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Spatial knowledge in a young blind child*

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Abstract

A set of eight experiments demonstrate spatial knowledge in a 2-year-old congenitally blind child and sighted blindfolded controls. Once the blind child had traveled along specific paths between objects in a novel array, she was able to make spatial inferences, finding new routes between those objects (Experiment I). She could also do so when the routes were between places in space, not occupied by objects (Experiment II). Deviations from precisely straight routes in Experiments I and II were not due to faulty inferences, but probably came from imprecise motor control, since the same deviations occurred when inferences were not required—when the child moved to a place designated by a sound source (Experiment III). This child's performances could not be accounted for by artifactual explanations: sound cues, experimenter bias, and echolocation were ruled out (Experiments IV, V, VI). Further, sighted blindfolded controls performed at roughly the same level (Experiment VII). Finally, Experiment VIII shows that the blind child could access her spatial knowledge for use in a simple map-reading task. We conclude that the young blind child has a system of spatial knowledge, including abstract, amodal rules

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and principles that incorporate metric geometric information that can be used to guide navigation about the world.

Introduction

In this paper, we describe some of the spatially oriented actions of a young blind child: a set of navigational performances that we take as indications of an underlying system of *spatial knowledge*. Once the child has traveled along specific paths between objects in a novel layout, she is able to move efficiently from one object to another along routes she has never taken before. This ability testifies to her knowledge of spatial properties of the layout.

Spatial knowledge and its manifestations

At the outset, it might seem that spatial knowledge is implicated whenever an organism engages in spatially oriented activity, be it reaching, locomotion, or even visual exploration. But this need not be so. Suppose, for example, that a person is asked to walk to an object within the field of view. The person could reach the object by moving in such a way that its image is centered relative to his body and expands symmetrically as he moves. If a person were asked to walk to an invisible object that emits a continuous sound, he could similarly reach the object by moving so as to equalize and increase the sound intensity at the two ears. In these situations, spatially appropriate behavior obviously depends on mechanisms that are sensitive to visual and auditory stimulation—even to spatial characteristics of that stimulation, such as whether a projected image is centered on the retina. But navigation in these cases need not depend on knowledge of the spatial properties of the distal world in which one moves.

Now consider a second task in which a blindfolded person is walked repeatedly between two silent objects, and then is asked to move between the objects on his own. There is no distal information to guide locomotion in this situation. Nevertheless, it is possible that a person could accomplish the task without benefit of spatial knowledge. The subject might locate the object by performing a specific set of motor movements—those which he performed when he was previously taken to the object. Moreover, a subject's prior actions might be remembered in a form that is sufficiently abstract to allow for considerable response generalization. If a person's memories of different actions are related in the right ways, then an individual who had formerly walked along a given path might be able to run, hop, skip, jump, or even swim in the appropriate direction spontaneously (see Woodworth (1938) for a review). Remembering such motor patterns requires internal representations of some sort: representations of the actions themselves, or of the mental activities that initiate and guide actions. But these representations, like sensory representations, need not capture spatial information about the world.

In contrast, consider a third task, in which a blindfolded person is led about in a more complex pattern. He is taken from an object A to a second object B and back again. After this, he is taken from A to yet another object C. Now he is asked to move on his own, from C to B. This action cannot be guided by operations on patterns of stimulation from the objects, because no such stimulation is available. It cannot depend exclusively on memories of prior actions, because the path to be traveled is new. Successful navigation depends on the representation of information about the objects and their spatial relationships, and on a set of geometric rules for deriving further spatial information. These spatial representations and rules constitute spatial knowledge, in our sense.

The development of spatial knowledge

It is clear that human adults have spatial knowledge. We can use spatial representations to find efficient new paths through a city or a larger region, to imagine how configurations of objects would appear from a new perspective, and even to solve explicit problems in geometry. It is equally clear that some aspects of spatial knowledge develop quite early in human childhood, without specific tutoring (see Piaget, 1954). For that matter, there is good evidence for spatial knowledge in a variety of animal species (e.g., Menzel, 1973; Olton, 1978; Tolman, 1948; see Gallistel, 1978, for a review). This raises two questions. First, what is the nature of our early knowledge of space, from which all our later knowledge grows? Second, what are the environmental conditions under which this early knowledge arises? We have sought to address these questions through research with young children, and especially through a series of studies of one young, congenitally blind child.

In young children, blindness sharply limits the range of opportunities for perceiving spatial properties of the world. The spatial character of the immediate environment is best discovered through looking and through acting (reaching and manipulating objects, walking around a room, and so forth), yet both these classes of activity are restricted for young blind infants. Blind children obviously lack vision, the only perceptual system that allows us to apprehend vast and complex spatial arrays more or less at the same time. Blind children also reach, crawl, and walk considerably later than sighted children (Fraiberg, 1977). As a result, a young blind child might be supposed to have accumulated much less experience of the spatial properties of the world than her sighted counterparts. If spatial knowledge can nevertheless be shown to be present in a young blind child, it would appear that this knowledge can arise under a wide range of environmental circumstances, and under considerable deprivation.

Background

Our subject is Kelli, a child who was blinded shortly after birth. We observed her informally between the ages of 21 and 33 months and then tested her more systematically until she was about five years of age.[1]

Kelli is the first-born of two children, with a sister 12 months younger. She is the surviving member of a pair of twins, born approximately three months premature with a birth-weight of 940 grams. Kelli was quite ill as a newborn, and remained in the hospital for the first six months of her life, primarily in an isolette. During the first three weeks of life, she became a victim of Retrolental Fibroplasia, an oxygen-related cause of blindness that sometimes occurs in premature infants. During these first few months of life, her case progressed to leave her no residual vision in either eye (although there may be some slight sensitivity to light in the right eye). Since that time there has been no improvement: Kelli is totally blind.[2]

Kelli was dismissed from the hospital at six months of age, with a weight of six pounds and the developmental status of a newborn. When first observed, at 21 months of age, she knew how to locate objects by sound and how to recognize them by mouthing, fingering, or smelling. Our observations suggested, moreover, that Kelli possessed a considerable body of information about objects, information that guided a variety of spatially appropriate actions. For example, at 21–23 months:

1. She could correctly identify more than a dozen body parts on herself, and was beginning to find the corresponding parts on her mother's body.
2. She knew about the spatial configurations of numerous common objects. For example, she could brush her hair by finding the handle end of the

[1]The ages reported are chronological ages, not corrected for prematurity.

[2]The severity of Retrolental Fibroplasia (RLF) is judged in terms of grades 1 through 5, increasingly worse with higher grade. Grades 1–3 leave some residual vision and are reversible. Grade 4 leaves no vision but some possible light perception, and Grade 5 leaves no vision or light perception. Kelli had grade 5 RLF in both eyes. Kelli's sensitivity to light was noticed in her fourth year, when she appeared to notice light from a lamp when facing it from about 1–2 feet away. However, she does not perceive objects and is considered totally blind by her ophthalmologist.

hairbrush, and using the opposite end (bristled) to brush; she used different hand and arm positions to retrieve objects, depending on the spatial structure of the container (e.g. bowl *versus* plate); she could climb up on different pieces of furniture using different motor behaviors; and all these were in one degree or another *anticipatory* actions. For example, once the hairbrush was touched, it was immediately rotated to its correct position; once she put a foot on the highchair's bottom rung, she immediately hoisted herself up (rather than flipping over, as she did for the couch), etc.

3. She knew about the spatial layout of the kitchen cabinets: which ones were permitted for play, and which were not; which required a push to open, and which required a pull. This was shown by her systematic movements between the cabinets, and her ensuing actions.

4. Early in the observations, Kelli was unable to find her way from room to room in her own home, and even failed to find certain landmarks within different rooms. As time went on, however, she became better at these tasks, and by 30 months, she was able to proceed correctly from room to room on command.

Despite these accomplishments, it is of course unclear whether Kelli possessed knowledge of the spatial properties of objects and the layout. Rotating a hairbrush, stopping at a certain cabinet, and even moving between familiar rooms could depend on learned sequences of actions. Hence our experiments.

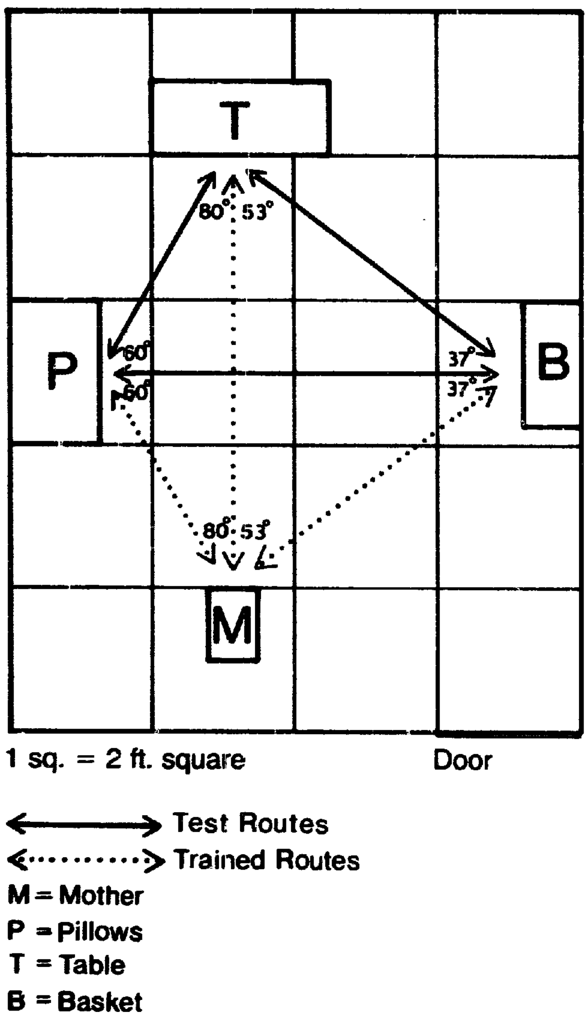
Experiment I

All our experiments used procedures patterned after those of Tolman (1948) and N.R.F. Maier (1929) in their studies of spatial learning and reasoning. Kelli was first taken along certain paths between certain objects or places. Then she was asked to find a new, not-yet-traveled path between these places.

