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Geometric Complexity and Object Search in Infancy

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In four experiments we investigated the role of geometric path type in infants' ability to make spatial inferences about the location of a hidden object after they themselves had been moved through space. Nine-month-old infants were moved along geometrically simple paths of rotation (Experiments 1 and 2) or translation (Experiment 3) or along geometrically complex paths of combined rotation and translation (Experiment 4). In all but the fourth experiment, infants were able to retrieve an object hidden before they were moved, as long as the object was not located behind them at test time. Direct comparisons among the conditions showed that moving infants along geometrically simple paths led to significantly better performance than moving them along geometrically complex paths. We found the length of a path, the time needed to traverse it, and the likelihood of fixation of the target to be unrelated to the infants' performance. These findings are discussed in the context of theories of the development of spatial knowledge.

After moving through space adults can usually relocate stable objects and positions even if the objects are not visible and their positions are not marked by distinctive landmarks. We can determine the location of an object by using knowledge of its original position and of our path of movement. Given the distance and direction of the object relative to our starting point and of our starting point relative to our final position, we can infer the object's distance and direction from our final position. Such inferences about location follow logically from geometric principles relating spatial positions; they are similar to logical deductions, although they are neither conscious nor effortful. The ability to make such inferences is fundamental to human spatial activities, allowing humans both to relocate invisible objects and to plot new paths toward invisible goals. This ability is also of theoretical interest, because inferences require premises, that is a body of principles concerning geometric objects and geometric relationships that has been termed "spatial knowledge" (Landau, Spelke, & Gleitman, 1984).

In this article, we focus on the developmental origins of spatial knowledge in infancy. Although spatial inferences of the sort discussed above come quite naturally to adults and even to 2-year-old children (Landau et al., 1984; Rieser & Heiman, 1982), studies of infants have revealed some significant difficulties in relocating objects after self-movement (Acredolo, 1978). In the absence of rich external landmarks, for example, 6- and 11-month-old infants have been found to search for a hidden object at egocentrically defined locations, ignoring the effects of their own displacements. Such results have been taken to imply that infants are incapable of performing the sort of spatial inferences that are the foundations of spatial knowledge (Acredolo, 1978). It is possible, however, that infants make inferences about object location under certain circumstances but fail to do so if the geometric problem that they must solve becomes sufficiently complex. One intriguing possibility is that infants, like adults, are affected by the geometric nature of the path that they travel or the consequent complexity of the change in their own position. We focus on this possibility here.

Path types can be divided into three categories in accordance with their geometric properties: rotations, translations, and rotation–translation combinations (Gans, 1969). In rotations, the orientation of the subject changes relative to every stable object, but the subject's distance relative to the objects is constant. In translations, the subject maintains a constant orientation but moves a certain distance to a new location. In rotation–translation combinations, the subject both changes orientation and moves to a new location. Rotations and translations are geometrically simple in that each of them involves a change in a single parameter, orientation or location, whereas rotation–translation combinations bring changes in both parameters. If geometric complexity affects infants' performance, then movements of the observer along complex paths might produce more errors in an object-relocation task than movements along simple paths.

Informal observation suggests that adults may be affected by geometric complexity. Certain paths that combine rotation and translation—for example, a zigzag path or a series of curves—seem to result in total disorientation of the observer. For example, camera movements along such paths disorient viewers of motion picture films (Hochberg, personal communication, 1986). If variations in path type affect adults' ability to relocate a stable object, infants might be affected as well.

Existing studies are consistent with the hypothesis that geometric complexity affects infants' ability to relocate objects after self-movement. Acredolo (1978) trained 6- and 11-month-old infants to look toward their right or left in anticipation of an event at a constant position. The infants then underwent a combined rotation–translation in which they were moved

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around a circular table to a new location and orientation several feet away and at a 180° rotation from their original position. The infants appeared not to update their position, continuing to search for the event in the egocentrically defined direction of training. In contrast, infants have been found to relocate objects successfully after a self-movement of pure rotation. McKenzie, Day, and Ihsen (1984) reported that 8-month-old infants looked toward the correct place of an expected event over rotations of up to 90° around the body axis after they had viewed the event from a number of different perspectives prior to testing. Cornell and Heth (1979) reported that 8- and 12-month-olds could learn to account for 180° rotations under similar circumstances. These findings suggest that infants can account for self-rotations under certain conditions.

Finally, research by Ruff (1982) provides an intriguing analogy to studies of spatial navigation. Ruff investigated object recognition under different conditions of object motion. She found that 6-month-old infants were better able to recognize an object after a simple translation of the object than after an object motion combining rotation and translation. In Ruff's experiments, objects could only be recognized by detecting their geometric properties: Recognition depended on analysis of the spatial relationships among each object's parts. This problem is formally analogous to the understanding of spatial relationships among objects in an array and it too points to the greater difficulties imposed by geometrically complex transformations.

We designed the present studies to investigate the effects of three transformations—rotations, translations, and rotation–translation combinations—on infants' ability to relocate objects after self-movement. We presented infants with spatial problems in which they had to locate a hidden object in one of a set of identical containers. To do so, they had to use the object's initial location as well as their own path of movement and final position to determine the object's final location. Such a conclusion about location is an inference, in our sense: It follows logically from spatial information but does not require immediate perceptual evidence about the object's location. Array configuration, object location, and infants' position before and after search were kept constant, whereas the paths that took infants from their initial to their final search position were varied. Our principal hypothesis is that infants find it easier to relocate objects after moving along geometrically simple paths.

