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# Young Children's Spatial Orientation With Respect to Multiple Targets When Walking Without Vision

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During locomotion, people need to keep up-to-date on their changing spatial orientation so that they can coordinate the force and direction of their actions with their surroundings. In 4 experiments concerning spatial orientation while walking without vision, 4-year-olds and adults viewed 1 or more targets, were blindfolded, were guided to a new point of observation, and were asked to aim a pointer at the target(s). Spatial orientation was assessed as a function of the number of target objects (1, 3, or 5), the complexity of the route walked, and the time delay between last viewing the targets and responding. The number of targets did not influence accuracy. The significant effects of age and route complexity on spatial orientation are discussed in terms of processes involved in visual perception of distance, in sensitivity to proprioceptive information while walking, and in calibration of the scale of vision and proprioception.

When people walk, their distances and directions relative to objects in their surroundings change. The ability to keep up-to-date on such changes limits people's ability to coordinate their actions with the locations of things in their surroundings. This article is about the accuracy with which young children and adults view their surroundings and then keep up-to-date on their spatial orientation while walking without vision or other forms of environmental information. Under such conditions, people can maintain spatial orientation only if they integrate the proprioceptive and efferent information associated with their walking activities with their remembered surroundings as viewed from an earlier point of observation.

Studies have shown that adults can navigate with respect to remembered objects when walking without vision and that the precision of their spatial orientation depends on the distance that they translate and rotate during the walk (e.g., Book & Garling, 1981; Rieser, Guth, & Weatherford, 1987). Theoretically, the study of walking without vision provides a means of understanding the development of perceptual–motor coordination and the processes by which people come to know the calibration of the scale of their actions relative to the scale of their surroundings. When walking without vision to reach a remembered object, how do people know how far they have walked, as specified by the efferent and proprioceptive information, in terms of the self-to-object relation that was visually perceived at the start of their walk?

Methodologically, the comparison of children's walking with vision versus their walking without it is a means of assessing the degree to which spatial orientation while walking with vision is mediated by visual flow and landmark information, on the one hand, and by nonvisual information associated with the biomechanical act of walking, on the other. Practically, it is important to understand walking without vision because deficits in its perception may underlie the deficits in spatial orientation and spatial learning typically observed among congenitally blind children and adults (Hollins, 1989; Rieser, Guth, & Hill, 1986; D. H. Warren, 1984).

The issue-of-how and how well children know the scale of their actions relative to the scale of their visual perceptions is central to an understanding of perceptual–motor development and relates directly to the control of all ballistic acts coordinated with environmental targets (Gibson, 1966; W. H. Warren & Kelso, 1985). For example, when walking with vision, how do people know how hard to jump in order to cross a stream or sink hole? When playing sports, how do people know how hard to throw or kick a ball to reach a goal? Our method of studying children's spatial orientation while walking without vision allows investigation of the early development of perceptual–motor coordination in the context of a locomotor search task that makes sense even to very young children.

## Analysis of Walking Without Vision

When people walk, their distances and directions relative to different objects change at different rates and by different amounts, depending jointly on the object locations and on the properties of the walk. For example, during simple rotation movements by which people change their heading while standing in place, the network of self-to-object distances remains the same while the radial directions all change by a constant that is

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equal in magnitude and opposite in direction to the amount of rotation. During simple translation movements, in which people move along any line without changing their facing direction, the self-to-object distances and directions change at different rates for different objects. The rate of change depends on the initial self-to-object distance and the direction of the walk relative to the object's direction (Cutting, 1986). Spatial orientation while walking without vision implies the ability to keep up-to-date on relatively complex geometric changes such as these.

### *Component Processes*

The task in the present experiments was to show observers one or more target objects arrayed in a room, outfit them with a blindfold and equip the room with a sound system to eliminate their access to environmental flow and environmental landmark information, guide them on a short walk to a new point of observation and ask them to aim a pointer at the target object(s). Consider four of the component abilities that logically must be involved and how errors in each component might affect task performance. First, observers must visually perceive the self-to-target distance(s) and direction(s), and errors of visual perception could cause errors in walking without vision. Adults' visual perceptions seem to be veridical in the 2- to 10-m range (e.g., Purdy & Gibson, 1955; Rieser, Ashmead, Talor, & Youngquist, in press; but see also Foley, 1985; Gilinsky, 1951); however, little is known about the psychophysics of children's visual perception of such distances. DaSilva (1985) suggested that children's visual perceptions are a nonlinear function of actual distance, such that farther distances are foreshortened relative to nearer ones. If this is the case, then in the present task children's errors of walking should increase as a function of self-to-target distance at a greater rate than those of adults.

