

Toddlers' Use of Metric Information and Landmarks to Reorient

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Mobile organisms can keep track of spatial location (both their own location and that of objects in the environment) using either an external referent system or one centered on the self and updated by information about movement through space. When the latter system is disabled (e.g., by rapid turning), aspects of the external world must be used to reestablish orientation. Recently, it has been claimed that, both for rats and for human toddlers, reorientation is achieved using a geometric module that accepts only information about the metric properties of the environment (C. R. Gallistel, 1990; L. Hermer & E. S. Spelke, 1994, 1996). In a series of experiments, this paper confirms that geometric information is used for reorientation by young children, but gives reason to doubt that the use of this information is achieved using a module impenetrable to nongeometric information. © 2001 Academic Press

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The ability to locate objects in the surrounding world is crucial to any mobile organism. Humans are no exception. In order to perform the simplest acts required for life, to know where to go to find food or avoid danger, people must be able to remember the location of objects within an environment, in relation to

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their own current location. There is now considerable reason to believe that humans and other mobile animals use two fundamental methods of remembering location, an externally referenced system that relates a location to the external environment, in terms of distance and direction from landmarks, and a self-referenced system that relates a location to the position of the self, compensating for self movement by encoding the distance and direction of that movement (Gallistel, 1990; Sholl, 1995). Normally, these two systems are in agreement. However, when they disagree, the externally referenced system seems to be used to correct the self-referenced system. Such correction is an adaptive choice because the self-referenced system is subject to drift, when the exact distance traveled or number of degrees turned is slightly misencoded.

Several decades of research have led to substantial progress toward the goal of understanding the developmental basis of spatial behavior (Newcombe & Huttenlocher, 2000). There is considerable evidence that, by 6 months, infants possess many vital components of the two mature systems. In terms of the externally referenced system, they are able to code the location of an object using coincident or surrounding landmarks (Acredolo, 1977), and they are also able to code distance in continuous space (Newcombe, Huttenlocher, & Learmonth, 1999). Toward the end of the second year, they seem to combine these abilities by showing evidence that they can code distance to distal landmarks, i.e., show what has been called place learning (Newcombe, Huttenlocher, Drummey, & Wiley, 1998). In terms of the self-referenced system, they begin by coding location in terms of the responses required to access that location (e.g., Acredolo, 1977), but as their motor abilities increase, they acquire the ability to compensate for movement (see overviews by Acredolo, 1990, and Millar, 1994). Refinement in the ability to code and compensate for self-produced movement extends across subsequent years (Rider & Rieser, 1988; Rieser & Rider, 1991). Overall, this picture of spatial development is one in which infants begin with strong starting points, but in which there is important developmental change, guided by interactions of the maturing child with the physical and social environment (Newcombe & Huttenlocher, 2000).

Until recently, no developmental research had examined whether the use of externally referenced systems to correct a self-referenced system is evident early in life, develops with experience, or is evident early but yet shows developmental change. One aspect of understanding correction of a self-referenced system using external information is what occurs when orientation using the self-referenced system has been lost due to fast and/or complex motion, not controlled by the organism, with visual and auditory cues unavailable. Development of this reorientation ability has been studied by Hermer and Spelke (1994, 1996), using a paradigm originally developed to investigate reorientation in rats (Cheng, 1986).

In Cheng's experiments, food-deprived rats were shown food hidden in one corner of a rectangular box. Then the rats were removed and disoriented. After disorientation the rats were allowed to search for the food. In an unmarked box, the rats searched equally often in the two geometrically identical corners (i.e., the

diagonally opposite corners of the box, for both of which the short wall was on the left and the long wall on the right or vice versa). There were relatively few responses to the other two corners. This search pattern showed that the rats had encoded and remembered the relative length of the walls and their relation to each other and could use this information to search for food.

While use of such information was impressive, the rats also showed a surprising limitation on their reorientation ability. Even when Cheng introduced salient landmarks, such as an odor or color or texture, that could differentiate the diagonally opposite corners, the rats searched equally in the two corners, failing to use the landmark information. Similar findings have been reported by other investigators (Biegler & Morris, 1993; Margules & Gallistel, 1988) and have led to the proposal that disoriented rats are guided by a "geometric module," impenetrable to nongeometric information (Gallistel, 1990).

Each of the terms in the phrase "geometric module," requires some explication. Gallistel (1990) defines a "geometric" property as a property that a solid, surface, line, or point possesses by virtue of its position relative to other solids, surfaces, lines, and points. Nongeometric properties are all other properties, not defined by relative position alone. "Any property whose description requires language that does not ordinarily appear in a textbook on geometry is nongeometric" (Gallistel, 1990, p. 212). The term "module" derives specifically from Fodor's (1983) claim that the brain contains domain-specific systems for certain functions, analogous to dedicated circuitry within an electronic device. These modules serve the purpose of making relatively complicated tasks easier by limiting the number of available inputs.

Hermer and Spelke (1994, 1996) extended Cheng's paradigm to use with children. They found that toddlers of 18 to 24 months, like rats, were unable to use objects that could be treated as landmarks, such as a colored wall or toys in the room, to reorient themselves in an enclosed rectangular space. Instead, the toddlers used the shape of the space they were in to determine where to search for an object hidden before they were disoriented, dividing their searches evenly between diagonally opposite corners whether possible landmarks were present or not. On the other hand, disoriented adults were able to use features that could be treated as landmarks to focus search on the correct corner. Hermer and Spelke argued that these results indicate that human children share an innate geometric module with other species. They further suggest that this module is eventually overridden, in the course of development, by use of linguistic spatial codings that allow integration of nongeometric and geometric information. In support of this argument, Hermer-Vazquez (1997) found that, for 6- to 7-year-old children, success in using possible landmarks to reorient was correlated with successful use of spatial linguistic terms, and Hermer-Vazquez, Spelke, and Katsnelson (1999) found that adults were impaired in using such features to reorient when also required to perform a verbal shadowing task.