A secondary issue concerns the relative difficulty of relocating objects after rotation versus translation. A geometric analysis suggests that the two types of transformation would be equal in difficulty. Different predictions appear to follow, however, from action-centered theories of spatial development (Acredolo, Adams, & Goodwyn, 1984; Bremner & Bryant, 1985; Piaget, 1954). According to such theories, infants relocate objects only over those movements that they themselves can produce. As infants produce increasingly more complex movements, they come to understand the spatial transformations that follow from such movements. As with the geometric hypothesis, an action-centered theory would predict that rotations would be simpler than combination paths, because they are produced quite early and freely by the infant. Small translations of the head and trunk might also be available to the child within the first 6 months. Larger translations, however, must await independent locomotion, with the forward translation accompanying early crawling being understood before large sideways translations. The action-centered view, therefore, would not predict a strict equivalence between rotation and translation; the difficulty of each transformation would depend on the infant's state of motoric development.

General Method

The four experiments reported here used the same method, except for the path along which infants moved and the configuration of the positions in which an object could be found. In each study, infants were trained to recover an object that was hidden in one of several identical containers. After attaining a criterion of success (two successful searches in a row), infants were shown the object being hidden again in the same position and were then moved to a new orientation, a new location, or both. At the new position, infants were equidistant from at least two containers, one of which contained the object. They were allowed to search for the object. Data analysis focused on the infant's tendency to search in the object's true location.

Subjects. The subjects in each experiment were 12 healthy, full-term, 9-month-old infants residing in the Philadelphia, Pennsylvania area.

Materials. Each study was conducted inside of an 8 × 10 ft (2.44 × 3.05 m) space defined by pale yellow 4-ft-high walls. Objects were hidden inside one of a set of two or three identical upright, heavy yellow cardboard cylinders, each 12 in. high × 8.5 in. (30.48 × 21.59 cm) in diameter and open at the top. They were designed to tip on a slight tug of the upper edge but to return to their original upright position after such a tug. Pretesting had shown that this design readily elicited search in 9-month-olds, who manipulated the cylinders easily. A set of small toys (e.g., keys, a rattle) served as the target objects. Objects were changed as needed to maintain the infants' interest.

Design. Each infant was presented with two trials for each path of movement and array type, for a total of eight trials in Experiments 1, 2, and 4 as well as four trials in Experiment 3.[1] On half of the trials, infants searched for an object hidden in an array of two cylinders; on the other trials they searched for an object hidden in one of three cylinders. Within each of these array types, the position of the object was kept constant for each subject but was varied over subjects. In addition, the extent or direction of the subject's movement was varied (see the individual experiments for details). The order of array type (two cylinders first vs. three cylinders first) was counterbalanced across subjects, and the choice of target hiding place was randomly determined for each subject and array type, with the constraint

[1] In Experiment 3, two trials were given for a single translation over each of the two array types for a total of four test trials. We did this to keep constant the hiding location and direction of training within a given array as in the other experiments. Although this resulted in half of the total trials of the other experiments, the alternatives would have been to change Experiment 3 by doubling the number of trials per array, increasing the number of arrays, changing the direction of training within an array, or including more than one hiding location per array. Because each of these would have introduced confounds into the comparison across experiments, we deemed it more reasonable to use the same design with half of the number of trials.

that the target not be located directly in front of the subject after movement and that two containers, one of which hid the target object, be equidistant from the infant at search time. These constraints eliminated the possibility that the infants would solve any search task merely by reaching for the most accessible object (Butterworth & Cochran, 1980; Diamond, 1981).

Procedure. Infants and their mothers entered the experimental space and were seated on the floor, with infants facing the cylinder array and their mothers directly behind them. The experimenter stood behind the walls of the space, moving from wall to wall at random times during the experiment so that she did not serve as a stable landmark. All procedures were carried out by the mother, with running instructions from the experimenter. The entire procedure was videotaped.

The procedure had two parts: training and testing. First, infants were trained to retrieve a small toy from the target cylinder. The mother was instructed to draw her infant's attention to the toy and then to drop the toy into the cylinder. Usually, the infant would reach up and tug at the side of the cylinder, causing it to tip and reveal the toy, and retrieve the toy from the cylinder. If the infant did not immediately retrieve the toy, the mother was instructed to help. Most infants readily caught on to this game and searched for the hidden object on subsequent trials. A few infants had difficulty contacting the toy after tipping the cylinder. In these cases, on both training and test trials, the mother was permitted to retrieve the toy after the infant had actually reached and tipped the cylinder. Testing began after two successful searches (reach and tip).

During testing, the mothers again dropped the toy into the target cylinder. Before there was time to search, however, the mother moved the infant to the new orientation or location. The infant was then allowed to search for the toy, and the first reaching response was recorded. Mothers were instructed not to touch or look at the infant during the search. Inspection of the videotapes revealed that two mothers did not adhere to this rule; these mother–infant pairs were replaced with new subjects. After their initial search for the toy, infants were moved back to their original position, where they underwent one more training trial before each subsequent test trial until all the test trials were completed. No infant failed to search correctly from the original position on the intermittent training trials.

Experiment 1: Rotations

In this experiment, infants were rotated in place, changing their orientation but not their location relative to the objects in the array.

Method

Subjects. The 6 boys and 6 girls in Experiment 1 had a mean age of 9 months, 10 days (the range was 9 months, 7 days to 9 months, 14 days).

Materials, design, and procedures. Each subject was tested after both 90° and 180° rotations, presented twice each in alternating order for each array type. Hiding location was chosen randomly for each subject and array type. On test trials, the mothers rotated their infants in place, maintaining the infants' original location but changing their orientation. Mothers remained at their original location and orientation before, during, and after the infants' movement.