Method

At the time of Experiment I, Kelli was 31 months old. She and her mother were brought into a novel environment, an 8 ft × 10 ft laboratory playroom, which was gridded into 20 2 × 2 foot squares. Four separate objects served as landmarks: a chair, several pillows, a table, and a basket containing toys. The positions of these objects is indicated in Fig. 1. After her mother was seated in a chair, Kelli was told that she would be shown around the new playroom.

Figure 1. *Room layout and training-testing in Experiment I.*



She was led directly to each of the four objects as follows: from her mother (M) to the pillows (P) and back again, twice; from M to the table (T) and back again, twice; and from M to the basket (B) and back again, twice (see Fig. 1). Each time, Kelli was told where she was at the beginning of the route and also where she was at its end. In addition, she always touched the initial and terminal landmark.

After the training trials were completed, the testing immediately began. Kelli was positioned at M and was then led to T. She was then asked to find the remaining routes between P, T, and B on her own. Specifically, she was asked to "go to the toy basket," "find the pillows," and so forth. She was tested twice on each route, for a total of 12 trials that were given in the following order: T-B, B-T, T-B, B-T; T-P, P-T, T-P, P-T; P-B, B-P, P-B, B-P (see Fig. 2). Thus, the target location of each trial was the starting position of the next trial. Both training and test trials followed each other with no special inter-trial interval.

As Kelli moved along her routes, the experimenter stayed close enough to her to provide encouragement (e.g., "That's it; find the toy basket.") but far enough away so as not to interfere with the child's movements. The trial was considered terminated when Kelli came close to the target on her own; specifically, within a 1 foot radius of the block containing the target. On such occasions, the experimenter encouraged her ("That's right; there's the basket.") and helped her if necessary to bring her into contact with the object. The trial was also terminated if Kelli was moving in an incorrect direction along an as yet untested inference route (e.g. Trials 4, 6, 8 in Experiment I), if she began circling in a confused manner, or if she explicitly said she could not find the target. The only data used for the analysis were those provided by the child's own independent movements, so that the last usable data point was obtained just prior to the moment when the experimenter touched Kelli and ended the trial.

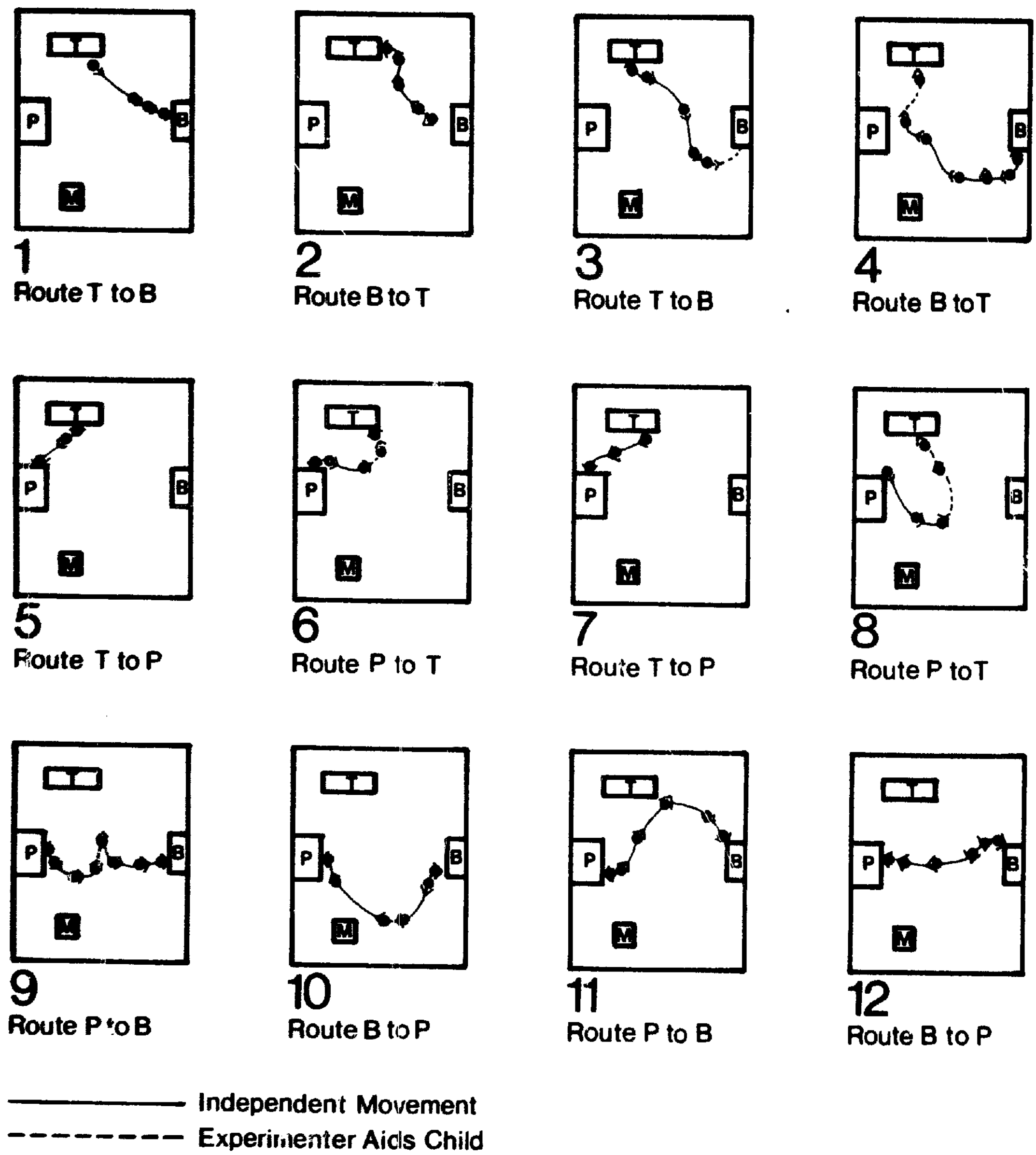
The entire experiment was videotaped and the tapes for each trial provided the data for the subsequent analysis. The movements were transcribed as follows: The child's path on each trial was plotted by recording her *position* and *frontal direction* at successive three-second intervals from the time she began to move away from the starting point. Figure 2 shows the transcriptions for all 12 trials of the experiment. In the figure, Kelli's *positions* are indicated by solid circles; her *frontal directions* by arrowheads which show how she was facing at the time. Between the points on the circles, a curve indicates the actual path that Kelli followed. Solid curves indicate her independent movements, and dotted curves indicate experimenter-guided movements.

Results

An inspection of the 12 panels of Fig. 2 indicates that Kelli took an approximately appropriate path on the majority of the trials. This suggestion is buttressed by analysis of three numerical indices of her performance:

1. *Initial turn towards or away from the goal.* This measure determined whether Kelli was better oriented to the goal after the first 2 feet of her path than she was at its beginning. We first measured the angle formed by Kelli's initial orientation (which was always called 0°) and the goal (e.g., 100° to the

Figure 2. *Test trials of Experiment I. Kelli's positions are indicated by solid circles; her frontal directions by arrowheads; solid curves indicate her independent movements; dotted curves indicate experimenter-guided movement.*



right). We then measured Kelli's position after 2 feet of movement (e.g., 80° from initial orientation and towards the goal) and expressed this position as a proportion of the entire angle required for reaching the goal (e.g., +80°/100° = +.80).[3] The number of trials where initial turn was towards the target was evaluated statistically by the Binomial test ($p = 0.50$, the random probability of success).

Kelli's initial turns were towards the goal within the first two feet of travel in 11 out of 12 trials ($p = 0.0029$). Using a more conservative estimate that excludes trials where she started out with her back to the goal (hence orientation would be improved by either a right or left turn), her initial turns were towards the goal in 7 out of 8 trials ($p = 0.0312$).

2. *Final position.* This measure indicated Kelli's position when the trial was terminated, successfully or unsuccessfully. The final position measure was determined by means of a circle whose perimeter included Kelli's final position and whose center was the starting point. Since each of the landmark objects in the study (e.g., the toy basket, the pillows, etc.) subtended an angle of about 40 degrees, this circle was divided into nine 40° segments. A final position was scored as a success if it fell within the 40° segment that contained the target object. A less stringent criterion was based on a division of the circle into four 90° segments one of which included the target object.[4] The number of successes and failures were evaluated statistically by the Binomial test ($p = 0.11$, the random probability of success for 40° segments; $p = 0.25$ the random probability for 90° segments). Kelli's final position fell within the 40° target range on 8 out of 12 trials ($p = 0.0001$). Of the four errors, two were by 15° or less. If the range of success is defined less stringently by using a 90° target range, success was achieved in 11 out of 12 trials ($p = 0.0000$).