Gallistel (1990) offers an evolutionary argument as to why it is useful to be sensitive to the shapes of objects in the environment. In a natural environment,

geometric information (i.e., the information provided by the positions of solids, surfaces, lines, and points relative to other solids, surfaces, lines, and points) would include the shape and size of physical features of the environment, both large features such as mountains, and smaller features such as trees. Sensitivity to these aspects of the environment, rather than to odors, textures, or colors, maximizes encoding of aspects of the environment that do not change frequently or rapidly. Mountains do not move appreciably, rivers do not usually change course, and oceans do not disappear. This constancy in the natural world could be of great use to an animal that uses the geometry of his world to find his way around. In the natural world, because there are very few spaces that are rotationally symmetric, there would be few confusions of the sort reported by Cheng (1988) and Hermer and Spelke (1994, 1996).

Exactly what is meant by a geometric module is not, however, as clear as it may initially appear. The central question that arises concerns how geometrical information would be useful in the natural environment, as opposed to the bounded, enclosed spaces that have been used in experiments so far. In nature, there are relatively few obvious surfaces to define the geometry of an area; one is not always within sight of a body of water or a prominent land form. In other environments (e.g., a flat forested area), geometry would have to be derived as an act of construction by the viewer from separated objects in the environment that have relative position with respect to each other. For example, various trees or boulders might define a geometry of an animal's range. However, considering this situation closely raises difficult problems.

How are the various landmarks that define the "geometry of the natural environment" to be distinguished from each other (e.g., various boulders from each other and so on)? One obvious solution is to differentiate them using the many important attributes of identity available, including color or markings or texture, but it is exactly such attributes that the geometric-module proposal claims are not relevant to spatial orientation. Exact size and shape might be offered as differentiating properties that are geometric in nature. But doing so raises a further question, namely, how finely graded might such differentiation be? If two rocks are only slightly different in size or shape, as they might be in many natural circumstances, it is a psychophysical question as to whether the slight geometric differences would be sufficient for differentiation.

Proponents of the geometric module could simply assume that the module was very sensitive, but this move in the argument has a cost as well as a benefit. Minor aspects of the physical environment are likely to change rapidly and fairly frequently (e.g., a boulder might shift its position after a storm or have a section loosen and fall off). In addition, changes in lighting conditions or viewing perspectives are likely to alter estimations of size and length. Thus, a very sensitive geometric module might lead to disorientation if such variations were too easily picked up. In sum, it is less obvious than it may appear at first what information should be considered "geometric information" and whether natural environments could be encoded and navigated using only such information.

Empirical work on the use of the external environment to reorient does not resolve these issues. Several studies have shown that animals often rely on landmarks to complete a spatial task when their sense of orientation has been reduced or provides ambiguous information, in seeming contradiction to the work of Cheng (Etienne, Teroni, Maurer, Portenier, & Saucy, 1985; Goodridge & Taube, 1995; Knierim, Kudrimonti, & McNaughton, 1995; McNaughton, Leonard, & Chen, 1989; McNaughton & Nadel, 1990; Wilson & McNaughton, 1993). Indeed, most work with animals suggests the existence of multiple orientation systems that are normally redundant, but that are relied on differentially in various environmental contexts (Newcombe & Huttenlocher, 2000). Wang, Hermer, and Spelke (1999) try to account for the animal data by pointing out that the landmarks used in these studies may project far enough into the spaces enclosing the animals to provide geometric information. However, such an argument clearly raises the problem of how fine a grain of geometric information is used by the geometric module and whether an overly sensitive module would indeed be adaptive.

Another problem with the geometric module comes from the fact that most experimental work to date has concerned enclosed spaces, whereas theoretical arguments assume the extension of these findings to the natural environment. Recent evidence shows that 3-year-old children cannot reorient using a distinctive geometric configuration formed by three landmarks, that is, an "imaginary" configuration rather than one formed by enclosing surfaces (Gouteux & Spelke, 2000). Children did not use the geometric information provided by three landmarks, even when lines were taped on the floor to highlight the geometric relations. A geometric module that could only work with enclosing surfaces would obviously be of little use in natural environments.

Another kind of question about the geometric module proposal concerns the hypothesis that the advent of spatial language is responsible for the ability of adults and older children to use nongeometric information to reorient. Searching the correct corner and the geometrically identical corner of a rectangular enclosure requires coding relative length of the walls and their sense information (i.e., the long wall is to *the left of* the short wall). It is not clear why young children would be able to do this and yet would need additional spatial language to incorporate other information such as color (i.e., the long wall is to *the left of* the short blue wall). Recent data from primates suggest, in fact, that language is not essential for the integration of geometric and nongeometric information. Gouteux, Thinus-Blanc, and Vauclair (in press) found that rhesus monkeys use a colored wall to reorient and find a goal on the corner of an otherwise featureless rectangular room. How the monkeys accomplished this is not known, but clearly they did not use language.

Given these questions about a geometric module, further investigation of the reorientation ability of young children is important. Specifically, children too young to have much if any spatial language might use landmarks to reorient if certain aspects of the Hermer and Spelke (1994, 1996) procedure were modified. One consideration is that landmarks must be spatially stable in order to be functionally use-

ful, an attribute one would expect to be crucial to a spatially adapted organism. (They may additionally be conspicuous features of an area—e.g., perceptually salient—even though such attributes are not logically necessary. For some discussion of landmarks, see Acredolo, 1988; Nadel, 1988; Presson & Montello, 1988.) However, Hermer and Spelke's (1996) Experiments 1 and 2 and Wang et al.'s (1999) Experiments 1 and 2 were conducted within participants, so that half the children saw the room without the colored wall before it was introduced, a procedure that would surely suggest that the fabric was not a stable feature of the room and make it less likely to be treated as a landmark. Although comparisons involving the order effect and interactions of order with other variables were nonsignificant, the experiments used very small numbers of children, so that statistically, the power to detect interactions would be expected to be very low. Other experiments used small and obviously movable objects as landmarks, such as bears, trucks, and boxes (Hermer and Spelke's Experiments 3 through 6). Evident portability is likely to reduce the probability of people using an object as a landmark, as is small size (Gouteux et al., in press). While Wang et al.'s Experiments 3 and 4 were designed to examine whether a stable colored wall would be used as a landmark, by giving children repeated exposure to a room that always contained a colored wall, only four children were used in each of those studies.