The array types were arranged so that the infant was always seated equidistant (11 in. or 27.94 cm) from all the cylinders, both before and after rotation. This resulted in the use of a two-cylinder linear array and a three-cylinder triangular array (see Figure 1). These two arrays were chosen for several reasons. First, use of a two-cylinder array permitted a comparison between the present results and those reported in the literature for combined rotation and translation, because these tests have most often been performed with two choice points positioned to the infant's right and left (e.g., Acredolo, 1978; Bremner, 1978). The use of a three-cylinder array permitted a test of the generality of infants' behavior under simple rotations, with the triangular arrangement maintaining equidistance between the infant and each cylinder.

Furthermore, the use of these two arrays dissociated the effects of degree of rotation from the effects of target location relative to the body. Both before and after rotation within a two-cylinder array, a 180° rotation results in location of the objects to the infants' right and left—hence within their visual field. A 90° rotation within this array results in location of one object to the infants' right and one to their left prior to rotation, but one object in front and one behind them after rotation. Failure under such a condition could mean that infants were either unable to account for a 90° rotation or that they were unable to locate objects behind themselves. Currently, there is virtually nothing known about infants' encoding of space behind them because search tasks usually have been limited to locations in front of the infant (cf. McKenzie, Day, & Ihsen, 1984).

Thus, the present experiment sampled four locations around the body: Across both rotation types, the target was hidden either in front of infants, or to their right or left; after rotation, the target was located either behind the infants, or to their right or left. (Test locations in front of infants were excluded as described in the Design section above; for example, in no case was an object hidden to the infant's left and followed by a 90° rotation to the left.) Comparisons were then made between performance on various test location/rotation pairs to distinguish between difficulties with specific test locations (especially behind the infant) and difficulties with specific rotations (e.g., 90°). For example, if infants performed poorly on the two-cylinder/90° rotation trials (which resulted in location of the target behind the infant), the three-cylinder/90° trials would provide control trials (i.e., 90° trials on which the target would not be located behind the infant). If infants succeeded on the latter occasions but failed on the former, the difficulty could be ascribed to object location at test time, not to rotation degree. Similarly, in test-

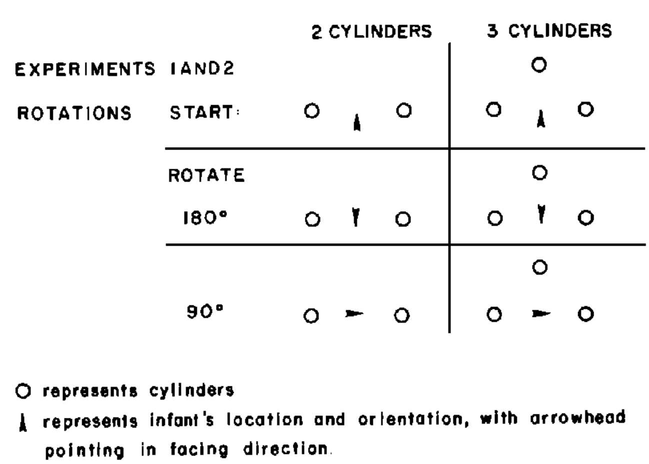

Figure 1. Paths of infants' movement in Experiments 1 and 2. (The infants were rotated in place, changing orientation only. Mothers remained in one stable location in Experiment 1 and behind their infants (moving with them) in Experiment 2.)

Table 1
Proportions Correct Over Array Type and Rotation

Experiment	Array type and rotation						Grand total
	2-cylinder			3-cylinder			
	90°	180°	Total	90°	180°	Total	
1							
All trials	.42	.79	.60	.46	.46	.46	
Without "behind"	—[a]	.79	.79	1.00	.69	.79	.79
2							
All trials	.29	.83	.56	.33	.54	.44	
Without "behind"	—[a]	.83	.83	.63	.81	.75	.79
3			.71			.79	.75
4							
Around			.58			.25	
Through			.58			.54	
Total			.58			.40	.49

[a] In all trials of the two-cylinder/90° rotation condition, the target cylinder was located behind the infant after rotation. Hence removal of "behind" trials resulted in an empty cell for this condition.

ing with a three-cylinder array, a 180° rotation resulted in location of a target behind infants at search time whenever the toy was initially hidden in the cylinder to their front. The control for this condition is found in the two-cylinder array, where a 180° rotation never resulted in a target located behind the infant.

Thus, failures to make a spatial inference after a given rotation type would result in uniform failures for all of those rotations, regardless of object location following the movement. In contrast, failure linked only to object location following movement would result in uniform failures for just those locations, regardless of rotation type.

Results

The mean proportions of correct responses for each condition are shown in Table 1. Subjects achieved the highest proportion correct in the two-cylinder/180° condition, with a mean proportion of .79 correct. Subjects achieved mean proportions of .42 for the two-cylinder/90° condition and .46 for both the three-cylinder/180° and three-cylinder/90° conditions. Individual t tests comparing proportion correct to the chance proportions of .50 for the two-cylinder array and .33 for the three-cylinder array were significant only for the two-cylinder/180° condition, $t(11) = 3.92$, $p = .003$. For the two-cylinder/90° condition, $t(11) = -.61$, *ns*, for the three-cylinder/180° condition, $t(11) = 1.00$, *ns*, and for the three-cylinder/90° condition, $t(11) = .93$, *ns*.