3. ***Relationship between initial turn and final position.*** If Kelli indeed knew where she was going when she set out on her path, one would presume that she would follow the shortest straight line path to the goal. If this were true, then her initial turn should predict her success or failure on the final position measure: if she moved immediately and directly towards the goal, then her

[3] On some trials, Kelli's first few steps turned her toward the goal, but she overshot the mark and turned too far in the opposite direction by the time she had moved two feet from the starting point. On such trials, a turn past the goal range by 40° or more was counted as a failure. For example, if Kelli turned 200° in the direction of a target located at 100° (with a range of 80° – 120°), she would be given a score of −80°/100° = −0.80.

[4] Given these criteria, it would be possible to credit Kelli with a success if she merely remained in front of the starting landmark, not moving at all towards the target. Since these would obviously not be legitimate successes, we considered all such trials as failures in both this and later experiments.

initial turn should fall on that shortest straight line path. Inspection of the data suggested that this was so: when Kelli initially turned substantially towards the target, she was likely to end up at the target; and when she initially turned only slightly towards the target (or occasionally past it), she was not likely to succeed.

This suggestion is supported by two analyses. First, the mean initial turn proportion (ITP) for those trials on which she had a successful final position was 0.87, while the mean ITP for failures on final position was 0.18. This is a reliable difference, $t_{10} = 1.86$, $p < 0.05$. Second, the ITPs were classified as 'successes' themselves if they nearly approximated the true angle of the target (i.e., the ITP value fell in the range of 0.75–1.25), and were then cross-classified by success or failure on final position. The relationship between these two measures showed that 9 of the 12 trials agreed in sign for both measures ($p = 0.05$, Binomial test). Such a relationship suggests that the mechanism underlying Kelli's inferences is not characterized by a continuous update of her position relative to the angle of the target; but rather, is more like pointing—an initial angular estimate, followed by movement along that estimated path. This suggestion is buttressed by similar findings in ensuing experiments.

It is important to note that the latter analyses speak to another possibility about young children's navigation through space: namely, that they might move to new points by retracing their steps, i.e. along previously learned paths. If Kelli was retracing her steps, then the test trials should show movement along the trained paths, M-P, M-T, and M-B in Experiment I. Inspection of the paths (see Fig. 2) shows that Kelli did not move along these trained paths on the successful test trials.

Discussion

The findings of Experiment I show that Kelli did indeed make spatial inferences, finding new routes between the pairs of landmarks in the room. While these routes were not always perfect estimates of the straight-line paths between the landmarks, Kelli did seem to make an initial accurate angular estimate which, if she had proceeded straight-line fashion, would have moved her along that ideal path. These inferences suggest that Kelli does indeed have what we call spatial knowledge.

Experiment II

The results of Experiment I indicate that Kelli has a fair degree of spatial knowledge that allows her to infer a new path if given some prior information about the placement of the two landmarks at the beginning and end of this new path. But a question remains concerning the role of these landmarks in guiding her navigation. Did Kelli use the landmarks to align herself with the goal object? Or, in contrast, did the landmarks only serve to mark the places to which Kelli was to move? Experiment II was undertaken to distinguish these possibilities. In this experiment, Kelli was asked to navigate between three places, two of which were not marked by any object. If Kelli used landmarks to align herself with the target objects, then her performance should be much worse when no landmarks are present.

Experiment II had a second purpose: it was undertaken to investigate whether Kelli could deduce the distance relations among objects as well as the angular relations among them. In the first experiment, we know that when Kelli was asked to move between landmarks, she went in a roughly appropriate direction, indicating that she had deduced their angular relations. But there is no evidence that she could also deduce the lengths of the new paths. If she moved in the correct direction, she would eventually hit the target object and terminate the trial, whether or not she knew the distance of the target in advance.

In Experiment II, accordingly, Kelli was given a task rather similar to that of Experiment I, except for the elimination of two of the objects during training and testing. Two of the four places between which she traveled were occupied by no object: they were places where landmarks would be placed *later*. As in Experiment I, Kelli was first given experience with some of the paths between the four locations and was later asked to find new paths. But this time she had to be able to find both the new angle and the new distance, for on the crucial trial there was no landmark to stop her in her path. She was instructed to stop by herself as soon as she reached the appropriate place (which she might overshoot or undershoot), thus allowing an independent determination of her ability to find the new distance as well as the new direction.

Method

At the time Experiment II was performed Kelli was 43 months old.[5] The procedure was the same as in Experiment I, with the following modifications.

[5]Of necessity, this entire experimental series was carried out over a long period of time (Kelli's ages, 31–54 →

Kelli was brought into a 10 ft × 10 ft laboratory playroom in which there were two object landmarks. One was her mother, seated in a chair, occupying the same position as M in Experiment I (see Fig. 1). The other was Kelli's table, occupying the same position as P in Experiment I.

Kelli was walked from her mother's chair to the table landmark and back again, twice in a row. At this point Kelli was told that both she and the experimenter would have separate places at which they were to sit in order to play a certain game. (The two places, here designated E and S, occupied the same positions as did T and B in Experiment I, respectively). Kelli was then walked from her mother to each place, and back again, twice in a row. At each place she was told, "This is where you will sit. This is your place," or "This is where I will sit. This is my place." These words, then, served to indicate the existence of landmarks, to Kelli, without actual objects.

Kelli was walked back to the table (T) and was asked to find routes between T and E, T and S, and E and S. Specifically, she had to indicate where she believed the place to be by placing an object (a rattle or a pillow) in the correct location. For example, she was told, "Here's the rattle. Put it where you are going to sit. Put it at your place." As in Experiment I, she was tested twice on each route, in blocks of four between each pair of locations, for a total of 12 trials. Six of these trials were crucial for our present purposes for they involved travel to a place without object landmarks, E or S.

Results

Kelli's paths were transcribed and analyzed as in Experiment I. In 12 out of 12 trials, Kelli's initial turn was towards the target (p = 0.0002). Using the more conservative procedure of ruling out trials in which she began with her back turned to the goal, she turned towards the goal on 8 out of 8 trials (p = 0.0039). Her final position fell within the 40° target range on 7 out of 12 trials (p = 0.0001), and within the 90° range on 10 out of 12 trials (p = 0.0000). On three of her five errors in the 40° range, she missed the target range by 8° or less; on one (Trial 2) she seemed confused at the very start of

→ months). The experiments were designed to test whether or not a blind child could come to have spatial knowledge: therefore, their goal was to demonstrate the existence of such knowledge, and also to rule out alternative interpretations of her spatial behavior. The experiments do not address the existence of possible developmental changes in such knowledge. Hence, the experiments are not presented in the order in which they were conducted (chronologically), but, rather, in the order of their underlying experimental logic. Each experiment is modeled after Experiment I, and thereby assures that Kelli could perform spatial inferences at all ages tested.

the trial, and on another (Trial 5), she ended up at the wrong location altogether which happened to be the one she had just come from on the trial before.[6] Finally, as in Experiment I, a positive relationship was shown between Kelli's initial turn (ITP) and final position: the mean ITP for final position successes was 1.04, while it was 0.77 for failures ($t_{10} = 1.59$, $p < 0.10$). Cross-classification of ITP by final position showed 8 out of 12 trials agreed in sign ($p = 0.12$, Binomial test).

These overall results are basically the same as the results of Experiment I, and thereby replicate the major finding: Kelli's ability to make spatial inferences. In this experiment, however, we wished to determine what role landmarks played for Kelli, in plotting her new routes. A comparison of those trials where Kelli started from a landmark (Trials 1, 3, 5, 6, 8) with those where she did not start from a landmark (Trials 2, 4, 7, 9, 10, 11, 12) suggest that starting one's route from a landmark may enhance performance, but only slightly. First, there was no difference in Kelli's initial turns, since they were all towards the target (see above). Second, Kelli's final position fell within the 40° range on three of the five landmark trials, and on four of the seven no-landmark trials. She fell within the 90° range on four of the five landmark trials, and on six of the eight no-landmark trials. Again, there is comparable performance, regardless of whether Kelli starts at a landmark or not.

However, for the third measure—ITP relative to final position success—there was a small difference between conditions. For both conditions, there was a higher mean ITP for final position successes than for final position failures. The values for trials beginning with a landmark were 1.31 ($N = 3$) for successes, and 0.83 ($N = 2$) for failures. The comparable values for trials not beginning with a landmark were 0.84 ($N = 4$) and 0.72 ($N = 3$). Hence the difference between values was larger for trials beginning with a landmark than for trials not beginning with a landmark. The cross-classification of ITP by final position showed roughly the same relationship for both sets of trials: three of five trials starting with a landmark and five of seven trials not starting with a landmark had the same sign for both measures.

The small difference in mean ITPs suggests that presence of a landmark may enhance the accuracy of the initial turn towards the target. In fact, for all trials starting with a landmark, the mean ITP was reliably higher than for

[6]These two errors deserve further explanation. On Trial 2, it was not clear from the videotape whether Kelli really moved on her own or was corrected early in the trial. We conservatively assumed the latter, and did not credit her with what might have been a success. On Trial 5, Kelli moved purposively to the wrong location. This kind of error occurred only this one time throughout the entire set of experiments reported here. Our assumption is that Kelli misinterpreted the command. On the next trial, the command was repeated and Kelli moved off in the correct direction.

all trials not starting with a landmark (1.12 *versus* 0.79, $t_{10} = 2.06, p < 0.05$). This makes sense: even if one has a perfect mental map of an array, one needs to align one's current position with that map before making any inferences. Actual object landmarks provide such alignment devices. While these are apparently not necessary for success, they may enhance one's directional accuracy, especially in tasks with more complex memory demands. In the present task, Kelli depended only on internal representational landmarks (provided through language), and had no externally given landmarks to go on.