Another element of the Hermer and Spelke (1996) procedure that could potentially influence their results is that the space used was 4 by 6 ft, much smaller than rooms that children usually navigate and one which must have been quite crowded by the child, the adult, and the goal boxes. This unusually small size might influence children's use of landmarks in finding the hidden object by virtue of discouraging a view of the task as one involving spatial orientation.

In exploring the claim of a geometric module, we conducted six studies with the overall aim of determining whether there were circumstances in which young children could indeed use landmarks for reorientation, thus questioning the existence of an impenetrable geometric module of the sort discussed by Hermer and Spelke. The first study involved replicating Hermer and Spelke's (1996) work with disoriented young children in a rectangular space with no landmarks. To anticipate, we found that the children searched equally often in the correct corner and in the corner opposite the correct corner, not only confirming one aspect of Hermer and Spelke's findings but also offering assurance that our disorientation procedure was successful. The second experiment involved two landmarks placed in corners, in line with the walls of the room, so as not to alter the rectangular configuration of the room. These landmarks were objects that the children were likely to identify as immovable. The third study used only one landmark, not coincident with any of the hiding locations, in order to see if such a landmark is enough to reorient. The fourth study was conducted to ensure that the children in prior experiments were not somehow getting assistance from their parents. This study added a few procedural differences to ensure the parent did not know where the target object was hidden. In the fifth study, we directly examined the effect of a colored wall on reorientation, while also again examining performance without

any landmark cues. Finally, the sixth study was a replication of Experiment 1, conducted to ensure that there had been no change in our environment or procedure (e.g., less effective masking of directional sound) such that children in later experiments might have been less effectively disoriented than children in earlier experiments.

EXPERIMENT 1

The aim of the first experiment was to replicate Hermer and Spelke's finding that disoriented children in a featureless rectangular room can use geometric information to focus their search on two of the four corners in the room. Replication is important for two reasons. First, the result is important in itself, with or without acceptance of the further findings of Hermer and Spelke on the use of landmarks. Huttenlocher, Newcombe, and Sandberg (1994) found that children in this age range showed evidence of metric coding of extent, in that they were able to show finely differentiated searches for objects distributed along the length of a 5-ft sandbox. The Hermer-Spelke data do not necessarily imply this degree of accuracy in metric coding, since children merely need to differentiate between 4 and 6 ft. However, the data do indicate that children of this age can consider two distances at once and relate one to the other in a sense relation (i.e., the long wall *to the left of* the short wall). This result is a striking one and deserves confirmation by independent replication. Second, replicating the effect would not only confirm the finding but also show that our disorientation procedure was effective and that our use of a larger space did not change this aspect of the Hermer and Spelke results.

Method

Participants. There were 61 infants between 17 and 24 months in the study initially. Data from 9 children were discarded due to lack of cooperation from the parent; the experimenter monitored parents carefully for either failure to cover the child's eyes completely or for making some indication to the correct corner. Another 4 children refused to play or cried. The average age for the 48 remaining participants was 20.4 months (range 16.6 to 25.3).

Apparatus. The study was conducted in an 8 by 12 ft rectangular room whose boundaries were defined by white curtains. The area of this room was thus four times the area of the room used by Hermer and Spelke, but the ratio of the short to the long wall was the same. (See Fig. 1.) Three lights and a radio were centrally located in the ceiling to mask any external sound and avoid providing directional light cues. Four identical opaque green plastic boxes with removable lids were placed in the four corners of the room. Each box had two of its sides touching the two walls forming the corner.

Procedure

The children were brought into a large playroom where the experiment was explained to the parents and consent was obtained. This time also allowed the chil-

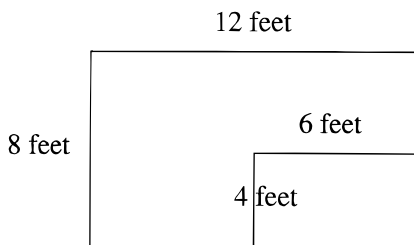


FIG. 1. Experimental setup used in Experiments 1, 5, and 6, with the space used by Hermer and Spelke shown for comparison.

dren to get comfortable with the experimenter and select a small toy to play with during the experiment. The child and parent were then brought into the experimental space by means of a door that led to a curtain that could be moved to allow entry and then shut with velcro after everyone was in. The experimenter, first getting the child's attention, hid the selected toy in one of the four boxes while the child watched. The parent then picked up the child and slowly turned in the center of the room, covering the child's eyes during the rotation. The parent turned a minimum of four times while the experimenter walked around the turning pair in the opposite direction. Both the experimenter and the parent sang a song (Ring-around-the-Rosie) during the turning. The experimenter ended her walking around the room in the center of a different wall on each trial and the parent put the child down facing the experimenter. The child was then encouraged to search for the toy. As soon as the child chose a box, the trial ended; if the child was at an incorrect box, s/he was shown the correct box. The child was allowed to play with the toy for a few seconds, and then the next trial began. There were four trials, all of which were the same except that the wall the child faced at the end of the turning was different for each trial. Following Hermer and Spelke, the toy was hidden in the same box across all four trials. However, across children, which box was used as a hiding location was counterbalanced, as was the location of the experimenter at the end of the spinning, the sex of the child, and whether the child was younger or older than 20 months.