The results can be understood best by considering the settings in which the infants made errors. Although almost half of the trials resulted in errors, analysis revealed that these errors occurred almost exclusively when the target cylinder was behind the infant after rotation. Of the 45 errors made by the infants, 35 fell in this category. The combination of these errors with the correct responses accounted for 90% of the infants' responses.

The difficulty with these "behind" trials is illustrated in Table 2, which shows proportion correct across array type, resulting location, and degree of rotation. In the two-cylinder array, the 90° rotations always resulted in behind trials; this condition elicited a mean proportion of .42 correct. The 180° rotations never resulted in such trials, and the mean proportion correct in this condition was .79, significantly better than chance. Comparison with the three-cylinder condition illustrates that this large difference in performance was not caused by degree of rotation, but, rather, by the location of the target at test time. The 90° rotations that resulted in a location behind the infant elicited a mean proportion of .19 correct; those that did not result in this location elicited perfect performance. Those 180° rotations that resulted in behind trials elicited no correct responses at all; those that did not result in this location elicited a mean proportion of .69 correct.

To examine infants' performance with objects that were not located behind them, the proportions of correct responses in each condition were recalculated after removing all behind trials. This left 48 of the original 96 trials: all of the 180° trials and none of the 90° trials in the two-cylinder array, and one-third of the 90° trials and two-thirds of the 180° trials in the three-cylin-

Table 2
Proportions Correct for Behind and Not Behind Trials

Experiment	Behind		Not behind	
	90°	180°	90°	180°
1				
2-cylinder	.42	—	—	.79
3-cylinder	.19	.00	1.00	.69
2				
2-cylinder	.29	—	—	.83
3-cylinder	.19	.00	.63	.81

Note. In the two-cylinder condition, 12 subjects had 90° rotations in which the object was behind them at test time and 180° rotations in which the object was never behind them at test time. In the three-cylinder condition, 8 subjects received these conditions and 4 received the opposite.

der array. The resulting proportions correct are shown in Table 1. On the assumption that infants never consider that a cylinder is located behind them, the random probability of success was now .50 for the three-cylinder as well as for the two-cylinder arrays. Infants performed significantly better than chance in two of the three relevant conditions, with marginal significance in the third: for the two-cylinder/180° condition, $t(11) = 3.92$, $p = .02$; for the three-cylinder/180° condition, $t(7) = 1.38$, $p = .11$; and for the three-cylinder/90° condition, there was perfect performance for all subjects.

Discussion

These results suggest that infants are capable of inferring the location of a hidden object after a simple rotation in space, as long as the rotation does not leave the target directly behind them. The error patterns were consistently related to the position of the target cylinder at search and were not related either to array type or to the extent of rotation. The fact that failures were strongly linked to object location following rotation suggests that infants are not generally deficient in making spatial inferences after rotation. Rather, there are limits on the areas of space where infants will search.

Although the results were suggestive, they appeared to merit replication in view of the failure of infants to search behind themselves and because of the possible role of the mother in guiding search. In Experiment 1, the mother maintained a constant position relative to her infant during the procedure. Because mothers were never part of the visible array before rotation and were always part of it after rotation, it seemed conceivable that infants were in some way using their mothers as spatial referents that could facilitate location of the hidden object without having to take account of their own movement. For example, the mother may have given the infant visual clues as to the location of the target cylinder by looking at the target herself. Butterworth and Cochran (1980) have shown that infants under 12 months can make use of mothers' gaze to locate an object as long as it is in their visual field. Thus, the infants might have failed on the behind trials because they were unable to use the mother's direction of gaze for objects located behind them after rotation. Another possibility was that the infants might have been using their stably located mother as a landmark by which to locate other objects in their visual field. Presson and Ihrig (1982) have shown that infants can do this, performing better after simple rotations when the mother remains in a stable location than when she moves. Both of these possibilities motivated Experiment 2, in which the mother could neither cue the infant by her own gaze or serve as a landmark.

Experiment 2: Rotations

Method

Subjects. The 7 boys and 5 girls in Experiment 2 had a mean age of 9 months, 14 days (the range was 9 months, 4 days to 9 months, 28 days).

Materials, design, and procedures. This experiment was identical with Experiment 1, except that mothers were instructed to remain behind their infants at all times, moving with them as they underwent rotation. Mothers were permitted either to stand or to kneel behind their infants. All the mothers followed this direction correctly.

Results

The mean proportions of correct responses for each condition are shown in Table 1. Infants showed the highest proportion correct in the two-cylinder/180° condition (M proportion = .83), with mean proportions of .29 for the two-cylinder/90° condition, .54 for the three-cylinder/180° condition, and .33 for the three-cylinder/90° condition. Individual t tests comparing proportion correct with chance level showed that only the two-cylinder/180° condition elicited better than chance performance, $t(12) = 4.69$, $p = .008$. The other conditions were either at or below chance level: for the two-cylinder/90° condition, $t(11) = -2.33$; for the three-cylinder/180° condition, $t(11) = 1.6$; and for the three-cylinder/90° condition, $t(11) = .000$.

The error patterns paralleled those in Experiment 1. Of the 48 errors, 38 (79%) occurred when the target was behind the infant after rotation. These errors combined with the correct responses accounted for 90% of all the trials. As Table 2 indicates, the error patterns were again tied to location of the target after rotation rather than to array type or to degree of rotation by itself.