To assess Kelli's knowledge of the distances between targets, we performed an additional analysis of Trials 1, 3, 6, 8, 10, and 12: those trials on which she traveled to a location with no object.[7] We compared the distance Kelli traveled before placing the markers, with the actual distance between her starting point and the true location. Table 1 presents these measures for the relevant six trials. As the table shows, Kelli ranged from being exactly on target to being off by 3.5 feet (an error of 70%). In percentage terms, her average error was 27%, and did not vary systematically across trials. This performance is far from perfect, and suggests that, at least with this method, Kelli's ability to estimate distances is moderate to poor.

Discussion

The findings of Experiment II indicate that Kelli does not need to refer to landmarks in order to navigate between locations in space. She can also navigate between unoccupied places, as long as she has had the opportunity to walk between each of those places and a third point in space. Kelli's success in this task indicates that she has a considerable ability to represent spatial properties of the paths she has taken.

The findings of Experiment II also shed light on Kelli's ability to represent the distance of one object from another as well as their angular orientation. The experiment suggests that Kelli's representations of distances between objects are not as impressive as her representations of the relative angular orientations between objects. It is possible, however, that her sensitivity to distance is underestimated by the present task. While she did not estimate distances perfectly, she was not grossly inaccurate: she never moved only 1 foot towards the target, nor did she ever insist on walking 20 feet to get to a target.

[7]The same procedure was followed on Trial 5, but as previously noted, there was a gross error in direction on that trial, which was therefore excluded from this analysis.

Table 1. *Distance estimates on inference trials*

Trial	Inside (+) or outside (−) of 40° range	Actual distance	Distance traveled	% Difference
1	+	5.0	8.5	70
3	+	5.0	5.0	0
6	+	7.5	4.5	40
8	− (8°)	7.0	5.0	28
10	− (6°)	5.5	6.5	18
12	+	5.5	5.5	0
Mean		5.9	5.8	27

Experiment III

Although Kelli appears to have spatial knowledge and to use it in guiding her locomotion, her performance was clearly far from perfect. On about one-fourth of the trials, she missed the target, and there were many odd wobbles in her path even on trials where her orientation was appropriate. What might account for these flaws in her performance? One possibility is a deficiency in her spatial knowledge or in her ability to draw proper inferences from that knowledge. A different possibility is that her problem is one of spatial performance rather than spatial competence. Perhaps her navigation was adversely affected by such factors as lack of attention, memory lapses, distraction, and limited control of locomotion. To assess these possibilities, we compared Kelli's accuracy in the spatial inference tasks with her accuracy in finding a target when no such inference was required.

In this experiment, Kelli's task was to go to a place where a voice had come from a few seconds before. Moving directly to the target under these conditions did not call on spatial inference of the sort required in Experiments I and II; all Kelli had to do was to determine the location of the sound source and maintain it in memory while moving to the target.

Method

At the time this experiment was conducted, Kelli was 37 months old. She was brought into a 10 ft × 12 ft playroom, and was told that she was going to play "hide and seek" with the experimenter. In this game, the child sat on her mother's lap while the experimenter "hid," sitting some distance from her. The experimenter then called Kelli once ("Come find me"); Kelli stood and moved to find her. This procedure was repeated for a total of 12 trials with variations in both the angle and distance of Kelli's starting point relative to the target (that is, the experimenter). Kelli was never corrected or given any additional cues after she began on her route. Each trial was ended when Kelli was obviously distracted by some object she encountered or seemed genuinely confused. It was also ended if she came within two feet of the experimenter, in which case she was grabbed admidst gales of tickles and laughter.

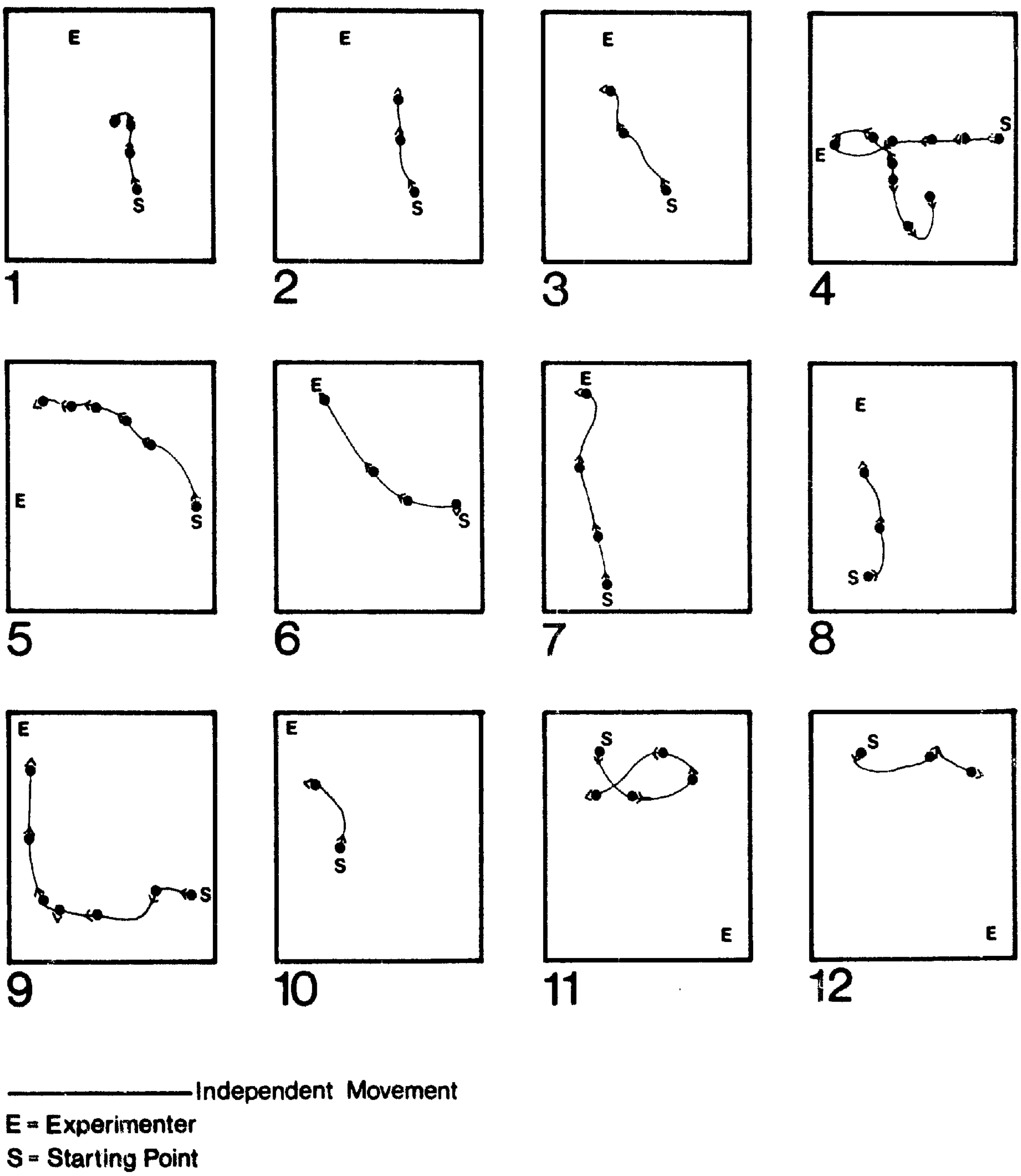
Results

Kelli's paths are shown in Fig. 3. On 9 of the 12 trials, Kelli initially turned towards the target (p = 0.05). On 8 of the 12 trials, her final position fell within the 40° target range (p = 0.0001), and on 8 of the 12 she fell within the 90° target range (p = 0.0024). The relationship between ITP and final position was slightly different from that of the previous experiments: the mean ITP was 0.43 for successes in final position, and 0.33 for failures (t_{10} = 0.07, n.s.). However, this was apparently due to one extreme score: in Trial 1, the ITP was −5.67, for Kelli turned 17° away from the target, which was positioned 3° from her initial facing direction. When this score is removed, the relationship becomes similar to that of other experiments: mean ITP is 1.30 for successes in final position, and is 0.33 for failures ($t_9 = 1.43$, $p < 0.10$). Cross-classification of all scores yields a different relationship between the two measures than in Experiments I and II, with only 4 of the 12 scores agreeing in sign (p = 0.12, Binomial test). Of the remaining 8 scores, 7 were negative ITPs with positive final position scores—trials on which Kelli's initial turns were outside of the success range, but she made it to the target anyway.[8]

These trials display an important characteristic of Kelli's directed movements: She did not, as a rule, move on a perfectly straight path toward the goal. Consider the eight trials on which her final position fell within the 40°

[8]This change in the distribution apparently reflects the distribution in this experiment of the absolute values of the target's angles from Kelli's starting position. In Experiments I and II, for example, the mean absolute angles of the target from starting positions were 116.3[illegible]° and 149.42°, respectively. In contrast, in this experiment, the mean target angle was 44.08°. This means that the same absolute deviation in this experiment will yield a larger proportional deviation (ITP), making many small absolute deviations fall outside of the range of successes for this measure (see p. 234). Therefore, many of the trials with a classified failure in ITP are nevertheless well-adjusted towards the goal.

Figure 3. *Test trials of Experiment III.*



range. On none of these trials did she move in a perfectly straight line to the goal. In fact, many of these trials (e.g., Trials 3, 6, 9) show paths which are rather serpentine, suggesting that, even when Kelli has sufficient information to move directly to the goal, she does not do so.