Results

For each child, there was a number ranging from 0 to 4 for number of correct choices, reversal errors, far errors, and near errors. In this and all subsequent experiments, there were no sex differences or interactions, no age differences (examined using a median split) or interactions with age, and no trial effects or interactions with trials. All t tests used one-tailed probabilities, as there were directional expectations for the results.

The children in this experiment went to the correct corner or the opposite corner (the rotationally equivalent one) the majority of the time, 42 and 36%, respectively. Responses to the correct corner and to the rotationally equivalent corner were not significantly different, $t(47) = 1.2$. There were relatively few responses to the corners that were not geometrically correct. Responses to the corner near

the correct corner (i.e., at the other end of the short wall) occurred on 11% of the trials, and responses to the far corner (i.e., at the other end of the long wall) were seen on 10% of the trials. The difference between the two geometrically correct and the two geometrically incorrect corners was reliable, $t(47) = 8.03$, $p < .0001$. The geometric error was significantly more common than either the near error or the far error, $t(47) = 4.78$ and 3.38 , respectively, both $p < .001$.

Discussion

The children in this study went equally often to the correct corner and the congruent corner diagonally opposite it, indicating that they were unable to determine which of the two corners contained the desired toy. In many cases the conviction that the rotationally equivalent corner was correct on a given trial was so strong that children did not believe there was nothing in the box they had chosen until it was opened. Thus, this study replicated the findings of Hermer and Spelke (1994, 1996) that disoriented children were unable to distinguish between the correct corner and its rotational equivalent. The finding is a striking one, because it indicates that children at this young age can encode information about the relative length of two surfaces and can encode the sense information that relates them (e.g., the shorter wall is on the left). In addition, the replication shows clearly that the disorientation procedure used in this and following studies is effective.

EXPERIMENT 2

The second experiment was designed to test the ability of 17 to 24 month olds to use landmarks in the same space as Experiment 1. The claim made in Hermer and Spelke's (1994, 1996) research is that young children have a geometric module that is impenetrable. In one interpretation of this argument, any use of landmarks would be impossible. However, as previously discussed, there are questions about the apparent permanence of the landmarks used in at least some of Hermer and Spelke's studies. To address this problem, we used landmarks that are generally seen as immovable, namely, the door to the room and a large bookcase. Children never saw the space without these landmarks present.

Method

Participants. There were 56 infants between 17 and 24 months seen for this experiment. None of the children had participated in the prior study (a design feature also true for all subsequent studies). Data from 8 children were discarded due to a lack of cooperation from the parent; either the parent did not cover the child's eyes completely or made some indication to the correct corner. The average age of the remaining 48 infants was 21.3 months (range 16.8 to 25.3).

Apparatus. The room and boxes were identical to those used in Experiment 1 with the addition of two landmarks (see Fig. 2). On one long wall the landmark was the door to the room, and on the other the landmark was a bookshelf set back into the fake wall so that it did not intrude on the shape of the space. The bookshelf was five feet tall and three feet wide, with four shelves. The bottom shelf

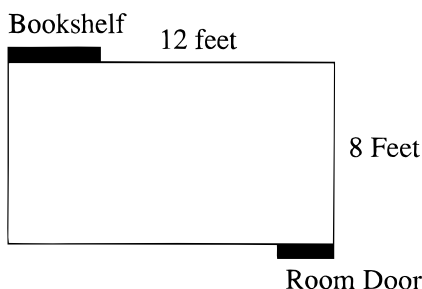


FIG. 2. Setup of the room used in Experiment 2 and 4.

had reprints of articles stacked on it, the second had more reprints and a set of in/out boxes, the third had journals on it, and the top shelf had little knickknacks on it. The two landmarks were located adjacent to opposite corners of the rectangle. The same set of boxes was used in the corners.

Procedure. The procedure was the same as that used in Experiment 1, with one exception. On one of the four trials (chosen by the experimenter such that the child was not facing the door), the child was asked to point to the door after the turning, but before the parent removed her hand from the child's eyes.

Results

Children in this study went to the correct corner significantly more often than the geometrically identical corner, 60% of the time as opposed to 26%, $t(47) = 4.6$, $p < .0001$. This overall result can be broken down into data for two groups of children, those who saw a toy hidden in one of the corners with a coincident landmark (i.e., next to the door or the bookcase) and those who saw a toy hidden in a corner not directly marked by a landmark. Children in the first group went to the correct corner far more often than to the geometrically identical corner, 64% versus 20%, $t(25) = 5.0$, $p < .0001$. In addition, children who saw the object hidden in one of the unmarked corners also went to the correct corner more often than to the geometric equivalent, 56% versus 32%, $t(21) = 1.85$, $p < .05$. Differences between these groups were not reliable, $t(46) = .96$. The errors made by the children, when they made them, were to the geometrically identical corner more often than to either the near corner or the far corner, $t(47) = 4.92$ and 3.22 , respectively, both $p < .005$, as well as more often than to the near and far corners combined, $t(47) = 2.35$, $p < .05$. Errors were 4% to the near corner and 10% to the far corner.

When the children were asked to point to the door on one of the trials, none could point to the door. The most frequent response was to point straight ahead, although some of the participants refused to point at all while their eyes were covered. The inability of the children to point to the door after disorientation was a further indication, in addition to the results of Experiment 1, that the disorientation procedure was effective in disrupting the self-referenced location system.

The children were sufficiently disoriented that they no longer knew which direction they were facing while their eyes were covered.

Comparisons were made between Experiment 2 and Experiment 1. The children in Experiment 2 went to the correct corner significantly more than those in Experiment 1, $t(94) = 2.89, p < .005$. The children in Experiment 1 went to the rotational equivalent of the correct corner more often than those in Experiment 2, $t(94) = -2.09, p < .05$.