Removing all behind trials yielded the proportions shown in Table 1. Using a random probability of success of .50 for both array types, performance was better than chance for two of the three relevant conditions: for the two-cylinder/180° condition, $t(11) = 4.69$, $p < .01$; for the three-cylinder/180° condition, $t(7) = 3.44$, $p < .05$; and for the three-cylinder/90° condition, $t(3) = 0.52$, *ns*. When the data from Experiments 1 and 2 were combined (hence, doubling the sample size) performance was better than chance for all of the conditions, including those that did not achieve significance in Experiments 1 and 2 individually: for the three-cylinder/180° condition, $t(15) = 3.16$, $p < .01$, and for the three-cylinder/90° condition, $t(7) = 2.38$, $p < .05$.

Discussion

Virtually identical performance was found in Experiments 1 and 2. In both studies, infants were able to infer the location of a hidden object after they had been rotated through space, as long as the target was not located behind them at search time. Thus, infants seem to be capable of inferring the location of hidden objects after their own rotations in space, even rotations of 180°. This finding contrasts with previous reports of infants' difficulties in accounting for movements involving left–right reversals produced by 180° rotation–translation paths (Acredolo, 1978). It extends the findings of previous investigations of object localization after geometrically simple rotations by providing evidence that 9-month-old infants account for even extreme rotations of 180° and that they manifest this ability without an extensive training period.

In both experiments, search performance was strongly influenced by the location of the target at test time. When the target was behind the infant at search time, performance decreased dramatically to below chance levels. This effect was observed for both array types and both degrees of rotation; as a consequence, it led to particularly poor performance in the two-cylin-

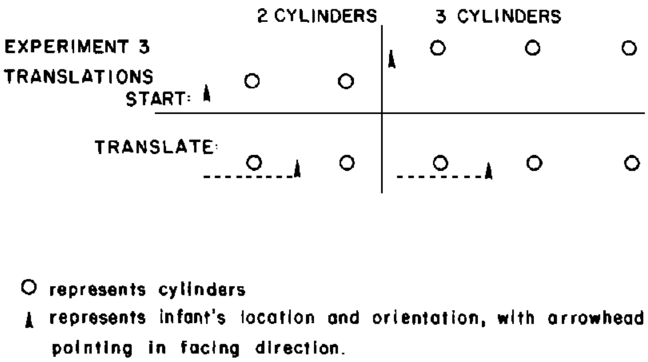

Figure 2. Paths of infants' movement in Experiment 3. (The infant was translated laterally, changing location only. Infants' starting positions were either to the left or right of the two-cylinder array and to the left or right of either the center cylinder or the entire array for the three-cylinder array.)

der/90° rotation condition, in which the object was located behind the infant on all trials. (We return to this constraint on search in the General Discussion.)

In summary, both Experiments 1 and 2 provided evidence that 9-month-old infants can infer the location of a hidden object in the absence of any distinctive landmark after they themselves have undergone a geometrical rotation. We now asked whether this ability also extends to inferring the locations of hidden objects over another simple type of movement—translation.

Experiment 3: Translations

In this experiment, infants were moved sideways along a path of translation (see Figure 2). We chose to test only sideways translation rather than forward or backward translation, because the results of Experiments 1 and 2 strongly suggested a constraint on 9-month-olds' searching linked to the front–back body axis. One would predict, therefore, that infants would have difficulties searching behind the body after movement along a path of forward translation and would fail to be trained to search for objects located behind themselves prior to movement along a path of backward translation. Pilot testing showed both of these predictions to be correct. These problems were circumvented by restricting the design to sideways translation.

Method

Subjects. The 6 boys and 6 girls in Experiment 3 had a mean age of 9 months, 11 days (the range was 9 months, 2 days to 9 months, 29 days).

Materials, design, and procedures. The materials were identical with those used in Experiments 1 and 2. The design and procedures were parallel to Experiment 2 except as follows:

Each infant was tested on a single translation within linear arrays of two and three cylinders. Infants were seated slightly behind the array, trained to their right or left, and then moved by a lateral translation in that same direction. This resulted in a testing situation where infants were equidistant both from the egocentrically defined location and from the true location of the hidden object (see Figure 2).

For example, if infants were trained to retrieve the toy from the cylinder to their right, they then would be moved sideways to the right, to a position where the target would now be located to their left and another (empty) cylinder to their right. Because subjects were always moved to a testing position that was equidistant between these two choices, they were trained to the left or right of the entire two-cylinder array (see Figure 2), whereas in the three-cylinder array, they were trained either to the left or right of the entire array or to the left or right of the center cylinder (see Figure 2).

Results

The mean proportions of correct responses for each array type are shown in Table 1. Infants performed quite well for both array types (M proportions for two-cylinder = .71, and for three-cylinder = .79). Individual t tests comparing proportion correct with chance responding showed better than chance performance for each array type: for two-cylinder condition (with $p = .50$), $t(11) = 2.19$, $p < .05$, and for the three-cylinder condition (with $p = .33$), $t(11) = 6.57$, $p < .005$. In the three-cylinder array, the infant was always equidistant between two cylinders, hence more distant from the third. Assuming that infants will never search in the more distant cylinder, chance probability of success was .50, rather than .33. Using this adjusted probability level, infants still performed better than chance ($p < .05$).

Discussion

The infants were able to determine the location of the hidden object after their own sideways translation in space, searching for the correct cylinder on a significant proportion of trials. Performance was high even though the competing choice occupied the egocentrically defined location where the infants had searched during training. When a hidden object was located within the visual field at test time, infants readily appeared to account for their own simple translation through space, finding the target at its correct location.

