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2 Spatial Knowledge and Its Manifestations

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Knowledge of space and of the objects that occupy and move through space constitutes a fundamental domain of human cognition. Adults perceive and move smoothly through space, search for and locate objects in spatial layouts, construct and use maps, and even reflect on the nature of their spatial knowledge. As psychologists, however, our understanding of this spatial knowledge is far from complete. What is the nature of this knowledge, and how does it arise?

To begin, we should specify what we mean by spatial knowledge. In our use, spatial knowledge is a system of representations and rules that supports the recording of spatial relationships among objects, and the deduction of new spatial relationships among the same objects. Note that many spatial performances can be explained adequately without reference to such a system. For example, navigation toward a visible or audible object can be explained by appeal to perceptual-motor mechanisms that enable directed locomotion (see, e.g., Hein & Jeannerod, 1983, for examples of such mechanisms). Or, navigation along a previously learned route can be explained by reference to motor memories that specify the muscle movements needed to reach some goal from some starting point. In contrast, some abilities can be captured best by appeal to a system of spatial knowledge. A straightforward example of such an ability is the creation of new routes or detours through a layout. In order to make a detour effectively through a region, one must know the position of the goal and its spatial relationship to the starting point, and one must be able to infer what path or paths will lead efficiently from the starting point to the goal. Construction of such paths requires spatial knowledge—knowledge of the distances and directions among the places in the layout. Adult humans clearly have such knowledge, and other species may have similar systems (Cheng & Gallistel, 1984; Maier, 1929;

Menzel, 1973; Tolman, 1948). Yet, there is surprisingly little evidence that human infants or young children have such knowledge. Why is this so?

First, many demonstrations of young children's spatial *abilities* can be explained adequately without referring to spatial knowledge. For example, infants and children are known to be able to locate objects in space, if sufficient information is provided to aid their search. For infants, this may be a colored cover coincident with the target (Bremner, 1978); for young children, it may be an obvious landmark near the target (Acredolo, 1979). There are interesting developmental changes in children's ability to use such information (DeLoache, 1984; Huttenlocher & Newcombe, 1984). However, efficient location of objects using such information can be explained adequately by one or a set of simple motor-behavioral rules: for example, "go to the red cloth" or "move to the couch, then go forward three steps." Since the performance *can* be explained in this way, there is no need to posit a spatial knowledge system, as described above. Second, existing studies of children's spatial knowledge may underestimate that knowledge by employing tasks that may systematically bias infants and children to fail for reasons other than a lack of spatial knowledge. For example, many experimental tasks require that infants or children find an object after a 180° rotation around an array. Such a task may be hard, however, *not* because there is no spatial knowledge system that could support a 180° transformation; but rather, because an immature motor system may be incapable of producing right-left reversals. In short, an independent constraint on the motor system might interfere with the expression of spatial knowledge.

In this chapter, we argue that a spatial knowledge system may be intact quite early in life, but that children may not always be able to demonstrate that knowledge. We support this argument in two parts, with evidence on the spatial abilities of a young congenitally blind child and normal sighted controls of the same ages. In the first part, we briefly review our previously published evidence for a spatial knowledge system in both the blind child and sighted children. The demonstrations are based on a set of navigation tasks requiring the construction of new routes through a room in the absence of immediate information about the positions of the target locations. The children's successes enable us to expand our description of the nature of the spatial knowledge system. In the second part, we present some new evidence for early spatial knowledge, focusing on one task that has heretofore been used to argue for deficits in the spatial abilities of infants and young children. This is a 180° rotation task, requiring reaching to the left or right before and after rotation. The blind child failed this task systematically through age 5, whereas most of the sighted children succeeded at the youngest ages tested. To explain these differences, we then consider task-specific variables that might lead to success in the navigation task but failure in the rotation task. We propose that one factor, in particular, underlies the dramatic performance differences. Most importantly, we propose that the blind child's difficulty in the rotation task does not in any way stem from deficiencies in her spatial knowledge.

In conclusion, we discuss the possibility that there is very little development in the nature of the spatial knowledge system itself. Instead, developmental changes in spatial navigation seem to reflect an increasing coordination of the knowledge system with action, and with spatial markers in the world. That is, we suggest that development does not change the basic units of the spatial knowledge system; rather, children learn how actions and information in the world can reliably be used to locate particular objects in space.

I. SPATIAL KNOWLEDGE AND THE NAVIGATION TASK

With this general description in mind, we have focused on a young blind child's ability to navigate the environment without benefit of current perceptual information about the locations of objects. The primary motivation for studying a blind child was the logic of forcing reliance on a mental representational system that might be concealed under the more advantageous conditions of looking and searching. Much of children's spatial behavior (as well as that of adults) may be perceptually guided—when we visually search for an object, when we navigate to seen landmarks, there may not be any need to rely on a mental representation of space. For the blind, the situation is different, for they are often without current perceptual information about landmarks and places. Methodologically, the blind child is an especially relevant case, since limitations imposed by blindness can quickly rule out certain hypotheses about the nature of early spatial abilities. Since the blind child's only distance sense is audition, she may be pressed into recruiting spatial representational capacities to locate objects beyond her immediate reach. Two candidates suggest themselves: memorized motor routines, which are burdensome and confined to specific prior experiences; and "cognitive maps" whose formation and use reflect a rule-governed knowledge system that allows endless computation of new spatial relations from the few that are stored in memory. The blind child may thus be especially well suited to revealing the nature of early spatial knowledge.

A second motivation was to discover whether the development of spatial knowledge necessarily involves visual experience. Blindness has often been negatively implicated in the development and use of spatial concepts (see Fraiberg, 1977; Millar, 1975; Potegal, 1982; Warren, 1977). For example, it has been proposed that blindness severely restricts accessibility to spatial information, leading to representational deficits (Fraiberg, 1977); that it biases against the construction of unified spatial representations, leading to difficulties in mental manipulations (Millar, 1975, 1976); and that it denies the perceiver access to a firmly imposed reference system, leading again to difficulties in constructing and manipulating spatial representations (Warren, Anooshian, & Bollinger, 1973). Cited in favor of these views are findings of delays in object location in blind infants and sighted infants who must rely on sound for localization (Bigelow, 1983; Fraiberg, 1977; Freedman, Fox-Kolenda, Margileth, & Miller, 1969); relative difficulties in reversing haptically traced routes in both blind and sighted subjects (Millar, 1975), and the relative superiority on a variety of tasks by late-blinded relative to early-blinded individuals (see Warren, 1977, for review).