Second, observers must perceive the route that they have walked from the temporal stream of efferent and proprioceptive information associated with the walk. In situations in which one is passively guided without vision, the proprioceptive inflow includes feedback from the muscles, joints, and vestibular system, and in situations in which one actively guides oneself, it includes the efferent commands directing the locomotion as well. One can imagine systematic errors in observers' perceived walks whereby they might under- or overestimate the distances rotated and translated.

Third, accurate responding depends on how well people know the relationship of the distances walked to the distances viewed from the initial points of observation. Visual perception and locomotor action must be calibrated such that the perceptual–motor system has access to the scale of the visual perceptions relative to the scale of the locomotor actions. Errors in this calibration, for example, overestimating the distance walked or turned relative to the self-to-object distance, would lead to systematic errors in pointing. And fourth, the task involves a working memory to manage the ongoing integration of input from the blindfolded walk with the remembered spatial layout of the surrounding objects. Developmental differences in the rate of decay of the spatial representation would result in differences in accuracy of performance.

### *Models of Perceptual–Motor Coordination*

Given that visual perception, proprioception, the calibration of vision and proprioception, and a working memory logically must be involved in good performance, how might these systems work together? Through what processes do people know how the temporal flow of efferent and proprioceptive information while walking without vision relates in space and time to the remembered spatial layout of their surroundings? Spatial representation theories (e.g., Piaget & Inhelder, 1956; Siegel & White, 1975) provide useful ways of conceptualizing what it is that people perceive and know, but they do not identify the processes through which they come to know it.

We have adopted a perceptual learning view in which we assume that spatial orientation while walking without vision is analogous to and based on spatial orientation while walking with vision. While walking with vision, optical flow specifies the network of changing self-to-object distances and directions (Lee, 1980; Nakayama, 1983). It is already known that optical flow gives rise to variations in postural control and to the perception of self-movement in adults and in infants younger than 1 year of age (Bertenthal & Bai, 1989; Butterworth & Hicks, 1976; Lee & Aronson, 1974). The perceptual learning view stems from the observation that while one walks with vision, the flow of proprioceptive and efferent information associated with locomotion covaries with optical flow that directly specifies how the self-to-object distances and directions change with self-movement. Recent evidence has suggested that adults are sensitive to variations in the covariation of optical flow and efferent/proprioceptive information and that this sensitivity influences their spatial orientation when walking without vision (Rieser, Ashmead, & Pick, 1988).

According to our view, the scale of distance walked (as specified by the biomechanical information) relative to the visible distances to objects in the surroundings is given in this covariation. We assume that people learn the covariation when walking with vision and then act on it when walking without vision. We think it is important to note that optical flow gives rise to a wholistic impression of spatial orientation in relation to one's surroundings as a whole, as if the processing occurs in parallel for the different features of the visual field, not in serial order. If the perceptual learning theory is correct, then walking without vision should give rise to similarly wholistic perceptions. That is, when walking without vision, people should keep informed of the array of changing self-to-object relations, not just their changing relation to a single object.

### *Children's Spatial Orientation Without Vision*

Previous studies have assessed young children's spatial orientation by showing them the location of a single target from one point of observation, occluding the target, actively or passively moving them to a new point of observation, and asking them to localize the target. Several previous studies have compared spatial orientation in lighted situations that were visually homogeneous with situations in which the target location was identified by a well-defined landmark (e.g., Acredolo, 1978; Bremner & Bryant, 1977; Lepecq & Lafaite, 1989; McKenzie, Day, & Ihsen, 1984; Rieser, 1979). These studies have shown that children as young as 6 months of age expect an event to reappear at a location marked by a landmark and that children at least as young as 14 to 18 months of age maintain their spatial orientation in situations without useful landmarks. However, even in such visually homogeneous situations that lack well-defined landmarks, spatial orientation might be mediated by optical flow or by the flow of efferent and proprioceptive information associated with the movement to the new point of observation. Such studies do not demonstrate the calibration of vision with the biomechanical activities of locomotion.

In one study, Rider and Rieser (1988) assessed the spatial orientation of 2- and 4-year-olds with respect to single targets after they walked with and without vision along routes involving two 90° turns. The results were that when walking without vision, both 2- and 4-year-olds localized the target correctly. However, when walking with vision, the 4-year-olds were still more accurate. In contrast, the 2-year-olds were worse when walking with vision; instead of attempting to localize the target directly, they incorrectly localized the direction of the last segment of their route away from the target. Thus, spatial orientation without vision emerges at least as early as 2 years of age, but nothing is known about whether the complexity of the to-be-localized surroundings or of the route walked influences children's performance.

## Design of the Present Experiments

Four experiments were conducted to assess the accuracy of young children's and adults' spatial orientation while walking without vision. In each experiment, subjects studied the locations of one, three, or five target objects. Then, they were outfitted with a blindfold and the room was equipped with a sound system to eliminate their access to environmental flow and environmental landmark information. Finally, subjects walked without vision along a route that involved either one or three 90° turns, and attempted to aim a pointer at the targets from the new point of observation.