Discussion

The results of this study indicate that children between 17 and 24 months can use landmarks when they search for a hidden toy. It is especially interesting to observe that they not only use landmarks that are adjacent to the hiding location but can also use landmarks that are at a distance from the hiding location. Children who saw the toy hidden next to one of the landmarks only needed to remember that fact, i.e., use the landmark as an associative cue. Children who saw the toy hidden in one of the unmarked corners had a potentially harder task, namely, to remember the relation of the landmark to the toy's hiding place, and yet they did as well as children who had a more direct cue.

The fact that the errors in Experiment 2 were overwhelmingly to the rotational equivalent corner indicates that the shape of the room, as well as the landmarks, is used to guide search behavior. However, there are two possible ways to think about how children are using shape and landmark information. One possibility is that children integrate these types of information on each trial, although occasionally, they forget one or the other piece of information. (In the environment used in Experiment 2, if shape information is forgotten, landmark information is still sufficient to locate the toy, whereas if landmark information is forgotten, shape information would lead about half the time to a geometric error.) A second possibility to explain the data might be that children do not integrate the two types of information, but merely use shape on some trials and landmarks on others in some random fashion. The purpose of Experiment 3 was to provide data relevant to this issue.

It should also be noted that the present results are not incongruent with one construal of the geometric module hypothesis. The door had a doorknob, and the bookcase had indentations and blank spaces where objects did not completely fill the shelves. A sufficiently sensitive geometric module could thus explain the children's reorientation and success in locating the toy. As noted in the introduction, there are some problems with this approach because this sensitivity would come at a certain cost. A modularity theorist would need to explain how the module avoided using minor and hence changeable aspects of the environment that would confuse the system. However, the issue becomes moot in light of the results from Experiment 5.

EXPERIMENT 3

In the third experiment the aim was to see if the children could succeed with only one landmark, analogous to the blue wall. The room was set up so that the

only visible landmark was the bookshelf used in the previous experiment, placed in the center of one of the short walls. There are two ways to succeed in finding the toy in this environment. First, children could remember both that the toy was close to (or far from) the bookcase and that it was in a corner with the long wall to the left of the short wall (or vice versa). In this case, they are integrating geometric and nongeometric information. Second, children could also find the toy by using left–right information. For a toy near the bookcase, they could remember that it was to the left or the right of the bookcase or to the left or right of their body as they faced the bookcase. For a toy far from the bookcase, they could remember that it was to the left or right of their body when the bookcase was at their back. Each of this second group of possibilities uses left–right information. Thus, if children succeed in this experiment by coding in this way, they need not be integrating geometric and nongeometric information; they might simply be using nongeometric information on some trials (enough to succeed) and geometric information on others (creating the geometric error). However, note that, on this account, they *would* be using left–right information, presumably nonverbally coded in some fashion, a fact that would also cast doubt on the Hermer–Spelke account of development.

Method

Participants. There were 63 infants between 17 and 24 months in the study. Data from 5 children were discarded due to a lack of cooperation from the parent; either the parent did not cover the child's eyes completely or made some indication to the correct corner. Data from 10 children were discarded because they refused to play or cried. The average age of the remaining 48 participants was 20.6 months (range 17.26 to 25.03).

Apparatus. The same room was used for this experiment, but the long walls were shortened to 11 ft in order to allow the bookshelf, which was placed in the center of one of the short walls, to be flush with that wall (see Fig. 3). The bookshelf was placed such that it did not intrude into the room. The same four boxes were used in the corners.

Procedure. The procedure was the same as that used in the first two experiments.

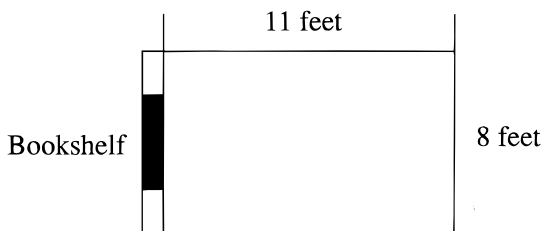


FIG. 3. Setup of the room used in Experiment 3.

Results

As in Experiment 2, the children in this experiment went to the correct corner significantly more often than the rotational equivalent, 62% versus 20%, $t(47) = 8.11$, $p < .0001$. When they made errors they again made them to the rotationally equivalent corner more often than to the near corner or to the far corner, $t(47) = 2.89$ and 2.91 , respectively, both $p < .005$, as well as more often than to the other two corners combined, $t(47) = 2.67$, $p < .01$. Errors were 9% to the near corner and 9% to the far corner.

Discussion

In this study the children showed that, after disorientation, they can use a single landmark to complete a search task. In order to be successful at this task, children must either integrate geometric and nongeometric information or use nonverbally coded left-right information. Their capacity to do this task thus raises further doubt about the existence of an impenetrable geometric module that is changed in development by the acquisition of linguistic coding of the concepts of left and right.

There are some objections that may be raised about Experiments 2 and 3. First, one might be concerned that the parents in our studies were somehow cuing their children. Although this seems unlikely because data from children whose parents did not follow directions were discarded by the experimenter, Experiment 4 was conducted to evaluate this possibility more closely. Second, as noted previously, one might argue that the fact that the bookcase and the door did not present a completely smooth surface to the world provided "geometric" cues. This issue was the focus of Experiment 5.

EXPERIMENT 4

In order to be sure our results were not due to assistance from the parent we conducted the experiment on 12 more children. In previous experiments, data from children whose parents did not cover the child's eyes, or who made any overt indication to the correct corner, were discarded by the experimenter. However, we wanted to be sure that there was not some more subtle form of parental cuing that the experimenter might not have noticed. In this experiment there were two important differences from the other experiments. First, we asked parents to close their eyes before the experimenter hid the object, so that they would not know its location themselves. Second, we used two hiding locations rather than one to provide assurance that parent would not guess where the toy was hidden.