Yet conflicting observations come from other sources, suggesting that perhaps blind infants and children have spatial capacities that have not been revealed by the preceding methods. Anecdotal reports suggest that blind infants and toddlers can often find their way about familiar environments (Norris, Spaulding, & Brodie, 1957), and experimental reports have shown that many spatial tasks are solved with close comparability by blind and sighted subjects (Jones, 1975), including apparently difficult tasks such as mental rotation (Carpenter & Eisenberg, 1978; Marmor & Zaback, 1976) and use of maps (Berla, 1982; James, 1982). Convincingly, it has been shown that blind adolescents can use properly constructed tactile maps to guide route and detour formation in unfamiliar geographic regions (Leonard & Newman, 1967). These more positive reports seemed to us consistent with our own naturalistic observations: The blind child we studied appeared to be quite capable of navigating around familiar environments, locating objects in familiar places, taking paths between objects, and predicting the direction of travel to known places from novel locations. Moreover, in related investigations of language learning, we have observed three blind children, none of whom appeared to be lost in space. Rather, they were all quite able to navigate their environments, to locate their favorite toys on command, and later, to verbally direct others in space (see Landau & L. R. Gleitman, in press). These informal observations prompted our experimental work.

In a series of experiments, we investigated the ability of a young blind child to learn paths between objects in a large space, and to use those experiences to generate further, novel paths among the objects.[1] The child, Kelli, was blind due to Retrolental Fibroplasia occurring shortly after birth. Kelli is totally blind, and has been so since approximately 4 weeks of age. We studied her spatial navigation abilities during the age range of 34–60 months.

Initial Experiment

In the first study, Kelli was 34 months old. She was brought into a novel 8′ × 10′ room, which contained four objects at the positions labeled A–D (see Fig. 2.1). She was seated at A, where she was told she would be shown where some toys were in the room. The ensuing procedures included a training and a testing phase, as follows.

[1]The navigation experiments are reported fully in Landau, Gleitman, & Spelke (1981), and Landau, Spelke, & Gleitman (1984). Experiments on Kelli's ability to spontaneously interpret and use simple 3-dimensional tactile maps to guide locomotion are detailed in Landau (forthcoming).

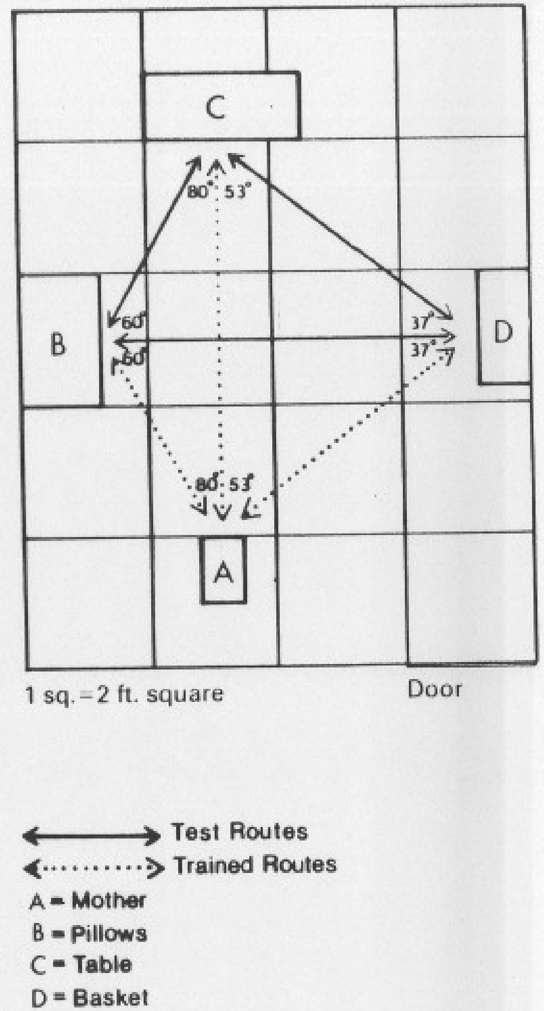

FIG. 2.1. Room layout for navigation task. (Adapted from Landau, Spelke, & Gleitman [1984] by permission of the publisher.)

During training, she was walked from A to B and back again, twice; then from A to C and back again, twice; finally, from A to D and back again, twice. Each time, Kelli was told where she was at the beginning and end of the route; when she reached the end of the route, she was shown the landmark object from a canonical viewing position, aligned in front and facing the object (see center arrowheads at each landmark in Fig. 2.1). She was allowed to explore the landmarks, and was then turned and guided back to A.

When these routes were completed, Kelli was walked to C, and she was then tested on her ability to find new routes among the three landmarks, B, C, and D. Specifically, she was asked to move from C to B and back again, twice; from C to D and back again, twice, and from B to D and back again, twice; for a total of

12 test trials. Kelli's position at the beginning of each test trial varied unsystematically, in a relationship determined by the route she had just taken. For instance, on the first test trial, she began facing landmark C, and moved to B. Her position on reaching B served as the starting position for the next test trial, moving from B back to C. Sometimes her position at B was identical to her position at B during training, i.e., front and facing B. Other times, however, she reached B at a corner, or a side of the landmark. These times, she was not oriented to front and facing, but rather, was given the next test command from whatever position she occupied at the moment.

For each test trial, Kelli was instructed using simple commands, e.g., "Can you find the pillow?" or "Can you please put this on the table?" When Kelli began moving after each command, the experimenter remained behind her, encouraging her (e.g., "That's good, find the table"), but did not interfere in any way. A trial was terminated when Kelli fell within a 1-foot radius of the block encompassing the target object. Trials were also terminated if Kelli began moving along an inference path that had not yet been tested (e.g., Trials 4, 6, 8), or if she indicated confusion, either by moving in circles, or by explicitly asking for help. In these cases, the trials were always counted as failures (see scoring procedures below). All sessions were videotaped, and Kelli's paths of independent movement were transcribed and used as raw data.

The results were analyzed by a number of methods we devised to determine (a) whether or not Kelli's movements were random with respect to the goal; and (b) whether or not Kelli's movements were directed more toward the goal than toward the other landmarks.

Kelli's paths of locomotion in this experiment are shown in Fig. 2.2. Simple observation of the paths suggests that Kelli did know where she was going and that she moved immediately and directly toward the goal. Her performance was not perfect, however; several trials were terminated upon apparent loss of bearings (Trials 4, 6, 8); and in others, her paths were not completely straight-line, but were somewhat curvilinear. Nevertheless, these simple observations of success in most trials are supported by several statistical analyses of her movement paths, as follows.