Taken together with the results of Experiments 1 and 2, these findings suggest that 9-month-old infants are capable of inferring the location of a hidden object after they themselves have undergone a geometrically simple movement through space, as long as the target is somewhere in front of them during the test. These findings are quite different from those of other investigators who have tested infants moving along combined rotation–translation paths. We next turned to the question of whether such combined paths of movement make the task of object relocation more difficult for infants of this age.

Experiment 4: Combined Rotation–Translations

Rotation–translation combinations can take many forms: continuously curving paths, translations followed by rotations, zigzag paths, and so forth. We chose to test two particular combinations: a continuous rotation–translation along a curved path around one side of the object array and a translation through the array along a straight path followed by a rotation (see Figure 3). The former was chosen because it is just the combination that has typically been used in studies of infants' abilities to relocate objects after they themselves have moved (e.g., Acredolo, 1978; Bremner & Bryant, 1985). This particular combination could be especially difficult, however, because it

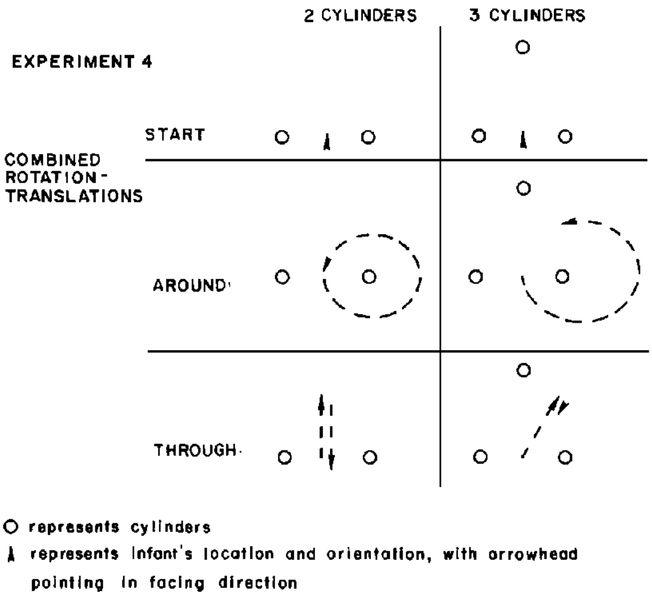

Figure 3. Paths of infants' movement in Experiment 4. (The infants were either moved around the outside of the array along a curved path or through the array on a straight path. Infants who were moved through the array were then either rotated 180° and moved back through the array along the same straight path—two-cylinder—or rotated 180° in place—three-cylinder.)

requires that the infant take account of simultaneous and continuous changes in both orientation and location. The sequential combination of translation followed by rotation was also tested because it does not require simultaneous accounting for the two changes. The choice of the particular combination paths was also guided by the desire to test whether factors other than geometric complexity affected performance. Although the two paths in the present study were equally complex from a geometric standpoint, the curved path was considerably longer, and one would expect mothers to take longer to traverse it. A comparison of these two path types would suggest, therefore, whether path length or movement duration affected search performance.

Method

Subjects. The 6 boys and 6 girls in Experiment 4 had a mean age of 9 months, 15 days (the range was 9 months, 3 days to 9 months, 29 days).

Materials, design, and procedures. Each infant was tested on the two-cylinder linear and the three-cylinder triangular array and was moved either around or through the array.

In the around condition, mothers were instructed to move their infants from the starting point around the outside of the triangular (three-cylinder) or linear (two-cylinder) array, stopping at the designated test position. These around paths were 26–28 in. (66.04–71.12 cm) long. In the through condition, mothers were instructed to translate their infants through the array along the designated path, rotate them 180°, and, in the case of the two-cylinder array, translate them back to test point (see Figure 3). These through paths were 7.75 in. (19.68 cm) long.

In order to ensure that two cylinders (one containing the object) were equidistant from the infant at test, the shape of the three-cylinder array was slightly modified from Experiments 1 and 2. Infants were seated 11 in. (27.94 cm) from the cylinders to their right and left both before and after movement. This meant that the cylinder in front of them in the three-cylinder array was slightly farther away (19 in. or 48.26 cm) than either of the other two cylinders (11 in. or 27.94 cm). It also meant that on one-third of the test trials, the hidden object occupied this more distant position. This was when the object was hidden to the infants' right and they were moved to the left or when it was hidden to the left and they were moved to the right. Analysis revealed no systematic effects of this test position.[2]

Results

The mean proportions of correct responses for each condition are shown in Table 1. The three-cylinder/around condition elicited the smallest proportion correct (M proportion = .25); the other conditions were roughly equal (two-cylinder/around = .58; two-cylinder/through = .58; three-cylinder/through = .54). Individual t tests comparing performance with chance level indicated that only the three-cylinder/through condition elicited better than chance level performance (for two-cylinder/around, $t(5) = .80$, *ns;* for two-cylinder/through, $t(5) = .57$, *ns;* for three-cylinder/around, $t(5) = -1.33$, *ns;* for three-cylinder/through, $t(5) = 3.00$, $p < .025$.

Discussion

Infants performed poorly when moved over a combined rotation–translation path. In three of the four conditions, they performed at or below chance level, with no systematic differences between around and through paths. This suggests that movement along geometrically complex path types causes difficulties for infants who are trying to keep track of the stable locations of objects. This finding is in agreement with others in the literature that have shown serious limitations on infants' abilities to relocate objects after movement along such paths (Acredolo, 1978; Bremner, 1978).

Comparisons Across Experiments

Infants' performance was poorer over both complex paths than over the simple paths of movement studied in Experiments 1–3. These findings suggest that geometric complexity affects infants' performance, with complex paths being equivalent to each other and more difficult than simple paths, which are equivalent to each other.