Method

Participants. There were 16 infants between 17 and 24 months in this study. Data from 2 were unusable due to a lack of cooperation from the parent and data from another 2 were discarded because they refused to play. The average age of the remaining 12 participants was 22.1 months (range 19.7 to 25.5).

Apparatus. The same room was used for this experiment, set up exactly as it was for Experiment 2. The bookshelf and the door were landmarks in opposite corners of the room. The same four boxes were used in the corners.

Procedure

The procedure was similar to that used in the first three experiments. The procedure differed from that used in Experiments 1–3 in that the parent was to be unaware of the hiding location for the toy. There were still four trials on which the child saw a toy hidden in one of the boxes in the corner of the room, but on each trial the parent was instructed to face a different wall of the room and close her eyes. For each subject two hiding locations were randomly selected, and the object was hidden in them in an A, B, B, A order. Once the parent was facing the correct wall with her eyes closed, the experimenter walked around the room in one complete circuit, attracting the child's attention throughout and telling the child she was about to hide the toy. The circuit always started to the left of the parent. When the experimenter reached the hiding location she hid the toy and continued her walk around the room, being sure to prevent the child from immediately going to the correct box. Once the circuit around the room was complete, the parent was asked to open her eyes and pick up the child for the spinning part of the procedure, after which the child was encouraged to search. As with the other experiments, once the child made one search attempt, the experimenter showed the child the toy if the search was incorrect and started the next trial by repositioning the parent and instructing her to close her eyes. The trials were in every other way the same as those in the previous experiments.

Results

The children in this experiment went to the correct corner significantly more often than the rotational equivalent, 65% versus 11%, $t(11) = 5.92$, $p < .0001$. However, unlike in previous experiments, when they made errors they did not make them to the rotationally equivalent corner more often than to the near or the far corners, $t(11) = .29$ and -0.67 , respectively, let alone more often than to the other two corners combined. The near corner was searched on 8% of the trials and the far corner on 16%.

Discussion

The results of this experiment indicate that the findings in the previous experiments were not due to parental assistance that the experimenter failed to notice. Adults closed their eyes during hiding and could not build up expectations about location because two different hiding locations were used. Nevertheless, disoriented children were successful in finding toys. This fact is especially impressive because the children in this study had to use two hiding locations not just one. Why error responding was not predominantly to the congruent corner is not known; perhaps it is simply a chance null finding due to the small sample size.

EXPERIMENT 5

The data in the studies to this point could be explained by a modified version of the geometric-module hypothesis that suggests that small variations in shape can be input to the module. As noted this version of the hypothesis raises some issues about how the module would work in the real world. We were curious, however, whether, at least in certain circumstances, children could avoid the geometric error using a definitively nongeometric cue, namely, color. Thus, the fifth experiment was a direct replication of Hermer and Spelke's (1996) experiment in which they covered one of the walls of their room with blue fabric. Children in our studies only saw the room with (or without) a blue wall, in a room larger than that used by Hermer and Spelke, because we had speculated that stability and scale were important factors in landmark use. Success in Experiment 5 would indicate that minor geometric contrasts need not be present for young children to reorient.

Method

Participants. There were 35 infants between 17 and 24 months in this study. Data from 2 children were discarded due to a lack of cooperation from the parent and data from another 2 were discarded because they refused to play. The average age of the remaining 31 participants was 20.15 months (range 17.1 to 24.7).

Apparatus. The same room was used for this experiment, set up exactly as it was for Experiment 1 except that one of the short walls was covered with a blue curtain. The same four boxes were used in the corners.

Procedure

The procedure was the same as that used in Experiments 1–3.

Results

The children in this experiment went to the correct corner significantly more often than the rotational equivalent, 60% versus 24%, $t(30) = 5.05$, $p < .0001$. Errors to the rotational equivalent were more frequent than errors to the other two corners considered individually, $t(30) = 3.41$ and $t(30) = 2.78$, both $p < .005$. However, errors to the rotationally equivalent corner were not reliably more frequent than errors to the other two corners combined, $t(30) = 1.26$. There were 7% of responses to the near corner and 9% to the far corner. There were no significant differences between the data obtained from children for whom the toy was hidden in a corner involving the blue wall and the data obtained from children for whom the hidden toy was in a corner formed by two white walls.

Discussion

This experiment did not replicate Hermer and Spelke's (1996) findings that children did not use a blue wall as a landmark following disorientation. The chil-

dren in the present study clearly did use the blue wall to find the toy, casting doubt on the idea that geometric information alone is used for reorientation. In addition, these data on very young children who cannot use the words "left" and "right," combined with those of Gouteux, Thinus-Blanc, and Vauclair (1999), who found similar results with nonlinguistic rhesus monkeys, cause one to question the hypothesis that language is necessary in order to treat a colored wall as landmark and to integrate such information with metric and sense (i.e., right-left) information. As with Experiment 3, the data compel one to conclude either that children can integrate geometric and nongeometric information or that they can use nonverbally coded left-right information (or both).

EXPERIMENT 6

This experiment was a replication of Experiment 1, the basic disorientation procedure in a room with four white walls. It was conducted simply to ensure that the experimenter had not subtly changed the disorientation procedure over time in a way that made it less effective and that no other changes had occurred (e.g., less effective masking of directional sound) that could allow children to reorient using cues other than the ones manipulated.

Method

Participants. There were 16 infants between 17 and 24 months in the study initially. Data from 2 children were discarded due to lack of cooperation from the parent (one may have been cuing the child and the other was pregnant and asked to stop) and data from 2 children were discarded because children refused to play. The average age of the remaining 12 children was 20.79 months (range 19.2 to 23.5).