First, we analyzed Kelli's initial turns from the source, asking whether these turns were better adjusted to the goal than to the other landmarks. Second, we analyzed Kelli's final positions prior to termination of each trial, asking whether these positions were better adjusted to the goal than to the other landmarks. Finally, we performed a correlational analysis of the relationship between the initial turns and final positions, asking whether accuracy of the initial turn would predict the final position. We assumed that if Kelli knew where she was going, she would make an initial turn that was quite well directed toward the goal, and would then proceed in straight-line fashion to the goal. If this were true, then trials on which her initial turns were accurate would also be those trials for which final position was accurate. Under all of these analyses, Kelli's movement paths were shown to be significantly better than chance: on 11 of 12 trials, Kelli turned

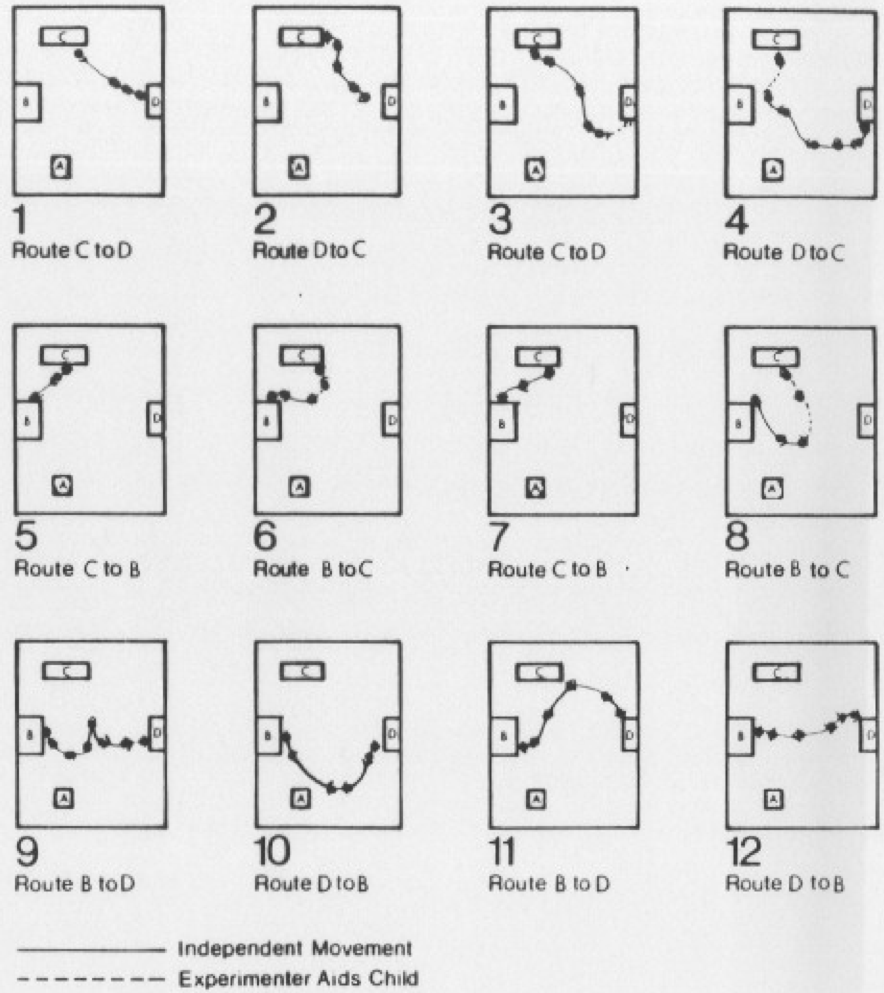

FIG. 2.2. Kelli's paths of movement on navigation test trials. Arrowheads indicate Kelli's frontal directions, and solid circles indicate her positions as she moves. (Adapted from Landau, Spelke, & Gleitman [1984] by permission of the publisher.)

toward the goal (instead of away from it; $p = .0029$, Binomial test); her final position fell within a 40° range subtending the goal on 8 of 12 trials ($p = .0001$, Binomial test). Finally, there was a significant relationship between success or failure on the initial turn, and success or failure on final position, suggesting that the initial turns could predict Kelli's ultimate performance (9 of 12 measures agreed in sign, $p = .05$, Binomial test).

These results suggested that Kelli could indeed use the experience of walking along a set of object-joined paths, to generate new paths among those same objects.

Follow-up Experiments

In later experiments, we sought to contrast Kelli's behavior in this first experiment with her performance under various other conditions. The methods all followed the paradigm of Experiment 1, but the configurations changed slightly and the landmarks changed entirely. In a second experiment (at 43 months), we studied her behavior when the paths were not always object-linked. Here, we removed two of the landmarks (C and D; see footnote 2)[2], and repeated the experiment, training Kelli to move to two places that contained object landmarks (A,B), and to two places containing no landmarks at all (C,D) defined as "your place" and "my place." When she was tested as in the first experiment, her performance showed that she could make inferences relating places in space that were not occupied by landmarks. Her performance was comparable to that in Experiment 1.

We also studied her performance under conditions where we removed possible extraneous sources of information: In a third experiment (36 months), we controlled for the effects of subtle sound cues in the room. We trained and tested Kelli as in Experiment 1. After half the testing session, however, Kelli was carried out of the room, and the array of objects was rotated 90° relative to the room: A was now placed at B's prior position in the room, B was now at C's prior position in the room, and so forth. Then, Kelli was carried back into the room and was placed at her prior position. If Kelli was moving by reference to subtle sound cues within the room, she should now make systematic errors, moving to the wrong landmarks. She did not make such errors; rather, she continued to move appropriately to the landmarks, performing at the same level as before her removal from the room. Further, her performance was not significantly different from that in Experiment 1.

A fourth experiment controlled for experimenter bias. Here, Kelli (53 months) was trained as before, but she was tested by an experimenter naive as to the correct identity of the target landmarks. That is, two identical landmarks were used, called by different names; the testing experimenter never heard the names and referents paired. When she gave Kelli commands to "find X," she did not know whether or not Kelli was moving in the correct direction. Kelli still performed at the same level as in previous experiments.

Finally, we studied Kelli's navigation in the absence of any training. Could Kelli (48 months) navigate to landmarks from various points in the room, without having had prior information about the landmarks' locations, but by using echolocation or some other sensory information? The answer here was clearly negative: in the 1 experiment out of 6 (1 additional not reported here), Kelli performed at chance on all measures. She was only able to navigate between landmarks when she had received prior information about their spatial relationships.

[2]The landmarks changed in each experiment, but the same initials are used here to allow the reader to locate the new landmarks in the array.

The findings of these experiments provided evidence that Kelli had spatial knowledge: She was sensitive to spatial relationships among objects, and she could infer new relationships among those objects. We also replicated the effect with sighted but blindfolded 2- to 3-year-old children, who performed at roughly the same level as Kelli, and with sighted blindfolded adults, who performed better than the children. The comparability of blind and sighted children in this task suggested that the spatial knowledge system arises independently of the particular source of sensory experience.

Kelli's successes in the navigation tasks raised one final question: Were her abilities confined to these navigation tasks, or could they be seen as well in tasks involving maps? Starting at 54 months, Kelli was tested on her ability to use maps to guide her locomotion. These experiments provided evidence that Kelli understood two-object maps from her earliest exposure to them. She could use the maps to locate objects in a large space (10′ × 10′); both when the maps were positioned directly in front of her, and when they were presented in several noncanonical positions: under vertical rotation, and sideways translation. Performance in this latter condition was particularly striking: when the map was to Kelli's left (hence both objects on the map were to her left), she was nevertheless able to find a target object located to her right in space (hence, to the right of the "Kelli-symbol" on the map). The experiments demonstrated, therefore, that Kelli understood the relationships displayed on the map to be independent of her own position relative to the map. Kelli's ability to systematically locate the target objects using only the information provided on these maps is testimony to an underlying system of knowledge that was sufficiently rich to make contact with a highly abstract form of experience—a real map.