Discussion

In this experiment, Kelli performed at roughly the same level as in Experiments I and II, which demanded a spatial inference. Her performance was not perfect in any of these experiments: she did not always walk to the correct place, and she seldom walked on a straight path. It would seem, however, that her errors and deviations did not stem from deficiencies in her spatial knowledge. The indirect paths seen in Experiments I and II may be ascribed to performance factors that concern directed locomotion rather than to a lack of spatial knowledge or deficits in drawing spatial inferences.

Why didn't Kelli move directly between landmarks? There are several possibilities. First, she is a young child, hence easily distractible. It may be that she starts out on a route, momentarily forgets where she is going and then remembers. Second, she may simply have preferred to walk on curved paths: moving in straight lines may have been boring. Finally, it may well be that it is more difficult for Kelli to maintain a straight path in locomotion than it is for her sighted peers (even when those are blindfolded). If so, this may reflect the important role of sensory feedback in integrating the components of motor behavior (see Gallistel, 1980, p. 378). There are various lines of independent evidence that render this hypothesis plausible. As we have noted, blind babies are delayed in developing self-initiated motor behaviors (Fraiberg, 1977). Moreover, blind pre-schoolers suffer from a variety of deficits in independent motor behavior (for review, see Warren, (1977)).

Experiment IV

Experiments I–III seem to justify the assertion that Kelli has spatial knowledge which allows her to make inferences so as to find new paths. But this assertion cannot be made with any confidence until several possible artifacts have been ruled out. For in principle, Kelli's performance might have been based on factors other than spatial knowledge. She might have picked up cues from (1) inadvertent sound sources in the room, (2) inadvertent cues from the experimenter, or (3) echolocation. Experiments IV, V, and VI were undertaken to control for these possibilities.

Experiment IV was conducted to determine whether any stimulation from the room (e.g., the smell of carpet cleaner, the sound of the video camera) provided a guide for Kelli's locomotion. We have noted that navigation to a goal is possible without the guidance of spatial knowledge if the goal provides continuous sensory stimulation. The navigator could then turn so as to equalize this stimulation at the two eyes, ears, or nostrils, and then move so as to increase it. In the preceding experiments, the goal objects themselves were silent, but it is possible that other sounds or odors might have guided Kelli to the goal. In Experiment IV, this possibility was eliminated.

The experiment was essentially equivalent to Experiment I, except that following training and prior to the testing phase, the entire spatial layout was rotated by 90°. This rotation preserved all of the spatial relationships among the landmark objects but changed their relationships to the rest of the room. If Kelli had been using external room cues to guide her locomotion, she should now navigate away from the new position of a goal object and towards its former position. If, in contrast, Kelli had been using a representation of the spatial relations among the objects, she should continue to navigate toward the objects in their new positions.

Method

At the time the experiment was conducted, Kelli was 34 months old. She was trained as in Experiment I, using a room layout with a similar configuration but with different relationships among the landmark objects used in that experiment. There were four object landmarks: a table (T), a toy basket (B), Kelli's father sitting in a chair (F), and Kelli's own small chair (C). The experiment was run in the same 8 ft × 10 ft laboratory playroom used for Experiment I and the four landmark objects were arranged in the same spatial relationships to each other, with B in the position previously occupied by M, F in that of P, C in that of B, and T in that of T.

In line with the procedure of the spatial inference experiments, Kelli was first trained to walk back and forth twice between C and B, C and F, and C and T. She then received six test trials, two for each of the three test routes (that is, from B to F and back, and so on). After the sixth test trial, her father picked her up and carried her out of the room, ostensibly to get a drink of water. While Kelli was out of the room, the experimenter moved all of the landmarks so as to rotate the entire array by 90°. The father then re-entered the room alone and took his new position, while the experimenter carried Kelli back into the room and placed her at the table. Kelli was then given an additional eight test trials on three routes (two routes with two trials each, one route with four trials).

Results and discussion

Before rotation, Kelli turned towards the goal on six of six trials ($p = 0.015$), and after rotation, she did so on eight of eight trials ($p = 0.004$). Before rotation, Kelli's final position fell within the 40° range on three of six trials and within the extended 90° range on five out of six trials ($p = 0.02$ and 0.004 respectively). After rotation, her final position fell within the 40° range on four out of eight trials, and on five out of eight trials again for the 90° range ($p = 0.007$ and 0.02, respectively). The relationship between ITP and final position was the same as in Experiments I and II over all trials, and approximately the same before and after rotation. Over all trials, the mean ITP was 0.91 for final position successes, and 0.73 for failures ($t_{12} = 1.50$, $p = 0.08$). Before rotation, the mean ITP was 1.08 for successes ($N = 3$) and 0.64 for failures ($N = 3$). After rotation, there was no difference, with the mean ITP 0.79 for both successes ($N = 4$) and failures ($N = 4$). Cross-classification of the two measures over all trials again showed that eleven of fourteen trials agreed in sign ($p = 0.02$, Binomial test). Before rotation, six of six trials agreed in sign; after rotation, five of eight trials agreed in sign. These last few measures suggest that Kelli's performance was slightly worse after rotation than before. This can most probably be attributed to forgetting and distraction during the interval when she was removed from the room. Most important, Kelli's path after rotation could not be attributed to room cues: she moved to the old absolute location of an object (in its 40° range) on only one of the eight post-rotation test trials ($p = 0.38$, Binomial test).

Thus, Kelli's performance before the layout was rotated was not much different from what it was thereafter. It would seem that we have ruled out one counter-interpretation of Kelli's spatial achievements: she evidently did not find her way by orienting to sources of sound or odors in the room.

Experiment V

Information from the room did not guide Kelli's navigation, but what about subtle information from the experimenter? The experimenter could see the objects; thus it is possible that she guided Kelli by speaking in a different tone of voice when Kelli was moving in the correct direction than when she was not, or by other means. To rule out this possibility, Kelli was trained as she was in Experiment I but was then tested by an experimenter who did not know which of the landmark objects was the correct target on any trial.

Method

The experiment was conducted when Kelli was 53 months old. She was brought into the 10 ft × 10 ft playroom in which there were four objects: a small chair (C), a table (T), and two identical, five-foot wooden planks that served as "playing boards." Kelli was told that one of the boards (K) was for her toys, while the other (S) was for her sister's toys. She was allowed to explore one of the boards before the experiment began. The overall spatial configuration of the landmarks was the same as that used in Experiment I (see Fig. 1), with C in the position previously occupied by M, T in that of T, K in that of P, and S in that of B.

Training was conducted by a research assistant and was quite analogous to that provided in Experiment I, except that two of the landmark objects were identical. There were four training trials between C and K, four between C and T, and four between C and S. When training was completed, Kelli was asked to remain at T while the assistant who had trained her left the room. A second experimenter entered, and walked to landmark T. Kelli was then told that the experimenter wanted to put various toys on the playing boards, and she explained, truthfully, that she did not know which board was Kelli's and which her sister's. Kelli's task was to carry toys to the appropriate playing boards, some for herself and some for her sister.

There were a total of eight test trials, four to each board, administered in the order K, K, S, S, K, K, S, S. After each trial, Kelli was called back to T by the experimenter who remained there throughout all of Kelli's movements, giving enthusiastic encouragements throughout as in previous experiments.

Results and discussion

The results are straightforward. Kelli turned towards the target on eight of eight trials ($p = 0.0039$). She also ended up at the correct board on each of the eight test trials ($p = 0.0000$). The mean ITP for the final position successes was 0.97 (there were no failures), and eight out of the eight measures agreed in sign for ITP and final position ($p = 0.0039$, Binomial test).

In this experiment, Kelli was found to navigate successfully among the objects despite the experimenter's ignorance of the paths that constituted "success." This finding suggests that Kelli's successes on the various spatial inference tests were not due to inadvertent cues produced by the experimenter. Kelli's locomotion depended on her own knowledge of the spatial layout.

Experiment VI

Experiment VI investigated the last of the possible artifactual interpretations of Kelli's performance: could Kelli have moved to the objects by means of echolocation? There is a sizable literature that testifies to the use of echoes—sometimes called "facial vision"—in the perception of obstacles by blind adults (e.g., Cotzin and Dallenbach, 1950; Griffin, 1974; Rice, 1967). It is unlikely that such echoes guided Kelli's performance on the spatial inference tests we have described, for three reasons. First, her navigation among the objects was unaffected by rotation of the entire array of objects, a change that might be expected to alter the pattern of echoes in the room considerably. Second, the landmark objects to which Kelli navigated were small and lacked a uniform surface off which sound could bounce. Third, use of echolocation in this task would require that Kelli discriminate the echoes of the different landmark objects. It is unlikely that these echoes can be discriminated from each other. Nevertheless, the existence of a capacity for echolocation in blind adults raises questions about its antecedents. It is possible that echoes from a single object would provide a young blind child with some information about the object's position: information she could use in a simpler task. In Experiment VI, we tested whether echolocation would guide Kelli to an object when no other source of information was available.

Method

Kelli was 48 months old at the time the experiment was performed. At the start of each trial, she was carried into a 10 ft × 10 ft playroom where a single object landmark had been placed. She was then put down on the floor, standing, was told that a particular (familiar) object was in the room, and was asked to find the object. Four different object were used, one at a time, each for a block of three trials, yielding 12 trials in all.

The spatial configurations of the objects and starting positions approximated those used in the original inference experiments. For each three-trial block, the target object was placed in the center square along one border of the playroom. On each trial within a given block, Kelli was placed in the center square along one of the other three borders not occupied by the object. Thus for each trial, the object remained in the same location, but Kelli started from a new one. After each trial, she was carried about the room a bit, and placed at the next starting point, to prevent her from gaining any spatial information via kinesthesis and other body senses. After Kelli started on her route, she was followed and encouraged just as in all previous experiments.