Apparatus and procedure. The room was set up and the experiment was conducted exactly as described in Experiment 1.

Results and Discussion

The children in this study, like those in Experiment 1, went to the correct corner or the rotationally equivalent one the majority of the time, 42 and 33%, respectively. The responses to these two corners did not differ significantly from each other, $t(11) = .62$. Responses to those two corners were marginally more frequent than responses to the two other corners, $t(11) = 1.54$, $p = .07$. There were 17% of responses to the near corner and 8% to the far one. Overall, the children in this study performed very similarly to the children in Experiment 1, with no significant differences in number correct or numbers of each kind of error, all $t < 1.06$. Thus, it appears that no aspect of the setup or disorientation procedure had changed over time in such a way as to allow children to choose the correct corner using cues other than those manipulated in the experiments.

GENERAL DISCUSSION

The studies in this paper produced a very consistent set of findings, summarized in Table 1. The data show that disoriented children under the age of 2 years

TABLE 1
Means and Standard Deviations for All Experiments

	Correct	Rotational equivalent	Near error	Far error
Experiment 1				
Means	1.73	1.43	.44	.42
SD	1.16	.87	.65	.71
Experiment 2				
Means	2.42	1.02	.15	.42
SD	1.25	1.06	.46	.71
Experiment 3				
Means	2.46	.81	.38	.35
SD	.87	.76	.42	.53
Experiment 4				
Means	2.58	.42	.33	.67
SD	.90	.67	.49	.99
Experiment 5				
Means	2.39	.97	.29	.36
SD	.88	.88	.46	.61
Experiment 6				
Means	1.67	1.33	.67	.33
SD	.99	1.07	.78	.49

use landmarks as well as geometric information to locate objects and that they can either integrate the two forms of information when necessary or use nonverbally coded left–right information. These findings go against the claim that spatial development begins with a geometric module that is a domain-specific and informationally encapsulated cognitive structure, with linguistic coding required to overcome the hypothesized limitation in early spatial behavior.

The discrepancy between our findings and those of Hermer and Spelke (1994, 1996) requires some discussion. In the introduction, we mentioned two possible sources of the differences in findings. First, the landmarks in each of Experiments 2–5 were permanent features of the room, as far as the children knew; that is, they looked permanent and the children had never seen them move. By contrast, some of Hermer and Spelke's studies involved play sessions before the study during which the experimenter and the child played with the "landmarks," and almost all studies involved within-participants manipulations in which half the children always knew that the "landmark" was movable. (The only exception was two small studies in Wang et al., each involving only four children.) Second, Hermer and Spelke (1996) used a very small space. It seemed possible that our space, with an area four times the size of theirs, would engage the spatial orientation system in a different way, one that allowed for landmark use.

The relevance of the size of the space may seem to be questioned by two recent reports that children fail to use colored walls to reorient, even with larger spaces than those used in the Hermer and Spelke work (Gouteux & Spelke, 2000; Stedron, 2000; see also Stedron, Munakata, & O'Reilly, 2000). However, there is

reason to question these new data. The Gouteux and Spelke study, as with the previous work by Spelke and her associates, used a within-participants design in which some children also viewed the space without a colored wall; the small number of children again made testing for order effects or interactions difficult. In addition, although the total area of the circular space used by Gouteux and Spelke was larger than those in previous studies from that group, the search boxes were not located at the edge of the space, so that the “actively used space” was still quite small. In the Stedron study, which used a space with an area larger than that used by Hermer and Spelke but smaller than that used in the present work, the children *did* use the colored wall on the first trial, although not on subsequent trials.¹ Other recently gathered data, from experiments explicitly varying the size of the space, indicate that size may in fact be a crucial determinant of whether young children use landmark information to reorient (Learmonth & Nadel, 2001).

However, determining the source of the difference among studies is not crucial to the key argument of this paper. A module that operated only under some unspecified boundary conditions would be of limited theoretical interest and, indeed, by Fodor’s criteria, would not qualify as a module at all. That is, showing that children do use nongeometric information to reorient in some set of circumstances (minimally, the set used in the present studies) is basically an existence proof. Specifying what circumstances produce what sort of behavior may provide valuable information about young children’s spatial knowledge, but, whatever the research uncovers, there would be no basis for claiming modularity.

Although the present data call into question a particular account of development that involves a particular modular architecture, they do not, strictly speaking, constitute an argument against modularity as a starting point for development in general. There might be other modules in spatial development or modules in other lines of cognitive development. However, Karmiloff-Smith (1992) has raised doubts about the innate-module approach to cognitive development in general, and Newcombe and Huttenlocher (2000) critique other aspects of the nativist approach to spatial development in particular. At this point, the burden of proof may be on the proponents of modularity to advance specific descriptions of innate encapsulated abilities.

The experiments reported in this paper should not, however, be taken to raise doubts about strong biological starting points for spatial development, a hypothesis quite different from that of innate modularity. As briefly discussed in the introduction to this paper, Newcombe and Huttenlocher (2000) argue for such strong starting points. However, the capacities envisioned as part of the infant’s innate equipment, such as coding amount of self-movement, are part of general perceptual systems and are modified by interaction with the physical world. Additional support for the idea of strong starting points is provided by the aspect

¹ It is also possible that the fact that Stedron allowed children who failed to find the object to continue to search changed children’s attitude to the task from a locational one to a more unfocused gamelike attitude.

of Hermer and Spelke's work that *was* replicated in the present studies. Young children can apparently compare two distances and encode right-left information about these values. Such sensitivity is remarkable, far beyond the sort of early ability postulated in classic Piagetian theory (e.g., Piaget & Inhelder, 1948). Ability of this sort suggests that a complete theory of spatial development needs either to posit an innate sensitivity to certain aspects of the spatial world or to account for rapid acquisition of such sensitivity from experiences during the first months of life.