Some Implications about the Nature of Spatial Knowledge

We suggest that the performances of Kelli and other children provide evidence for a spatial knowledge system with certain definite properties. In particular, solution of the navigation tasks requires a system in which one can record and manipulate metric properties of space. To see why this is so, consider again the navigation tasks. In these tasks, the children were walked along three paths relating four objects: One object served as the origin (A), and each of the three paths lay between A and one of the other three objects in the array. This spatial array could be encoded in a variety of ways. For example, the array could be encoded as a set of landmarks *connected* to each other by the experienced paths. From such a representation, the child would know that paths exist between the pairs of landmarks so encoded. However, if the representation contained only the notion *connectedness*, then one could make inferences only about further connectedness relationships. For example, the child might be able to infer that two other objects are also connected by some path, but he would not be able to differentiate among the infinite number of such paths. He would have no basis for differentiating between paths that lead him randomly around the room, ending up at the goal, and those that are directionally specified straight-line paths between start and goal.

In contrast, the array could be encoded as a set of objects that are connected to each other by paths holding distinct distance and direction relationships to each other. From such an encoding, the child could infer new distance and direction relationships between pairs of the objects. The children's inferences showed that they could determine the new angular relationships between pairs of objects, relationships among paths they had never traveled before. This solution can be described in simple geometric terms: given an angle and two distances (e.g., <BAC and distances AB, AC), one can compute the new angle-distance relationship between objects B and C. The significance of this description is that it suggests a much richer set of geometric properties manifest in early spatial knowledge than has heretofore been imagined (but see Huttenlocher & Newcombe, 1984; Mandler, 1983; for similar notions). Where Piaget (1954; Piaget & Inhelder, 1967; Piaget, Inhelder, & Szeminska, 1960) had envisioned development of spatial knowledge from Topological through Projective and finally Euclidean geometries, it appears from our evidence that Euclidean (or other metric) geometric properties are highly accessible early in life. Note that by this we do not mean that the child's knowledge can be described completely and exhaustively as a Euclidean geometry; this would be highly unlikely, for it would rule out spatial properties such as orientation, which we know to be extremely important in human spatial representations. Rather, we mean that the child's spatial knowledge system incorporates certain metric properties, notably, angles and distances, that can be used to solve navigation-type problems.

To summarize, the use of the navigation paradigm has revealed the presence of a spatial knowledge system that is intact early in life and that has arisen in children with different modalities of sensory experience. However, as we hinted in the beginning, children may not always show that knowledge; certain task demands may bias them toward failure even if they have spatial knowledge. The example we offer in this paper is a rotation task, requiring location of an object in a small array, over 180° rotations. We turn to the results of this paradigm with the blind child and with sighted controls.

2. MASKING OF SPATIAL KNOWLEDGE IN ROTATION TASKS

In these experiments, we sought to compare the spatial capacities uncovered by the navigation tasks to the capacities revealed by a traditional rotation task. We followed procedures similar to those used by Acredolo (1977, 1978) and

Bremner (1978), with the same subjects who had participated in our navigation tasks. To our great surprise, the blind subject who had shown competence in simple detour tasks systematically failed the rotation task. Moreover, we repeated the experiment at intervals spaced over 2 years and found repeated failures, with final success only when she reached 5 years of age. In contrast, most of the sighted blindfolded children succeeded in solving the rotation problem at the same ages at which they had solved the navigation inference task.

EXPERIMENT 1: REACHING OVER ROTATIONS

Subjects

Kelli participated in this experiment at 34 months of age. Four sighted subjects participated, all wearing opaque goggles to prevent vision. They ranged in age from 35 months to 47 months, mean age 37.5 months. These sighted subjects had all participated in the navigation studies reported above, at the same ages. Although Kelli was slightly younger than the sighted subjects at this session, replication over time allows comparison of blind versus sighted subjects at the same age.

Procedures

Each subject was seated in the middle of one side of a rectangular table, 30″ × 18″ in size. The experimenter sat across from the child, and a third and fourth person (the child's mother and a research assistant) sat at each of the shorter sides (see Fig. 2.3). The child was told she would be having a tea party, and that her task would be to give people cups, napkins, and cookies. To prevent the sighted children from seeing the array, they were equipped with opaque goggles before entering the room. Each child was guided to his or her chair, and allowed to explore the table. They were also told where each person was sitting, and each person confirmed this by saying "I'm here." All the children had met the experimenter and assistant before the experiment, and none had any difficulty recognizing each person's voice.

After the child was seated at the table, training began. The experimenter handed the child a cup and asked, "Would you please give this one to ______?" Each child reached in the appropriate direction (left, right, or straight ahead), and the target person took the cup, thanking the child aloud. The request was repeated, until everyone had a cup. Then, the child was asked to give each person a spoon, then a cookie, always in the following order: mother (A), assistant (B), experimenter, child. Each time a person received something, he or she thanked the child verbally, confirming their location. All children performed perfectly in this part of the task.

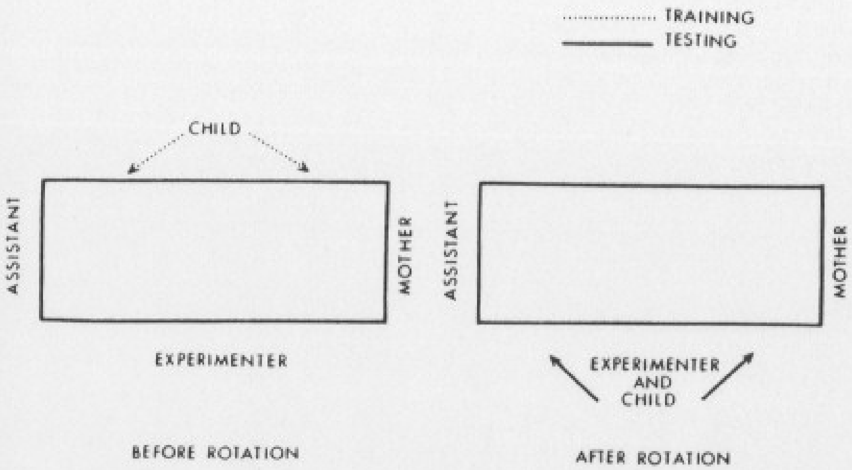

FIG. 2.3. Table layout for spatial rotation task. Children were trained in the position labeled "before rotation." They then moved around the table, and were tested in the position labeled "after rotation."

After training, the child was asked to move around the table to join the experimenter: "Would you please come around and help me?" Each child then walked around the table, past his or her mother, found the experimenter, and climbed up on her lap, to face the table (see Fig. 2.3). Testing then began.