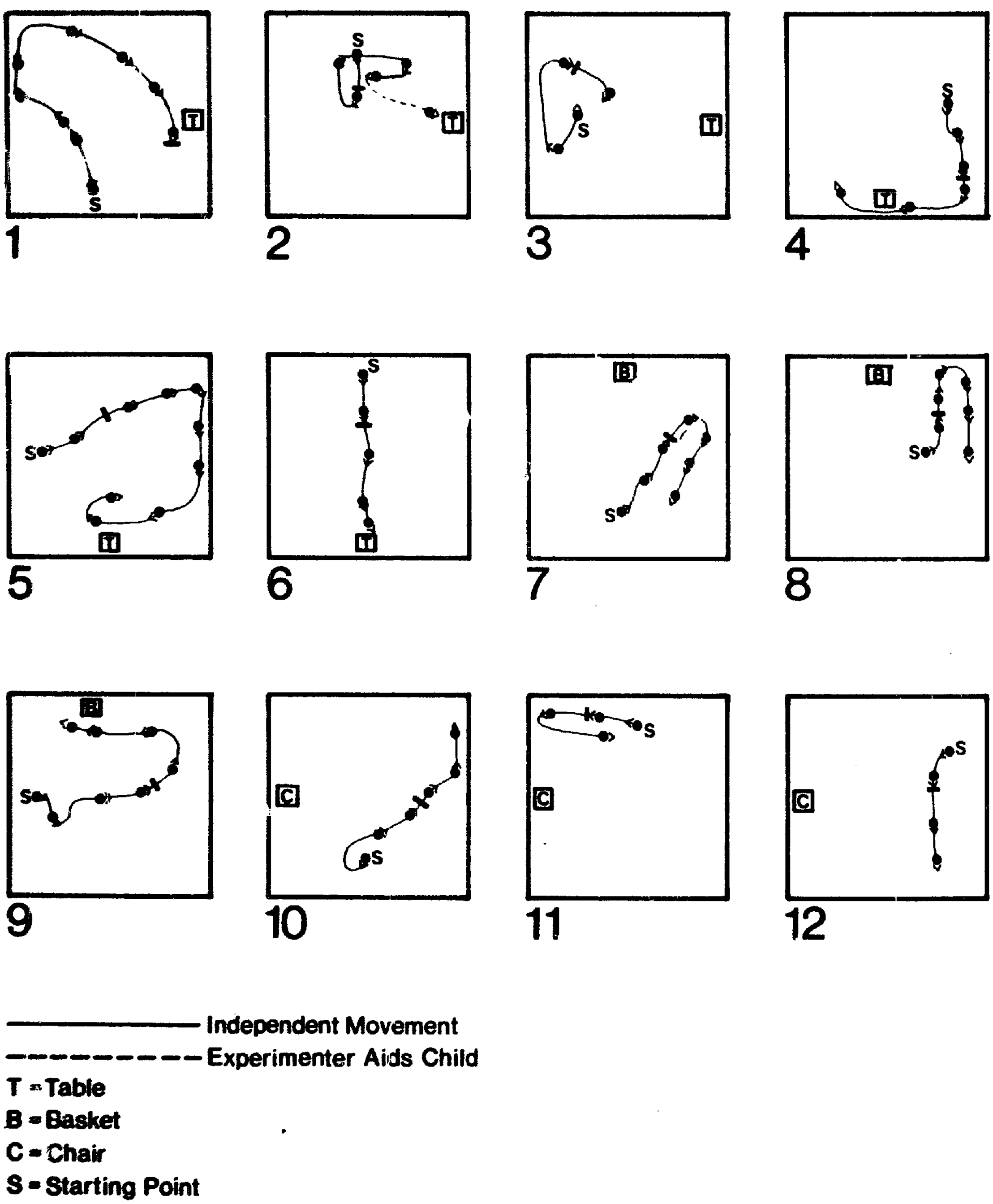
On many trials, Kelli appeared confused, and she circled around the room. All of the trials would have been terminated quite early (and marked as failures) in the previous studies. We chose not to do this here, but instead allowed her to continue on her own path to see what this path might look like under these conditions—whether there would be any semblance of directed movement toward the object. Kelli was never shown the landmark object unless she came to within a foot or two of it herself; again, this was to eliminate any relevant kinesthetic information.

Results

Kelli's routes for the 12 trials are shown in Fig. 4. A simple inspection of the figure shows that her paths are quite different from those seen in the previous experiments. On many trials, she turned away from the target at the very start; on others, she made a complete circle from the starting point; on yet others, she turned until she found a wall, then followed the wall in one or another direction. Most dramatically, the figure indicates that on four occasions, Kelli walked right past the target object without giving the slightest indication that she knew it was there. On one trial, she complained, "I can't find it," when she was standing right next to the target. On virtually all the trials, Kelli expressed confusion at or shortly after the start of the trial. Thus, these trials would have been terminated as failures by the criteria of the earlier experiments; the data analyzed below are taken from her paths up to these termination points.

Kelli's poor performance is reflected in the experimental measures. First, her initial turns were towards the target on 4 out of 12 trials ($p = 0.12$). This is in marked contrast with her performance in Experiments I and II, where her initial turns were in the correct direction on 23 out of 24 trials. Second, she fell within the 40° target range on only 2 out of 12 trials ($p = 0.24$), and within the 90° range on only 2 out of 12 ($p = 0.23$), a considerable contrast with her performance in Experiments I and II, where she came within the 40° range on 15 out of 24 trials, and within the 90° range on 21 out of 24 trials. Third, the relationship between initial turn proportion and final position was quite different from that of previous experiments. The mean ITP was −0.21 for final position successes, and −0.02 for final position failures ($t_{10} = 0.31$, n.s.). This suggests that even when Kelli successfully ended up at the target, her initial movements were not guided by knowledge of the direction of the target, but rather, were random. When ITP and final position were cross-classified as success *versus* failure, 10 of the 12 trials were of the same (negative) sign ($p = 0.016$, Binomial test).

Figure 4. *Test trials of Experiment VI. Heavy bars indicate points of termination by criteria of earlier experiments.*



In sum, there is little doubt that Kelli did not know what she was doing under the conditions of this experiment. Furthermore, she appeared to *know* that she didn't know. She repeatedly asked for help in finding the target object (fitting the criteria for termination in all 12 trials, see Fig. 4). For example, she asked: "Would you please help me?", or "Where's the basket?" "I can't find it," and so on. Such requests were made on every single trial of this experiment. This contrasts with her behavior in all the previous experiments, in which she asked for help on exactly one trial.

Discussion

The results of this experiment show that Kelli did not find the target objects when she was given no prior information about their positions. The experiment thus provides no evidence that Kelli can navigate by detecting echoes from a goal object. Echoes did not guide her even at close range. These findings suggest that a young blind child is more apt to navigate among small objects by using spatial rules and representations than by detecting echoes from the objects—at least under these task conditions. What is more, the findings of Experiments IV, V, and VI together confirm that Kelli's performance depends on spatial knowledge, not on the detection of sensory information.

Experiment VII

In Experiment VII, we sought to compare Kelli's performance on these navigation tasks with the performance of normal, sighted but blindfolded children and adults. Following the method of Experiment I, each subject was walked from a starting position to each of three objects, and then he or she was asked to walk directly between pairs of the objects.

Method

Five children (two boys and three girls, ranging in age from 2 years and 10 months to 3 years and 9 months, with a mean age of 3 years and 1.5 months), and six undergraduates (three men and three women) served as subjects. None of them had seen the room prior to the experiment and none knew the spatial layout.

Both the layout and the procedure were identical to those employed in

Experiment I, except that the experiment was performed in the 10 ft × 10 ft room (rather than the 8 ft × 10 ft room). All subjects had their eyes covered before they were brought into the experimental room. The children wore opaque rubber swimming goggles; the adults wore blindfolds. As in Experiment I, there were 12 training trials and 12 test trials.

Results

The performance of the blindfolded children was remarkably similar to Kelli's own. Their initial turns were towards the goal on 10 of 12 trials ($p = 0.016$), with a range of 9 to 12. The average number of test trials in which the children's final position fell within the 40° target range was 7.4 ($p = 0.0001$), with a range of 7 to 8—essentially identical to Kelli's score of 8. With the extended 90° target range, the children's mean number of successs was 9.0 ($p = 0.0004$), with a range of 8 to 10, as compared to Kelli's score of 11. Their mean ITP for final position successes was 0.93, and 0.40 for final position failures ($t_{58} = 4.07$, $p < 0.005$). Note that the mean ITP for successful final positions is quite close to Kelli's in Experiments I and II (0.87 and 1.04, respectively). This suggests a similar mechanism (like pointing) common to both blind and sighted children. Cross-classification of the two measures for successes *versus* failures showed a significant relationship between them, with 49 of the 60 scores agreeing in sign ($p < 0.005$, Sign test).

Not surprisingly, the performance of the blindfolded sighted adults was better than that of the children. The mean number of test trials on which they initially turned towards the goal was 11.5 of 12 ($p = 0.0015$), with a range of 11 to 12. Their final positions fell within the 40° range on a mean of 10.8 trials ($p = 0.0000$), with a range of 10 to 12; with the extended range of 90° it was a mean of 11.5 ($p = 0.0000$), with a range of 10 to 12. The mean ITP for successes in final position was 0.97, and the mean ITP for failures in final position was 0.70 ($t_{70} = 4.00$, $p = 0.005$). Cross-classification of the successes and failures for the two measures showed that ITP and final position were related, with 52 of the 72 scores agreeing in sign ($p < 0.005$, Sign test).