REFERENCES

- Acredolo, L. P. (1977). Developmental changes in the ability to coordinate perspectives of a large-scale space. *Developmental Psychology*, **13**, 1-8.
- Acredolo, L. P. (1988). From signal to "symbol": The development of landmark knowledge from 9 to 13 months. *British Journal of Developmental Psychology*, **6**, 369-372.
- Acredolo, L. P. (1990). Behavioral approaches to spatial orientation in infancy. In A. Diamond (Ed.), *The development and neural bases of higher cognitive functions* (pp. 596-607). New York: N.Y. Acad. Sci.
- Biegler, R., & Morris, R. G. M. (1993). Landmark stability is a prerequisite for spatial but not discrimination learning. *Nature*, **391**, 631-633.
- Bremner, J. G., & Bryant, P. E. (1977). Place versus responses as the basis of spatial errors made by young infants. *Journal of Experimental Child Psychology*, **23**, 162-171.
- Cheng, K. (1986). A purely geometric module in the rat's spatial representation. *Cognition*, **23**, 149-178.
- Etienne, A. S., Teroni, E., Maurer, R., Portenier, V., & Saucy, F. (1985). Short-distance homing in a small mammal: the role of exteroceptive cues and path integration. *Experientia*, **41**, 122-125.
- Fodor, J. A. (1983). *Modularity of mind: An essay on faculty psychology*. Cambridge, MA: MIT Press.
- Gallistel, C. R. (1990). *The organization of learning*. Cambridge, MA: MIT Press.
- Goodridge, J. P., & Taube, J. S. (1995). Preferential use of the landmark navigational system by head direction cells in rats. *Behavioral Neuroscience*, **109**, 49-61.
- Gouteux, S., & Spelke, E. S. (2000). *Children's use of geometry and landmarks to reorient in an open space*. Unpublished manuscript, CNRS, 31, chemin Joseph Aiguier, 13402 Marseille, France.
- Gouteux, S., Thinus-Blanc, C., & Vauclair, J. (in press). Young rhesus monkey's spatial reorientation: The use of geometric and featural information. *Journal of Experimental Psychology: General*.
- Hermer, L., & Spelke, E. S. (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.
- Hermer-Vazquez, L. (1997). *Cognitive flexibility as it emerges over development and evolution: The case of two navigational tasks in humans*. Ph.D. thesis, Cornell Univ.
- Hermer-Vazquez, L., Spelke, E. S., & Katsnelson, A. (1999). Sources of flexibility in human cognition: Dual-task studies of space and language. *Cognitive Psychology*, **39**, 3-36.
- Huttenlocher, J., Newcombe, N., & Sandberg, E. H. (1994). The coding of spatial location in young children. *Cognitive Psychology*, **27**, 115-148.
- Knierim, J. J., Kudrimonti, H. S., & McNaughton, B. L. (1995). Place cells, head direction cells, and the learning of landmark stability. *Journal of Neuroscience*, **15**, 1648-1659.
- Learmonth, A. E., & Nadel, L. (2001, April). Geometry, landmarks, and different sized spaces. Paper presented to the Society for Research in Child Development, Minneapolis, Minnesota.
- Margules, J., & Gallistel, C. R. (1988). Heading in the rat: Determination by environmental shape. *Animal Learning and Behavior*, **16**, 404-410.

- McNaughton, B. L., Leonard, B., & Chen, L. (1989). Cortical-hippocampal interactions and cognitive mapping: A hypothesis based on reintegration of the parietal and inferotemporal pathways for visual processing. *Psychobiology*, **17**, 230–235.
- McNaughton, B. L., & Nadel, L. (1990). Hebb-Marr networks and the neurobiological representation of action in space. In M. A. Gluck & D. Rumelhart (Eds.), *Neuroscience and connectionist theory* (pp. 1–63). Hillsdale, NJ: Erlbaum.
- Millar, S. (1994). *Understanding and representing space: Theory and evidence from studies with blind and sighted children*. Oxford: Clarendon.
- Nadel, L. (1988). Landmarks: Neurobiological perspectives. *British Journal of Developmental Psychology*, **6**, 383–385.
- Newcombe, N., & 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. (1998). The development of spatial location coding: Place learning and dead reckoning in the second and third years. *Cognitive Development*, **13**, 185–200.
- Newcombe, N., Huttenlocher, J., & Learmonth, A. (2000). Infants' coding of location in continuous space. *Infant Behavior and Development*, **22**, 483–510.
- Piaget, J., & Inhelder, B. (1948/1967). *The child's conception of space* (F. J. Langdon & J. L. Lunzer, Trans.). New York: Norton.
- Presson, C. C., & Montello, D. (1988). Points of reference in spatial cognition: Stalking the elusive landmark. *British Journal of Developmental Psychology*, **6**, 378–381.
- Rider, E. A., & Rieser, J. J. (1988). Pointing at objects in other rooms: Young children's sensitivity perspective after walking with and without vision. *Child Development*, **59**, 480–494.
- Rieser, J. J., & Rider, E. A. (1991). Young children's spatial orientation with respect to multiple targets when walking without vision. *Developmental Psychology*, **27**, 97–107.
- Sholl, M. J. (1995). The representation and retrieval of map and environment knowledge. *Geographical Systems*, **2**, 177–195.
- Stedron, J. (2000). *Spatial reorientation in children: A case of modularity or hippocampal function?* Master's thesis, University of Denver.
- Stedron, J., Munakata, Y., & O'Reilly, R. C. (2000, July). *Spatial reorientation in young children: A case of modularity?* Paper presented at the International Conference on Infant Studies, Brighton, England.
- 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.
- Wilson, M. A., & McNaughton, B. L. (1993). Dynamics of hippocampal ensemble code for space. *Science*, **261**, 1055–1058.

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