pigeons encode relative geometry. *Journal of Experimental Psychology: Animal Behavior Processes, 27,* 417–422.

Kelly, D. M., & Spetch, M. L. (2004a). Reorientation in a two-dimensional environment: I. Do adults encode the featural and geometric properties of a two-dimensional schematic of a room? *Journal of Comparative Psychology, 118,* 82–94.

Kelly, D. M., & Spetch, M. L. (2004b). Reorientation in a two-dimensional environment: II. Do pigeons (*Columba livia*) encode the featural and geometric properties of a two-dimensional schematic of a room? *Journal of Comparative Psychology, 118,* 384–395.

Kelly, D. M., Spetch, M. L., & Heth, C. D. (1998). Pigeons' (*Columba livia*) encoding of geometric and featural properties of a spatial environment. *Journal of Comparative Psychology, 112,* 259–269.

Landau, B., & Spelke, E. (1988). Geometric complexity and object search in infancy. *Developmental Psychology, 24,* 512–521.

Learmonth, A. E., Newcombe, N., & Huttenlocher, J. (2001). Toddlers' use of metric information and landmarks to reorient. *Journal of Experimental Child Psychology, 80,* 225–244.

Learmonth, A. E., Nadel, L., & Newcombe, N. S. (2002). Children's use of landmarks: Implications for modularity theory. *Psychological Science, 13,* 337–341.

Levine, S. C., Huttenlocher, J., Taylor, A., & Langrock, A. (1999). Early sex differences in spatial skill. *Developmental Psychology*, *35*, 940–949.

Lourenco, S. F., & Huttenlocher, J. (2006). How do young children determine location? Evidence from disorientation tasks. *Cognition 100*, 511–529.

Lourenco, S. F., Huttenlocher, J., & Fabian, L. (2005a). *Coding geometric information in infancy.* Poster presented at the biennial meeting of the Cognitive Development Society, San Diego.

Lourenco, S. F., Huttenlocher, J., & Vasilyeva, M. (2005b). Toddlers' representations of space: The role of viewer perspective. *Psychological Science, 16,* 255–259.

Margules, J., & Gallistel, C. R. (1988). Heading in the rat: Determination by environmental shape. *Animal Learning & Behavior, 16,* 404–410.

Newcombe, N. S. (2002a). The nativist-empiricist controversy in the context of recent research on spatial and quantitative development. *Psychological Science, 13,* 395–401.

Newcombe, N. S. (2002b). Spatial cognition. In H. Pashler & D. Medin (Eds.), *Stevens' handbook of experimental psychology: Vol. 2. Memory and cognitive processes* (3rd ed., pp. 113–163). New York: Wiley.

Newcombe, N. S. (2006). Evidence for and against a geometric module: The roles of language and action. In J. Rieser, J. Lockman & C. Nelson (Eds.), *Action as an organizer of learning and development.* Minnesota Symposium on Child Development Series. Lawrence Erlbaum Associates, New Jersey.

Newcombe, N. S., & Huttenlocher, J. (2000). *Making space: The development of spatial* representation and reasoning. Cambridge, MA: MIT Press.

Newcombe, N., Huttenlocher, J., Drummey, A. B., Wiley, J. G. (1998). The development of spatial location coding: Place learning and dead reckoning in the second and third years. *Cognitive Development, 13,* 185–200.

Pearce, J. M., Good, M. A., Jones, P. M., & McGregor, A. (2004). Transfer of spatial behavior between different environments: Implications for theories of spatial learning and for the role of the hippocampus in spatial learning. *Journal of Experimental Psychology: Animal Behavior Processes, 30,* 135–147.

Piaget, J., & Inhelder, B. (1967). *The child's conception of space* (F. J. Langdon & J. L. Lunzer, Trans.). New York: Norton. (Original work published 1948.).

Platt, J. E., & Cohen, S. (1981). Mental rotation task performance as a function of age and training. *Journal of Psychology, 108,* 173–178.

Presson, C. C. (1982). Strategies in spatial reasoning. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *8*, 243–251.

Rieser, J. J., Pick, H. L., Ashmead, D. H., & Garing, A. E. (1995). Calibration of human locomotion and models of perceptual-motor organization. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 480–497.

Rosser, R., Ensing, S., Gilder, P., & Lane, S. (1984). An information-processing analysis of children's accuracy in predicting the appearance of rotated stimuli. *Child Development, 55,* 2204–2211.

Rosser, R., Ensing, S., & Mazzeo, J. (1985). The role of stimulus salience in young children's ability to discriminate two-dimensional rotations: Reflections on a paradigm. *Contemporary Educational Psychology, 10,* 95–103.

Schwartz, M., & Day, R. H. (1979). Visual shape perception in early infancy. *Monographs of the Society for Research in Child Development, 44*(7, Serial No. 182).

Simons, D. J., & Wang, R. F. (1998). Perceiving real-world viewpoint changes. *Psychological Science*, 9, 315–320.

Slater, A., Morison, V., Town, C., & Rose, D. (1985). Movement perception and identity constancy in the new-born baby. *British Journal of Developmental Psychology, 3,* 211–220.

Slater, A., Mattock, A., Brown, E., & Bremner, J. G. (1991). Form perception at birth: Cohen and Younger (1984) revisited. *Journal of Experimental Child Psychology, 51,* 395–406.

Sovrano, V. A., Bisazza, A., & Vallortigara, G. (2002). Modularity and spatial orientation in a simple mind: Encoding of geometric and nongeometric properties of a spatial environment by fish. *Cognition, 85,* B51–B59.

Tommasi, L. (2005). Geometric determinants of spatial reorientation: Reply to Cheng and Gallistel (2005). *Journal of Experimental Psychology: Animal Behavior Processes, 31,* 260–261.

Tommasi, L., & Polli, C. (2004). Representation of two geometric features of the environment in the domestic chick (*Gallus gallus*). *Animal Cognition, 7,* 53–59.

Vargas, J. P., Lopez, J. C., Salas, C., & Thinus-Blanc, C. (2004). Encoding of geometric and featural spatial information by goldfish (*Carassius auratus*). *Journal of Comparative Psychology, 118,* 206–216.

Wang, R. F., & Spelke, E. (2002). Human spatial representation: Insights from animals. *Trends in Cognitive Sciences, 6,* 376–382.

Wang, R. F., Hermer, L., & Spelke, E. S. (1999). Mechanisms of reorientation and object localization by children: A comparison with rats. *Behavioral Neuroscience, 113,* 475–485.

Wraga, M., Creem, S. H., & Proffitt, D. R. (2000). Updating displays after imagined object and viewer rotations. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26,* 151–168.

Wraga, M., Creem-Regehr, S. H., & Proffitt, D. R. (2004). Spatial updating of virtual displays during self- and display rotation. *Memory and Cognition*, 32, 399–415.