Discussion

At three years of age, sighted blindfolded children perform at roughly the same level of accuracy as did Kelli. None navigated perfectly, but all were able to find new, direct paths among the objects to a considerable degree. Adults clearly performed better than any of the children, although they too did not perform perfectly. It appears that the ability to navigate without vision improves with age, but this ability is already quite well-developed by the third year, in both the sighted and the blind.

Experiment VIII

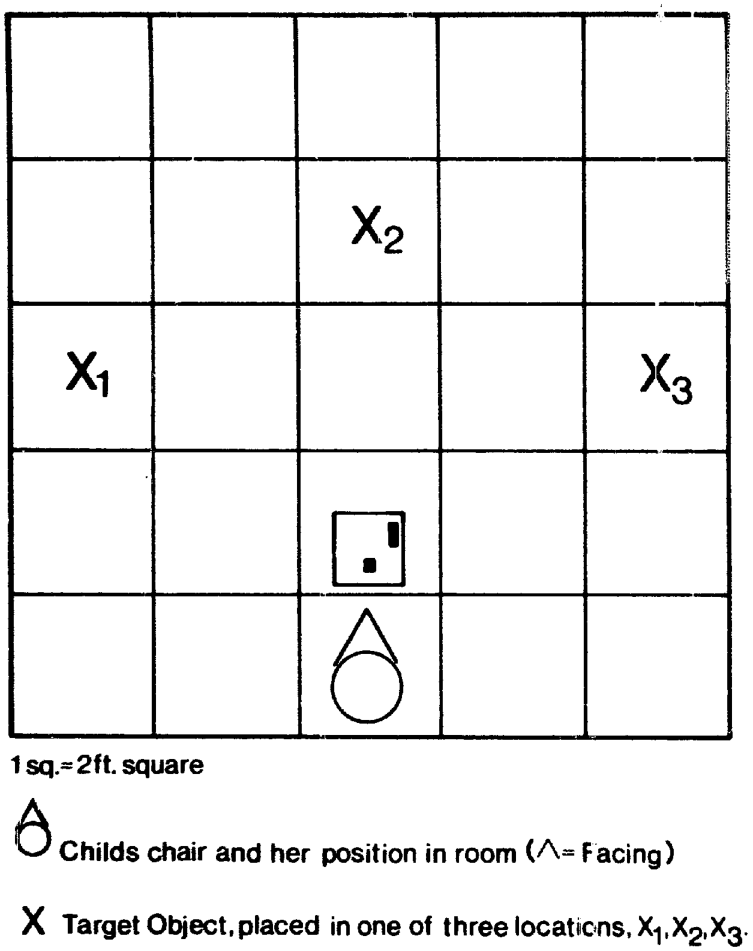
The preceding studies show that Kelli has a considerable degree of spatial knowledge. Can Kelli use this knowledge in an explicit fashion? Some of our work with Kelli suggests that her spatial knowledge is more explicit than one might have guessed.

Preliminary experiment

When Kelli was 4½ years old, she was brought into the now-familiar laboratory playroom and was seated in her little chair. She was told that she would now learn how to use a "map." She had never seen a map before and asked what a map was. She was told that "it's something that shows you how to find things in the room." She was then handed an 8½ inch × 11 inch piece of cardboard, on which two wooden blocks had been glued (see Fig. 5): one represented her own position in the room, and the other represented a toy basket that had been placed in the room in the same relationship to herself that was shown on the map. This tactile "map" was placed on her lap and aligned directly in front of her so that the actual objects represented on the map could be reached by simply moving forward in the appropriate direction. The experimenter took Kelli's hands, moved them over the map and said: "This (moving the child's hands across the entire cardboard) is the whole room. And this is you, this is where you are sitting in the whole room (touching one of the blocks). And this is where the toy basket is, right here (touching the other block)." Kelli responded by asking: "It's the pretend room? And this is the pretend basket?" She was told she was right and the test of her map-reading skills began.

On the first trial, the toy basket was placed in front and to the right of Kelli. The map of Kelli and the basket, represented as above, was placed on Kelli's lap, and she was allowed to explore it. The experimenter held the map steady in position on Kelli's lap, so she would not distort the spatial relationship between map and room by moving the map. Kelli was again shown each

Figure 5. *Room layout and map of Experiment VIII.*



block and told what they represented. The experimenter then asked her what each block represented ("What is this block? And this one?"), to ensure that Kelli understood. Finally, Kelli was asked to find the toy basket in the room, as follows: "Kelli, now can you find the toy basket in the real room? Go to where the toy basket is in the real room." Kelli responded by standing, turning to the right, and walking ahead to where the toy basket was situated. On the first trial, she bumped into it, smiled, and was praised for finding it. On the second trial, the toy basket was moved to another location in the room with a corresponding placement on the map. Again, Kelli was shown the map, and was then asked to find the basket. She responded by going straight to it. On a third trial, the basket was moved straight ahead of Kelli (in the room and on the map), and again she found it directly, after exploring the map. More formal testing was, accordingly, conducted.

Method

The experiment took place in the 10 ft × 10 ft playroom, gridded into 25 2 × 2 foot squares. On each trial, the target (e.g., the toy basket) was placed in one of three possible locations in the room (see Fig. 5). Kelli was presented with the map, and, as in the pilot experiment, was shown which block on the map represented herself and which stood for the target. She was then asked to find the target, with the same queries as in the pilot work. One change in procedure was made: after each trial, the child was carried out of the room, and the location of the target object was changed (on the map and in the room). She was then carried back into the room, placed in her seat, given the new map (noting that the 'real room' had been changed too), and tested as before. A total of 13 test trials were run, 4 each with the basket to Kelli's left and straight ahead of her, and 5 with the basket to her right.

Results

Kelli's paths of locomotion were analyzed as in all prior experiments. Kelli's initial turns were towards the goal in 10 of the 13 trials ($p = 0.0349$). Removing trials where the target was perfectly straight ahead (so that any movement other than one that was perfectly straight ahead would be away from it), she turned towards the goal on 10 of 11 trials ($p = 0.0054$). Her final position fell within the 40° range on 10 of 13 trials ($p = 0.0000$), and within the 90° range on 11 of 13 trials ($p = 0.0000$). Finally, her mean ITP for successful final positions was 1.90, and 1.31 for failures ($t_{11} = 0.32$, n.s.). This lack of significant difference was also reflected in the distribution of cross-classifications of ITP *versus* final position successes and failures: only 7 of the 13 scores agreed in sign ($p = 0.21$, Binomial test). The remaining 6 scores were failures in ITP that were successes in final position.[9]

[9]As in Experiment III, it appears that the small mean angle of the target from starting position (32.38° compared to 116.33° and 149.42° in Experiments I and II) makes a small absolute deviation a large proportional deviation, resulting in many ITP failures that are nevertheless quite well-adjusted towards the goal.

Discussion

This experiment provides strong evidence that much of Kelli's spatial knowledge had become accessible to activities other than locomotion. The very first time that the concept of a map was explained to her, she understood it, used it, and recognized its representational nature (for further discussion, see Landau, forthcoming). This ability testifies to her capacity to represent spatial information, and to use that representation to make inferences about spatial properties of the world.

General discussion

It is clear that Kelli had a considerable degree of spatial knowledge at 2½ years of age, if not earlier. Moreover, this knowledge had become accessible for purposes of navigation by maps by the time she was five, if not before. We will now take up the questions raised in the introduction. First, under what environmental conditions does spatial knowledge arise? Does blindness limit this knowledge in any way? Second, what aspects of our spatial knowledge are most fundamental? Granting that blind and sighted children do have spatial knowledge, how is it best described?

Spatial knowledge in the blind

As we have noted, a number of previous reports suggest that spatial knowledge is seriously deficient in blind persons. Deficits of space perception and spatial comprehension have been reported in blind children and adults. In addition, persons who lost their sight early in life have been found to perform worse than those who became blind at a later age (see Warren (1977) for review). These findings seem to suggest that vision has a vital role in the development of capacities for spatial knowledge. But this conclusion conflicts directly with our own results. How can we square Kelli's successes with the failures of blind adults?

To begin, we should note that the large literature on spatial performance in blind people (including children from the age of eight on, adolescents and adults) is a mass of conflicting findings (see again, Warren (1977) for review and comment). Much of this conflict appears to stem from differences in the tasks meant to tap spatial competence. For example, blind and sighted people have been compared in such widely different tests of spatial abilities as maze learning, block reconstruction, locomotion in space, and length discrimination. Performance on these tasks could depend on a variety of factors unrelated to spatial knowledge (e.g., the fine tuning of motor coordination).

The pattern of results is somewhat more coherent if we only consider studies that used tasks similar to those we posed Kelli—tasks that require some kind of spatial inference after a limited exposure to a given spatial display. Blind adults have been found to perform quite well on tasks of this sort (e.g., Worchel, 1951; Leonard and Newman, 1967) even though they often do not perform as well as sighted people. But this may not mean that vision is a prerequisite for the acquisition of spatial knowledge. Vision may only aid in the use of such knowledge, once it is acquired.

A more serious issue concerns the apparent conflict between our own results and those of Selma Fraiberg on blind infants (Fraiberg, 1977). Fraiberg's view was that blind infants live in a "spatial void." For her, the visual array is the primary (and indeed, necessary) stimulus which prompts the infant actively to explore the world "out there." Blind infants who lack this stimulus do not develop an adequate knowledge of space.