In testing, the experimenter then repeated the same commands as above, asking the child to give persons A and B a cookie, twice in a row, A, B, A, B, yielding a total of 4 test trials in the rotated position. This time, however, no feedback was given about any person's whereabouts; the experimenter took each cookie from the child's extended hand, and said "OK," continuing with the next command. After these 4 trials, the child was asked to return to his or her seat. The original training procedure was then repeated, followed by a second rotation and testing. Thus there were 2 test trials each to A and B for each of two test series, in each of the two conditions—original position and rotated position. This yielded a total of 16 test trials per subject, 8 from the original position, and 8 from the rotated position.

Results

Performance from the original position was perfect, both for the first set of trials, and for later sets that followed testing from the rotated position. This indicates that without vision, both blind and sighted subjects were perfectly capable of determining the positions of all participants, and of holding those positions in memory, even after moving back and forth around the table several times.

The results from the rotated position are quite different and are shown in Table 2.1, as percentage correct, incorrect, and error type. The sighted but

TABLE 2.1
Kelli's and Sighted Controls' Performance in the Rotation Experiments

Experiment	*Percent Correct*	*Percent Incorrect*	*Percent of Errors*	
			Perseveration	*Other*[a]
Experiment 1				
Kelli (34 mos.)				
Rotation 1	0	100	100	0
Rotation 2	0	100	100	0
Sighted controls[b]				
Rotation 1	75	25	100	0
Rotation 2	75	25	100	0
Experiment 2[c]				
Kelli (35 mos.)				
Rotation 1	50	50	50	50
Rotation 2	67	33	100	0
Rotation 3	0	100	100	0
Experiment 3				
Kelli (37 mos.)				
Rotation 1	50	50	0	100
Rotation 2	0	100	100	0
Rotation 3	75	25	100	0
Experiment 4				
Kelli (51 mos.)				
Rotation 1	0	100	100	0
Rotation 2	0	100	100	0
Experiment 5				
Kelli (57 mos.)				
Rotation 1	25	75	100	0
Rotation 2	25	75	100	0
Experiment 6				
Kelli (60 mos.)				
Rotation 1	100	0	0	0
Rotation 2	100	0	0	0

[a]These responses were of one type only: where, although the child failed to reach to precisely the correct location, she nevertheless effected the proper right-left reversal, by reaching across from herself, to her original location. See text for discussion.

[b]Four sighted controls were all blindfolded before entering the room. Scores reported for these children are mean percent correct and incorrect.

[c]In all experiments, there were a total of 4 responses per subject for each rotation; but in Experiment 2, one test trial was inadvertently omitted for Rotation 2, hence the percents here are based on 3 responses for the rotation.

blindfolded subjects were correct on 75% of the trials, locating both A and B, even though this required a right-left reversal in response. The 25% errors were attributable to one child, who showed right-left perseveration on all these trials. Kelli also was systematically wrong, with all errors right-left perseverations. This initial finding raised two puzzles. First, why had Kelli and the one sighted child failed this task, when both had been so successful in the navigation task? Second, did blindness bias toward failure in this task, accounting for Kelli's failure in both this initial rotation task, and in later similar tasks (see below)?

If our analysis is correct of the requirements of the navigation task, then all of the children should have been able to solve the rotation task at the same time as they solved the navigation task. To be specific, we have argued that the children had a system of spatial knowledge, in our sense: They could detect the directional relationships among objects, and deduce new relationships among them as they moved through space. On initial inspection, the rotation task seems to require just this sort of ability: predicting new directional relationships after movement in space. In fact, an initial examination of the navigation and rotation tasks shows that the two are formally quite alike. First, both tasks use a four-object array, in a "baseball diamond" configuration. Second, both tasks include a training phase and a testing phase. The training phase in both tasks required the child to locate the three target objects, either by walking (navigation experiments) or by reaching (rotation experiment). Testing in both tasks required the child to walk to the landmark opposite his initial position, and then locate the objects from this new position. Both tasks seem to require a spatial inference, since the test routes were not experienced during training in either case. Yet, there must have been some task differences that caused Kelli and the one sighted child to fail the rotation task but succeed in the navigation task.

In the next sections, we propose three hypotheses about the relative difficulty of the two tasks, and evaluate them with some re-analyses of the navigation task data, and with data from later rotation studies with Kelli. In particular, we keep an eye toward answering the two puzzles raised above: Why would any child who succeeded in the navigation task then fail in the rotation task? And, why might a blind child be more likely than a sighted child to fail the rotation task?

The first hypothesis is that degree of rotation from the trained position at test time has an effect on the accuracy of one's inference: the greater the degree of rotation, the more difficult the inference. The second hypothesis is that tasks in which both training and testing require a left-right reaching response bias the subject toward perseveration. The third hypothesis is that lack of sufficient information about one's position in the array further biases toward a perseveration response. We argue that all three factors cooperate to make the 180° rotation task especially difficult for any child. We further suggest that the third factor may be particularly troublesome for a blind child. In discussion, we argue that these factors can help account for the numerous findings in the literature of failure by sighted infants and children in similar tasks. We conclude that the rotation task does not reveal spatial knowledge—not because such knowledge is lacking, but because systematic biases conspire to mask such knowledge.

Hypothesis 1: Increasing the Degree of Rotation Increases Task Difficulty

Intuitively, the two tasks seem to differ in the requirement to effect a significant mental rotation at test time. In the navigation task, the children were often given test commands from a position facing the target as in training ("canonical" position), or from a position slightly different from this; but they were rarely given a test command from a position that differed by 180° from their trained position (see Part I, p. 32). In contrast, in the rotation task, they were always given test commands from a position that was 180° rotated from the canonical position. We know that 180° rotations are difficult for adults and children alike, over different tasks (Acredolo, 1977, 1978; Cooper & Shepard, 1978; Huttenlocher & Presson, 1979). These facts would predict that the 180° rotation task should be significantly more difficult than the navigation task, simply because the degree of rotation at test time is more extreme. Furthermore, some investigators have suggested that blind children have particular difficulties performing such rotations. Specifically, it has been proposed that blind children's spatial representations are "kinesthetic" in nature, derived from their experience exploring an array; and that these kinesthetic representations are difficult to reverse or rotate, since they preserve the sequenced nature of the original experience. In contrast, vision-based representations are thought to be considerably easier to manipulate, since all parts of an array are available more or less simultaneously (Millar, 1975, 1976). This view would predict Kelli's failure in the rotation task, relative to the success of three of the sighted children; and if true, would suggest an important difference between blind and sighted children's spatial knowledge systems.