This pattern of results is consistent with our principal hypothesis that infants would relocate hidden objects better over

[2] On one-third of the test trials in the three-cylinder condition of Experiment 4, the hidden object was in the cylinder across from the infant. This was slightly farther away from the infant than the other test positions (19 vs. 11 in. or 48.26 vs. 27.94 cm; see Experiment 3, Method). Removing these trials yielded 46% correct compared with 40% for all trials of the three-cylinder array. Assuming now that the infant never searches in the most distant cylinder, chance probability of success is .50 rather than .33. Infants' level of performance is not better than chance using this adjusted probability level. The total percentages correct for Experiment 4 are 52% without these trials and 49% with all trials included. All comparisons across experiments remain the same with or without these trials.

rotations or translations than over combination paths. To test this hypothesis directly, planned comparisons were carried out comparing the mean proportions correct collapsed over array in Experiments 1, 2, and 3 with mean proportion correct in Experiment 4. (For Experiments 1 and 2, the means are proportions correct without behind trials; for Experiment 4, they are proportions correct collapsed over path type.) The results confirmed the hypothesis that combined paths elicit poorer performance than simple paths, $t(44) = 2.86$, $p < .01$. Individual pairwise comparisons showed that infants' performance in Experiments 1, 2, and 3 was in each case reliably better than in Experiment 4, $ts(22) = 3.22$, 3.64, and 3.32, $ps < .01$ (see Footnote 2).

A second question concerned the relative complexity of rotations and translations. On the basis of geometric complexity, we predicted that translations would be comparable with rotations. One could, however, predict that the translations used in Experiment 3 would be more difficult than rotations, on the basis of the view that infants can only account for those movements that they are capable of generating themselves. Although some of the infants in the present studies were crawling, the translations they underwent in Experiment 3 were extensive sideways movements that they would not be expected to execute by themselves at this age. There was no difference between performance in Experiments 1 and 2 compared with that in Experiment 3, which is consistent with the geometric hypothesis, $t(33) = .40$, *ns*. The same result was found comparing performance in Experiments 1 to 3 and 2 to 3, $ts(22) = .35$ and .52, *ns*, respectively.

Before concluding that geometric path complexity affected the infants' performance in these studies, certain nongeometric explanations of the findings must be considered. One concerns the possible effects of path length on the infants' performance. One might imagine that moving infants along a circular path would disrupt performance because the infants move farther than if they are moved on a straight line path or are only rotated in place. A similar explanation concerns the effect of movement duration. One might imagine that the movements along the complex paths took longer to execute and that movement time rather than geometric complexity influenced performance. Finally, the different path types may have differentially permitted fixation of the target, leading to better performance in those cases where target fixation could be maintained while infants were moved. This might have been the reason for infants' especially poor performance on the behind trials in Experiments 1 and 2. Moreover, the more complex path types might have forced the infants to break fixation more often than the simple path types, which, in turn, might have impaired performance.

To evaluate these possibilities, the lengths of the path types, the times required to execute the different movements, and the infants' fixation of the target during movement were measured from the videotaped records. Time to execute a path was defined as the time between the beginning of movement along the path and the point at which mothers positioned their infants and released them. Table 3 shows both the distances and mean times of the different path types. Fixation was judged by a naive observer who did not know about the goal or design of the experiments.

Inspection of the distance and time data suggests that neither variable could have accounted for the infants' levels of performance. In the case of distance, translations are longer than through rotation–translations and almost as long as around rotation–translations, yet they led to better performance than either of the complex path conditions. No effect of path length was found within the complex path conditions, moreover, despite the substantial difference in path length between the around and through paths.

Table 3
Lengths and Times to Execute Different Path Types

	Length (in cm)		*M* time (in s)	
Path type	2-cylinder	3-cylinder	2-cylinder	3-cylinder
Rotation (Experiment 1)	0[a]	0[a]	7.15	5.87
Rotation (Experiment 2)	0[a]	0[a]	7.15	7.60
Translation (Experiment 3)	55.88	55.88	7.48	7.80
Combinations (Experiment 4)				
Around	71.12	66.04	7.31	7.80
Through	19.68	19.68	7.38	6.43

[a] The length of any simple rotation path is 0.

Movement durations were remarkably similar for the geometrically different paths. Correlations were determined for the individual subject's time of movement and percentage of trials correct for each array type and experiment. None of the correlations was significant using either a Spearman rank-order or a Pearson product–moment correlation. The correlations ranged from −.16 to .38 (Spearman's ρ) and from −.26 to .33 (Pearson's *r*, $dfs = 11$, *ns*).

Judgments of fixation showed that only 8 of the 48 subjects ever fixated the target as they moved; 5 of these subjects were in Experiment 4, in which performance was the poorest. These findings cast doubt on the thesis that infants relocated objects by maintaining fixation on the containers. Because fixation can be difficult to judge from videotapes, however, an additional analysis was performed comparing proportion correct for those trials where continuing fixation of the target was possible (whether or not it, in fact, occurred) with proportion correct for trials where continuing fixation was impossible. The trials of Experiment 3 were not included in this analysis because fixation was always possible, eliminating any meaningful comparison.

In Experiments 1, 2, and 4, continuing fixation was possible when the subject's direction of movement was toward the target (e.g., a 180° rotation to the left when the target was hidden to the infant's left, a 90° rotation to the left or right when the target was hidden in front of the infant, or a combined movement toward the right when the target was hidden to the infant's right). Continuing fixation was not possible if the direction of movement was opposite to the target's hiding location (e.g., a leftward 180° rotation away from a target hidden on the infant's right).