How can we reconcile this account with what we know about Kelli? One possibility is that Kelli is an exceptional blind child. The best guess, however, is that she is not, for she does not excel in other respects. For example, an assessment of her language development (Landau and Gleitman, forthcoming) found her to fall in the lowest quartile of 86 blind children on certain measures (Norris *et al.*, 1957). Similar conclusions were suggested by an independent clinical assessment of her cognitive abilities at age 2, using a modification of the Bayley Scales of Infant Development (Bayley, 1969).

A second way to reconcile our findings with Fraiberg's would be to propose that blind infants do have spatial knowledge which Fraiberg's methods did not reveal. Fraiberg's view rests heavily on observations of blind infants' reaching behavior. She showed that reaching for an *audible* object in blind infants occurs at a much later age than does reaching for a *visible* object in sighted infants. In combination with observations of clinically deviant blind children—who, for example, lack any use of their hands for object use and exploration—Fraiberg took the reaching data as support for the view that spatial knowledge develops later in the blind. In fact, as Fraiberg herself has noted, sighted infants behave just like blind infants when required to reach for objects that can be heard but not seen. Reaching for audible objects develops later than reaching for visible objects in the sighted as well as the blind (Freedman *et al.*, 1969). We believe, therefore, that Fraiberg's observations do not show that blind children are unable to construct a spatial world based on non-visual experience. Blind infants may only have fewer means by which to express the spatial knowledge they possess.

Are the spatial representations of blind and sighted children identical, and do they arise in precisely the same way? We cannot answer these questions, for we have studied only one spatial phenomenon—the ability to make spatial inferences in navigation tasks. What we have shown is that vision is not a necessary condition for the development of spatial knowledge underlying such tasks. To the extent that the blind and sighted child perform these tasks in the same way, it would seem likely that there is at least partial identity in their mental descriptions of space.

Some properties of spatial knowledge

What are the characteristics of the spatial knowledge shown by Kelli, and by the other young children? We suggest three characteristics. First, this spatial knowledge is generative. Second, it is abstract and amodal. Third, it depends on a system of metric geometry, probably Euclidean geometry.

Generativity
A child who is taken on a set of paths among objects can find new paths among those objects. In principle, there would seem to be no limit to the paths she could find, long or short, straight or curved. In this sense, knowledge of space shares an attribute with other important systems of knowledge such as language. Just as the language learner can speak and understand sentences he has never heard, so the young spatial navigator can find new routes he has never traveled before.

Abstractness
Given that spatial knowledge can be manifested in a young blind child, there is good reason to believe that this knowledge can be captured by representations that are independent of input modality. The original information to the child is organized in such a way as to transcend the particularities of the perceptual system through which it is obtained. It is *spatial*, rather than visual, haptic, or auditory.

Metric properties
One way of describing spatial knowledge is as a system of geometric rules and principles that can be applied to spatial information so as to derive further spatial knowledge. Seen in this light, the use of spatial knowledge depends on a logical inference, in which the geometrical properties of the system (i.e., its primitives, axioms and postulates) serve as the major premises, the spatial properties of the familiar paths serve as the minor premises, and the conclusions from these premises are the spatial properties of the new path. But what are the spatial properties encoded in the minor premise, and what are the geometric rules for deriving further spatial properties?

We suggest, first that the relevant spatial rules and properties are those found in the *metric* geometries, particularly Euclidean geometry.[10] Within a Euclidean representation of space, a particular array, such as the configurations of objects presented to Kelli, could be encoded as a set of straight lines of particular lengths, intersecting at a single point, and spatially related to each other by particular angular deviations. Given this encoding, and the principles of Euclidean geometry, the distance of the appropriate straight line that connects the end points of these paths can be deduced, and so can its angular relation to the other paths.

One alternative proposal nevertheless requires more discussion—Piaget's claim that the representation of space in young children is topological. According to Piaget, their representation is limited to such topological features of space as 'closedness' and 'connectedness,' and does not include various metric properties such as angle and distance. In his view, metric properties are not represented until sometime in middle childhood (Piaget and Inhelder, 1967). As evidence for this view, Piaget cited findings on shape generalization and discrimination across different sensory modalities as in comparing a square felt by touch with a circle that is seen. On Piaget's hypothesis, young children ought to judge a square and a circle to be the same, since their spatial representation is limited to the topological and the two figures are topologically equivalent (both being 'closed'). Piaget and his co-workers have claimed to obtain precisely this result (e.g., Piaget and Inhelder, 1967), but their studies are difficult to interpret and have been challenged by other investigators (e.g., Edwards and Rieser, 1979; Schwartz and Day, 1979).

Whatever the ultimate verdict on such studies, we believe that our work on spatial navigation shows conclusively that Piaget's characterization of spatial knowledge in the preschool years is inadequate. Successful solution of the navigation problems we posed for Kelli and for sighted children requires

[10]Examples of some non-metric geometries are the *affine*, the *projective*, and the *topological*. Affine properties include parallelism of lines; projective properties include the cross-ratio of the distance of four points on a line; topological properties include connectedness. These geometries form a hierarchy, with the metric (including Euclidean) at the top, followed by the affine, the projective, and the topological in descending order. Geometries include all the properties of those below them in the hierarchy and not all the properties of those above them (see Gans, 1969). For example, a Euclidean description of a given spatial arrangement would preserve such topological properties as connectedness and closure. Cheng and Gallistel (1982) suggest that this hierarchy may yield an index of the 'power' of the representational capacity of a given organism, but as yet there is no evidence that any of these nonmetric geometries is an appropriate characterization of the way any creature represents space. Although Cheng and Gallistel suggest that Kelli's problem may be solvable with an affine geometry, their solution crucially depends on a representation of each landmark as a cluster of points. We believe that Experiment II—in which Kelli makes inferences among 'places' in space (not occupied by landmarks) rules out such an explanation.

spatial knowledge whose geometric properties go beyond those contained in any topological representation. Consider the studies in which Kelli was placed in a room that contained object landmarks M, P, and B, and was allowed to travel between M and P, and between M and B, and was then required to go to B when placed at P. If Kelli could only represent topological properties of space, she could only have known that M, P, and B are distinct and unconnected points which are enclosed within the same room and not enclosed relative to each other. Knowing this might help her to deduce that there is *some* connecting path that leads from P to B without any impassable barrier in between, but she would have no means of distinguishing among the infinity of such paths that exist. Moreover, she would be unable to find any path except by traveling at random, starting at P and continuing in random fashion until she finally bumped into B.

Thus, Kelli's performance requires a set of premises that are altogether missing in a topological representation. The situation is quite different given a Euclidean (or indeed, any metric) representation which includes properties such as angle and distance as well as the more general properties captured within such non-metric geometries as topology. Euclidean geometry, as we have noted, is sufficiently powerful to account for the spatial abilities our blind and sighted subjects have displayed. If the subject can represent two of the angles and distances holding among three objects, she can then determine—by straightforward geometrical computations—the third angle and distance between the objects.

Conclusion

To summarize, we have provided evidence that a young child born blind has a set of capacities that can be said to constitute a system of spatial knowledge. This system includes geometric rules that serve to form and build on geometric representations, permitting inferences that allow travel along new paths. The rules and principles are abstract and amodal, and they appear to incorporate information included in the rules and principles of Euclidean geometry.

This characterization should serve to highlight that we view the case of the blind child as an illustration of the problem any human faces in coming to know spatial properties of the world. While the blind child seems to be faced with a particularly impoverished environment from which to construct spatial knowledge, we believe that no environment is so rich as to impress a particular kind of spatial conception upon us, were we not prepared to embrace it. Spatial knowledge can never be viewed as a direct reflex of sensory information. Thus, the blind child serves as a particularly compelling demonstration of the problem that any child faces: the problem of constructing an abstract description of the spatial properties of the world.

This way of looking at the problem of spatial knowledge is hardly new. It goes back at least as far as Descartes (1637), and has entered psychology at a number of points through work as diverse as that of Tolman (1948) and of Helmholtz (1885). What is new is our evidence that spatial knowledge, like knowledge of language and knowledge of number, arises naturally in humans, with little thought or training and with no visual experience, and that this knowledge can guide some of our earliest attempts to venture through the world.

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Résumé

Une suite de 8 expériences a démontré qu'un enfant de 2 ans aveugle de naissance ainsi que des sujets contrôles aux yeux bandés, avaient une connaissance de l'espace. L'enfant aveugle, aprés avoir circulé le long de certaines voies entre des objets a été capable de faire des inférences spatiales et de trouver de nouveaux chemins entre les objets (Exp. I). Elle a réussi également à trouver son chemin entre des lieux non marqués par des objets (Exp. II). Les écarts à la ligne droite dans les expériences I et II ne sont pas dûs à de fausses inférences mais probablement à l'imprécision du contrôle moteur puisqu'on les retrouve quand des inférences ne sont pas nécéssaires, par exemple, quand l'enfant se dirige vers une source sonore (Exp. III). Le comportement de l'enfant ne peut être expliqué par des artéfacts: les indices sonores, les biais dûs à l'expérimentateur et l'écholocation sont contrôles (Exp. IV, V, VI). Les sujets voyants aux yeux bandés performent globalement de la même façon (Exp. VII). Enfin l'expérience VIII montre que l'enfant aveugle peut utiliser sa connaissance spatiale dans une tâche simple de lecture de carte. Les auteurs concluent que le jeune enfant aveugle a un système de connaissance spatiale incluant des régles et des principes abstraits, amodaux incorporant des informations géométriques métriques qui peuvent être utilisées pour guider les déplacements dans le monde.