To evaluate the hypothesis that degree of rotation (a) affects performance in sighted subjects and (b) differentially affects performance in the blind subject, we returned to the navigation task data. First, we computed each child's position at the time each test command was given. The results are shown in Table 2.2, which displays the positions (canonical or non-canonical, by degrees) held by the children at the beginning of each test trial. Canonical positions were considered to be those experienced by the child at each landmark during training, i.e., facing forward into each landmark (see center arrowheads at each landmark, Fig. 2.1). Kelli was in canonical position on 5 of the 12 trials, and the sighted controls were in canonical position on 33 of the 48 trials. The sighted control who failed the rotation task is S4, whose pattern of positions at test time is not different from either Kelli's or the other sighted children's. The most frequent deviation from canonical position was by 46–90°; in fact, most of these were actually 90°

TABLE 2.2
Deviations from Canonical Position at Test Time (Number of Trials)

		Non-canonical (degrees)			
Subject	*Canonical*	*5–45*	*46–90*	*91–135*	*136+*
Kelli	5	0	4	3	0
Sighted subjects					
S1	11	1	0	0	0
S2	6	1	5	0	0
S3	9	0	1	1	1
S4	7	3	2	0	0

deviations. A child was in a non-canonical 180° rotated position on only 1 out of the 72 trials across all subjects. Thus, although in the navigation task a child was virtually never tested from a 180° rotated position, still, the children were tested from non-canonical positions that would have required mental alignment of the actual space with the represented space. If increasing the degree of rotation increased difficulty of response, performance from canonical positions should be better than from non-canonical positions.

To see whether or not this was true, we cross-classified each trial for each subject in terms of canonical versus non-canonical starting position, and success versus failure on that trial. For the latter, we used the strict criterion of success on both measures (initial turn, final 40° segment; see Part I). The results are presented for Kelli and the sighted controls in Table 2.3.

As can be seen, the children appear to do well with canonical starts, but less well with non-canonical starts. They clearly *can* perform inferences from non-canonical starts, although these tend to be less accurate than from canonical starts. Kelli's performances pattern the same way as the sighted children's. In addition, the single sighted subject who failed the rotation task showed the same pattern of performance here as both Kelli and the other sighted children; so failure in the rotation task does not appear to be related to a distinctive pattern of

TABLE 2.3
Canonical Position at Test Time and Success on Navigation Task

		Success	*Failure*
Canonical Start	Kelli	4	1
	Sighted	5.75	2.5
Non-Canonical Start	Kelli	4	3
	Sighted	1.75	2

performance in this analysis. Non-canonical starts produce worse performance than canonical starts for all subjects.

These results confirm the notion that increasing the degree of rotation from canonical position increases the difficulty of the response, and is in accord with other findings in the literature (see above). However, the second prediction—that of differential effect on the blind subject—is disconfirmed by the data: Kelli's performance patterns the same way as the sighted children's. This disconfirms the notion that blindness interacts with degree of rotation so as to produce poorer performance by the blind with increased rotation. Although our sample is too small to draw firm conclusions, it appears that inferences from non-canonical positions are less accurate than from canonical positions, but that degree of rotation does not differentially affect the blind child.

To summarize, degree of rotation does seem to affect performance, but similarly for Kelli and the sighted subjects. This suggests that although part of the rotation task difficulty can be attributed to the extreme degree of rotation required, it does not completely account for the difficulty some children experience in this task.

Hypothesis 2: Motor Interference Biases Toward Perseveration in 180° Rotation Tasks

The second hypothesis is that tasks requiring a left-right reaching response in both training and testing bias toward perseveration. The source of such a bias could be the normal tendency to use a body reference system within reaching spaces, coupled with motor interference after rotation. For example, we often encounter small (tabletop) arrays from a fixed position, hence we may be used to relying on fixed responses in such settings. Very often, such a bias will result in success, for instance, while searching for one's fork at the dinner table (always on one's left), or for one's stapler in the desk (always in the right-hand drawer), and so on. In contrast, for navigation tasks, such a bias would be successful only in very restricted circumstances in which the starting point is fixed, e.g., walking out the front door to go to the garage; walking into one's bedroom to go to the closet. In fact, anecdotal observations of Kelli in her home environment support the notion of a bias toward perseveration in reaching spaces, but not navigation spaces. For example, when Kelli was seated at a table, either to eat a meal or to do some work, the objects on the table were always in a fixed spatial relation relative to her. This was because her parents were quite careful to arrange them consistently: Her cup was always placed to the left of her plate during mealtime, her Braille slate was always placed to the right of her text during school work, etc. Kelli knew where to find these objects and where to replace them; and she also knew that they would always occupy these same positions. There were several occasions on which Kelli was unaware that she was in a new position at the table, and perseveration from previous responses was rampant. This rarely happened outside of these situations. Thus the in-principle difference in the utility of a body-reference system for reaching versus navigation tasks seemed to be a true difference in fact.

The utility of fixed responses in many small array reaching tasks introduces an important extra variable in tasks requiring reaching after movement. If fixed responses are normally used, then requiring a left-right reversal after movement may introduce interference from the motor system, independent of whether or not one *knows* where the objects are. If such interference exists, it should be possible to reduce or eliminate it either by omitting the trained responses, or by changing them relative to the tested responses. This logic can be seen in an experiment by Bremner (1978), who prevented 9-month-old infants from reaching before a 180° rotation, and found a significant reduction in perseverative responses after rotation. We used a similar method to evaluate the motor interference hypothesis with Kelli. Specifically, we tested Kelli in two modifications of the rotation task. These modifications were based on the logic that if reaching in both training and testing biases toward a self-reference system, then changing the response in either training or testing should improve performance. In Experiment 2, we trained Kelli on reaching, but tested her on walking; in Experiment 3, we trained Kelli on walking, but tested her on reaching. In both experiments Kelli's performance improved, although it was still not perfect.

EXPERIMENT 2: CHANGING THE TEST RESPONSE TO WALKING

The study was conducted when Kelli was 35 months old. We trained Kelli as before, and asked her to move around the table in a path resulting in a 180° rotation as before, but then tested her differently. We included three rotations: after each of the first two, we asked Kelli to *walk* to the target people; after a third rotation, we asked her to *reach*, as in Experiment 1. Thus, there were 12 trials from the original position and 12 trials from the rotated position (4 after each of three rotations).

As in Experiment 1, Kelli performed perfectly from the original position. The results from the rotated position are presented in Table 2.1. After the first rotation, Kelli got 50% correct, with half of the errors perseverations. The other half were errors in which she did not reach directly to the correct person (A), now on her right, but rather, reached across the table, in between B's and A's true positions. This response type was classified as an error, although it shows the proper left-right reversal. If this "error" is classified as correct on the basis of correct reversal, Kelli achieves 75% correct, with 25% perseveration. The results after the second rotation are similar. Here, Kelli got 67% correct, with 33% perseveration errors. These two sets of responses suggest that walking during testing does aid in breaking the set of perseverative responding. Further, the results after the third rotation reinforce this conclusion: When asked to reach during test, Kelli completely failed, with 100% of the responses perseverations. This is even though she had enjoyed some moderate success on the two previous rotations.