The percentages correct for these two fixation conditions were collapsed over both array types within Experiments 1, 2, and 4. The analysis excluded the behind trials of Experiments 1 and 2 in which the target's final position was behind the infant. The t tests for each experiment showed no difference in percentage correct related to fixation possibility, $ts(11) = 1.47$, 1.2, and .45, *ns*, respectively.

Neither time, distance, nor continuing fixation appears to account for the infants' performance, therefore leaving geometric complexity as the prime factor influencing infants' performance.

General Discussion

In three experiments, infants were able to relocate a hidden object after they had moved through space. They showed this ability after undergoing either a 90° or 180° rotation (Experiments 1 and 2) or a translation (Experiment 3), as long as the object to be retrieved was not situated behind them at test time. Infants failed to relocate a hidden object only if they were moved along a geometrically complex path combining rotation and translation (Experiment 4). Across these path types, array configurations were identical or quite similar, object hiding locations and the infants' starting positions were quite similar, and the infants' positions at search time were always equidistant between the hidden object and at least one empty cylinder. Performance could not be explained in terms of the extent or the duration of the movements that the different paths required or the tendency to break fixation of the target during certain movements. It appears that geometric complexity itself influenced infants' performance.

Geometric complexity could influence the spatial performance of infants in either of two ways. First, infants may have greater difficulty perceiving or representing changes of their own position when their movements combine rotation and translation. For example, the human vestibular system responds differently and separately to angular (rotational) and linear (translational) movement (Benson, 1982); combinations of these movements may be more difficult for infants to register. Observer rotation and translation are also specified by different patterns of optical flow (Gibson, 1979): the flow of patterns produced by a combination of these movements may be harder to detect as well. If infants cannot determine how they are moving through a scene without landmarks, they will not know where they are at the end of their movement and will therefore fail to locate objects relative to themselves.

As a second possibility, infants may have greater difficulty relating the arrays seen before and after their own movement if their movement is geometrically complex. When observers undergo a simple rotation, only their orientation changes relative to the array; the array they face after moving, therefore, can be made congruent with the initial array by an inverse rotation. Similarly, the array that observers face after a simple translation can be made congruent with the initial array by an inverse translation. When observers undergo both rotation and translation, however, they change both location and orientation relative to the array, and congruence between the initial and final arrays requires a geometric transformation combining rotation and translation. Even if infants know where they are after a combined movement, they may fail to relocate an object in the array because they cannot mentally rotate and translate arrays at the same time so as to determine which of the cylinders in the final array corresponds to the cylinder in which the object was hidden.

In either case, we may conclude that geometric complexity affects infants' spatial performance in tasks such as the object-relocation tasks used here. For the paths that we examined, infants were able to relocate objects after undergoing geometrically simple movements, but they performed poorly after undergoing geometrically complex movements. Future research may reveal that geometric complexity interacts with other factors, such as the number of rotations, translations, or combinations. The present results offer a foundation for such inquiry into the full range of path parameters that affect object relocation in infancy.

In Experiments 1 and 2, infants failed to search for an object after a simple rotation if the movement left the object behind them. This failure accounted for more than 75% of the errors in Experiments 1 and 2; it occurred both with two-cylinder and three-cylinder arrays and after rotations of both 90° and 180 °. This error is reminiscent of an error reported in other, quite different studies of infants' search. Butterworth and Cochran (1980) reported that 6- to 18-month-old infants generally used their mothers' gaze direction to guide their own visual search for a target, but that they were incapable of doing so if the target was located behind them at test time.

What is the source of these errors? Piaget (1954) and others have suggested that infants are unable to represent objects and places that are out of their direct view. This analysis can be questioned, however, because of recent studies of object permanence (Baillargeon, 1986; Baillargeon, Spelke, & Wasserman, 1984; Spelke & Kestenbaum, 1986). When infants are not required to search for objects, they demonstrate knowledge of both the existence and the location of objects that are out of view. The present studies provide further evidence against Piaget's thesis, because infants were able to account for 180° rotations that resulted in a complete reversal between the visible and invisible regions of the array. The ability to do this provides evidence that infants conceive of space as extending beyond the range of immediate visibility.

These considerations suggest that performance is limited by a constraint on search itself, rather than a limitation on cognitive representations. In infancy, search appears to be confined to the region of space that the major perceptual organs can most readily explore. Because the eyes and the hands are canonically oriented in the front of the body, one can only explore behind oneself by turning and reorienting these organs. This behavior requires a level of coordination that may be beyond the sensory–motor capacities of 9-month-old infants (Piaget, 1954).

These findings on the role of geometric complexity in infants' object relocation help to resolve a persistent conflict in the developmental literature between studies indicating spatial knowledge in infants (McKenzie et al., 1984; Presson & Somerville, 1985; Rieser, 1979) and studies documenting gross errors in infants' spatial performance (e.g., Acredolo, 1978; Acredolo et al., 1984). Errors occur when infants must relocate objects after they undergo geometrically complex movements. Errors are infrequent, in contrast, when infants must relocate objects after undergoing geometrically simple movements (e.g., McKenzie et al., 1984). Whether infants' poor performance after combined rotation–translation movements are due to difficulties in perceiving and representing the movements themselves or to difficulties in transforming the visible array following movement, it appears that 9-month-old infants do possess the foundations of spatial knowledge. They can represent the objective positions of things in space and can locate themselves and objects as they move through space on geometrically simple paths.

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