EXPERIMENT 3: CHANGING THE TRAINING TO WALKING

In this experiment, Kelli was 37 months old. We trained Kelli as in Experiment 1, except that she was asked to *walk* from her original position, directly to A and B. After the first and second rotation, Kelli was asked to *reach* to each of the participants; after a third rotation, she was asked to *walk* to them. As in the prior experiments, after each rotation, Kelli returned to her original position, and was re-trained—each time with walking.

As before, Kelli's performance from the original position was always perfect. Results from the rotated position are shown in Table 2.1. After the first rotation, Kelli was asked to reach, and was correct 50% of the time. The remaining 50% of the responses were errors of the sort described in Experiment 2: responses where Kelli reached across the table, achieving the proper left-right reversal, but without the precise accuracy required for a "correct" response. Collapsing these "errors" with the correct responses yields a total of 100% responses that were correct. After the second rotation, however, Kelli failed, with 100% of her responses perseverations, suggesting that whatever advantage had been gained by training her with walking was rather fragile. After the third rotation, Kelli walked to the targets correctly 75% of the time. This latter success may have been due to feedback on the initial trial: She erred by reversing left and right, reaching the assistant instead of her mother. She exclaimed "Kathy!" as if to say "What are you doing here?" Then, on the remaining trials, she reversed left and right correctly.

To summarize the results of Experiments 2 and 3, it seems that some improvement in responding was achieved by requiring a different response during training and testing. Kelli's performance was poorest in the condition in which she was trained by reaching and tested by reaching. Her performance improved somewhat when she was trained with reaching and tested with walking, trained with walking and tested with reaching, or trained and tested both with walking. The difference between reaching and walking tasks seems to reflect the greater likelihood of initially responding via a body reference system during training with reaching responses, coupled with the ensuing interference from the requirement to reverse this right-left response.

We should note that Kelli's improvement in Experiments 2 and 3 was not due to the mere fact that she was older at this time than in Experiment 1. Kelli continued to fail the original rotation task (train, reach; test, reach) two more times: once at 51 months and once at 57 months (Experiments 4 and 5, see Table 2.1), with all errors left-right perseverations. Finally, she was completely successful in the original task at 60 months (Experiment 6, Table 2.1). Thus, motor interference appears to account for part of Kelli's poor performance in the rotation task. However, it is not the only explanation: suspending the reach-reach requirement improved Kelli's performance, but did not make it perfect.

Hypothesis 3: Lack of Information About One's Current Position Leads to "Egocentric Localization" of Objects

An enormous body of literature attests to the fact that information about one's current position is crucial to making accurate spatial inferences. This fact was first discovered within the animal literature, in the context of the place-response debate (Tolman, 1948; Tolman, Ritchie, & Kalish, 1946; see O'Keefe & Nadel, 1978; and Restle, 1957, for reviews). The relevant paradigm here was one in which the animal is trained to run through a cross-maze, making either a right or left turn, to get to a goal box. After training, the maze is rotated, or the animal is started from a new location, and the experimenter observes whether the animal runs to the same *place* in the maze, or makes the same *response* as in training, running left if trained to the left, and right if trained to the right. The outcome of an enormous set of such studies suggests that animals are not constrained either to learn exclusively about their own actions or to learn exclusively about the layout of the environment. Rather, the particular behavior observed is a function of information provided in the environment. Rats will apparently take advantage of a variety of spatial cues in an environment, and their response depends on what cues are available. When very little information is available—especially when run in a homogeneous or poorly lit environment—the rats tend to be response learners. When rich extra-maze information is present, they tend to be place learners.

Surprising parallels have been found in developmental investigations of human spatial abilities. Infants and young children tend to learn to repeat actions that were previously successful when there is little information in the environment, and they tend to learn about places in space when there is more information available. For example, both infants and young children tend to behave like "response learners" in unfamiliar settings (Acredolo, 1977), with few or no landmarks (Acredolo, 1978), and when only parts of the background, not the objects themselves, are distinguishable (Bremner, 1978). In contrast, when there is more information, infants and young children learn about the locations of objects in the spatial layout (Acredolo, 1979; Bremner, 1978). For example, even 9-month-old infants can retrieve an object after they have undergone a 180° rotation when the objects are distinctively marked (Bremner, 1978). Moreover, an interesting developmental trend has been found: Infants seem predisposed to use landmark information that is proximate to target places, but toddlers and

children increasingly use landmark information that is more distant from the targets (see Huttenlocher & Newcombe, 1984, for a review).

These findings are relevant for an analysis of Kelli's failure in the rotation task. In general, it appears likely that Kelli may have perseverated with trained left-right responses because she had no information available to indicate where she had moved. The argument has several parts, each of which predicts a differential difficulty in this task for a blind subject.

First, the pragmatic situation for the blind child is very often one of information deficit: Whereas the sighted infant, child, or adult can look around and observe landmarks, there are few sources of information about the surrounding spatial layout that the blind can normally use, even in principle. Thus, the blind child is often in the position of not knowing where she is. There are, of course, ways that the blind learn to compensate in part for this lack—by taking advantage of subtle cues in the environment, or by keeping mental track of where they have been, inferring where they must now be. However, the normal pragmatic lack of information might plausibly lead the blind to rely on a body reference coding whenever possible. We have already argued above that the reaching task was one that Kelli would have been biased to code in this way, through her normal experience.

Second, it would be possible for Kelli to break this set if there were some compelling information available that would enable her to locate herself in the array as she moved around it. For example, if some constantly sounding object had been in the room, she possibly would have been able to determine where she was in the array after the rotation. The table itself provided no such information, since it was straight-edged and wooden, identical from both sides. There was one source of information, in principle,however—the experimenter's position. Kelli apparently did not use this information—a fact to which we return below.

In contrast to the conditions of the rotation task, the navigation task provided rich information about the child's current position in the array. For example, the child always either reached the target landmark, or was guided to it after a failure, before starting on the next test trial (recall that the child always started a test trial from some landmark). Each landmark had a distinctive spatial configuration, hence could be used to mentally align one's mental map with one's current position. In contrast, in the rotation task no feedback was given: The children were to reach out toward each target person, but no feedback was given as to whether or not the direction of the reach was correct (the experimenter took each cookie from the child's outstretched hand, and said "OK"). This informational difference in itself would predict the increased difficulty for the rotation task over the navigation task. But why did three of the four sighted and blindfolded children succeed, while Kelli failed?

There was one source of information that the sighted children must have been using: the position of the experimenter herself. The successful children must have known that she was seated opposite them before rotation, and must have been able to determine that when they reached her lap, they were in a position 180° rotated from their original position. There is independent evidence that sighted infants can use their mothers as a landmark (Presson & Ihrig, 1982); hence it seems likely that our toddler subjects used the experimenter as a landmark. But why didn't Kelli use this information?

The key issue here seems to be the selection of only certain kinds of information as reliable guides to locating objects. Although Kelli could have succeeded if she had used the experimenter's position as a landmark, it is well known that young children are not always capable of using information that in principle seems sufficient for guiding search (DeLoache, 1984). In the present case, we speculate that while people and other animate objects are never very good landmarks for any spatial animal, they are particularly poor landmarks for the blind. In order to be useful landmark information, an object must be stably located and predictable. Clearly, people are neither, although for the sighted child, it is certainly easier to track a person's whereabouts than it is for the blind child, whose only source of information for tracking moving objects is sound. In fact, sound alone appears to be a rather poor guide to locating objects for the blind as well as the sighted. Fraiberg (1977) showed that blind infants could not use sound to guide search behavior until late in the first year; Freedman, Fox-Kolenda, Margileth, and Miller (1969) showed the same was true of sighted infants who were prevented from using vision. Recently, Bigelow (1984) has uncovered some intriguing and compelling facts about search in blind infants: Although the infants cannot locate a sounding object that has been taken from their grasp and moved along a simple trajectory, they *can* locate a *silent* object that they have dropped spontaneously. This strongly suggests that information one might assume would be useful for the blind (i.e., sound) will not always be useful in fact. It is possible that the key difference between information about sound and information derived from dropping an object has to do with its relative predictability: One can predict the trajectory of a dropped object if one implicitly has knowledge of some basic physics; but one cannot necessarily predict the exact location of a sounding object unless it is very familiar.

In sum, it seems likely that Kelli was not using the information about the experimenter's position simply because she did not entertain the possibility that the experimenter was a good source of information about the layout. Given the frequent occasions when Kelli must have assumed someone was in a stable position, only to find out they had (silently) moved, this would be sensible behavior.

Summary of the Rotation Task Results

We have proposed three hypotheses to account for Kelli's and the one sighted child's failure in the rotation task, relative to their success in the navigation task. First, we proposed that increasing the degree of rotation will inevitably increase

the task difficulty for blind and sighted subjects alike. Second, we proposed that tasks requiring reaching in both training and testing might bias toward perseveration due to initial coding biases plus interference from the motor system when a right-left reversal is required during testing. Based on evidence from the infancy literature, we suggested that this bias might affect blind and sighted subjects alike. Finally, we proposed one serious difference between blind and sighted subjects, in the kinds of information they will use to guide their spatial behavior. Blind subjects may be less likely than sighted subjects to use people and other animate objects as spatial markers, because these potential markers are both unpredictable and often untrackable. It may well be more crucial for the blind child to select potential landmarks with extreme care, since the chances of getting lost increase tremendously if one cannot explore the world visually.

It should be clear that none of these differences alone will completely account for the difficulty of the 180° rotation task, nor for Kelli's failure relative to the three successful sighted children. However, each factor biases toward right-left response learning in this task, and the combination of factors must surely add up to a propensity to perseverate during testing. There may well be additional factors that have not been discussed here that contribute to the difficulty of this task. For example, recent evidence suggests that an important variable is the complexity of the movement the subject undergoes: When infants undergo a simple rotation (change of orientation, not location), or a simple translation (change of location, not orientation), they can account for 90° or 180° rotations, and simple translations. In contrast, if they undergo a combined rotation and translation—as in rotations around a table, changing both orientation and location—they tend to perseverate (Kramer, 1984; Landau, 1984). No doubt there are other factors as well that conspire to make the traditional rotation task extremely difficult. But we do not believe that any of these factors causes difficulty because of deficits in the spatial knowledge system.

3. CONCLUSIONS

In this chapter, we have presented evidence on the spatial abilities of young children, using two very different types of task. In a navigation task, a blind child and sighted but blindfolded children performed well, recording the spatial relationships among objects in a large array, and making inferences to predict new angle-distance relationships among those objects. These results suggested the existence of a spatial knowledge system that has arisen rather early in life, and independent of the modality of experience. In a rotation task, most of the sighted children at the same age were also seen to perform well; but the blind child systematically failed the task through age 5. The results of the rotation tasks suggested that it is not always possible for children to show their spatial knowledge. In particular, an analysis of the rotation task suggested several features that may conspire to bias children toward "egocentric localization" of objects, masking the expression of spatial knowledge that we have seen evidenced in the navigation task.

The results as a whole suggest that the basic elements of spatial knowledge may be intact rather early in life, but that the expression of this knowledge may require development of at least two kinds. One is the increasing coordination between knowledge and the systems that use this knowledge to act on the world. For example, in the case of the rotation task, a motor bias may result in the failure to locate an object after rotation, even if the child knows where the object is. As the child grows, increasingly precise coordinations between knowledge of space and the motor system will lead to increased success in locating objects under yet more demanding conditions. A second kind of development is the increasing coordination between knowledge and the markers that exist in the world and are used to address this knowledge. For example, children must learn that certain objects and not others make good landmarks. The blind child's difficulty in our rotation task may have been due partly to our provision of only a limited and rather ineffective kind of landmark—a person. Yet she, as well as sighted children, will come to recognize the existence of a much broader range of possible landmarks, and will no doubt become more flexible in her use of them.

Both kinds of development presuppose that the spatial knowledge system, even if present very early in life, must become aligned with devices that will allow its expression. One kind of alignment is with the action system that will enable the child to actually retrieve objects. Another kind of alignment is with the evidence provided in the real world—information that can be used to guide and address the knowledge system. For example, objects exist in the world, and they can be used as landmarks to mediate the interchange between the spatial knowledge system and the physical world. Children must discover which of these objects can and cannot be reliably used as landmarks, and which of these objects *typically* are or are not used as landmarks. These discoveries and alignments are part of the development of spatial abilities—but not part of the development of spatial knowledge itself.

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3 Active Movement and Development of Spatial Abilities in Infancy

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Problems about space are rarely static. Object search is probably the best example from everyday life that makes this point. When we put something away in a container, usually either we move or the container is moved before we look for it again. Thus relocating the object would be impossible unless we had some way of taking these sorts of movements into account. This raises an interesting question as far as infants are concerned, for during the first 9 months or so of life their movements are constrained. They certainly perceive and show interest in moving objects from very early on, and they are themselves moved around their environment. But it is not until the age of 9 months, when they begin to crawl, that they get active experience of moving around in space under their own control.

It is perhaps rather surprising that until recently (Bremner & Bryant, 1977; Campos, Svejda, Campos, & Bertenthal, 1982) the implications of this developmental change at 9 months have received very little attention. Although Piaget (1954) stressed the importance of walking for children's understanding of space, he seems to have laid very little stress on the effects of the earlier event of crawling. But it may very well be that there is a qualitative difference in the effect of information about the results of the passive movements that characterize very early infancy, and those of the active movements that predominate once the baby starts to crawl. Indeed, hypotheses about the greater significance of active movements over passive movements in perceptual development would lead to the suggestion that children's understanding of space, and particularly the role of their own movements, must be poorly developed until they begin to crawl (Held & Hein, 1963).