### *Dependent Variables*

Typically, accuracy in locating targets is assessed using the unsigned difference in degrees between an observed angle and the true angle. In the present task, however, unsigned errors would not distinguish imprecision in actual spatial orientation relative to the target from a response bias in how people manipulate the pointer, and so it is important to distinguish constant error from variable error (Attneave & Pierce, 1978; Schutz & Roy, 1973). In the present studies, the signed error of each response was assessed by subtracting the subject's response angle from the true angle as measured before testing, and variable errors and constant errors were computed from these. Variable errors (defined as the standard deviation of the signed errors) were computed to assess the precision of each subject's judged distances, for example, whether the angle was judged to the nearest 20°, 10°, and so on. These errors are a measure of the precision of people's spatial orientation and logically could not be contaminated by response biases involved in manipulating a pointer. Constant errors (defined as the average signed error) were computed to assess individuals' tendencies to err by pointing consistently to the left or right of a target's actual position across the repeated trials. In the present test situations, in which subjects walked along relatively complex paths, turning sometimes to the left and sometimes to the right, we assumed that constant errors reflected mainly a left–right bias in how individual subjects manipulated a pointer.

### *Independent Variables*

The aim of this study was to investigate effects of age, number of target objects, and number of turns on accuracy of spatial orientation. Our approach to understanding age differences in performance was to begin by studying the extremes: Adults were studied to assess mature levels of performance, and young children were studied to assess immature levels. Our previous work showed that repeated trials of walking while blindfolded and then aiming a pointer were too demanding for children younger than about 4 years of age (Rider & Rieser, 1988). Thus, 4-year-olds were tested.

Main effects of age in this task could be due to task and response factors (for example, differences in the precision with which people aim a pointer) and therefore could be independent of the precision with which people keep up-to-date on their spatial orientation. To control for this, subjects were asked to aim the pointer at targets from the study position and from the novel, test positions. Both sets of responses involved the same response requirements, but only the responses from the novel test positions involved the ability to keep up-to-date on changes in spatial orientation.

The number of targets was experimentally varied to evaluate the wholistic nature of the updating processes. We assumed that if children or adults tended to keep up-to-date on their changing position relative to the surroundings as a whole, then the number of targets would not significantly influence their responding. Alternatively, if updating occurs in an object-by-object fashion, then subjects' errors may be linearly related to the number of targets in the set.

Finally, the number of turns in the routes was varied experimentally to assess possible age differences in the joint effects of distance of rotation and of translation on accuracy of spatial orientation. If children's perception of the turns and distances walked without vision was distorted relative to adults', then their errors after the longer, more complex walks should be proportionately greater than those of adults.

## Experiment 1

The purpose of this experiment was to assess whether the spatial orientation of young children and adults relative to a single target is similarly affected by the complexity of paths walked. Walks vary along a number of dimensions, including their distances, their temporal durations, the number of changes in direction, and the direction and magnitude of the changes in direction. In this experiment, the more complex paths were longer in both distance and temporal duration and involved more turns than the less complex ones.

### *Method*

*Subjects.* The subjects were eight 4-year-olds (mean age = 4.5 years) attending a private day-care center serving middle-class families, and 8 college students. There were equal numbers of male and female subjects. Two additional children participated but complained about the blindfold and refused to complete the tests.

*Experimental space and equipment.* The tests were conducted in large empty rooms measuring about 5.5 × 5.5 m. Subjects were asked to aim a swivel-mounted pointer that was individually adjusted to waist height to localize a familiar target object. The pointer was a 20-cm dowel mounted above a 360° protractor calibrated in single degrees. The pointer was shaped like an arrow, one end pointed and one feathered, so that the ends would be tactually distinctive. Subjects were asked to aim the pointer by grasping its feathered end and circling around with it until they faced the target.

Vision was eliminated with a standard black "sleep mask" blindfold. People can sometimes see around the edges of such blindfolds, so the blindfolds were individually adjusted to each subject's head size at the start of a session and the occlusive fit was tested until subjects were unable to anticipate obstacles while wearing the blindfolds. Like other quiet rooms, the laboratory provided minimal ambient sounds (for example, those caused by the ventilation system). To make the ambient sounds ambiguous as reference cues, they were tape-recorded and then played through six speakers spaced around the edge of the room. Four adults were tested to make sure that subjects could not use the auditory cues to determine their spatial orientation. These tests consisted of guiding blindfolded adults along an intentionally confusing route for several minutes and then asking them to say where they were by guessing which wall they faced. The subjects all guessed with only chance levels of success, showing that the room's auditory cues per se did not help them maintain their spatial orientation.

*Procedures, routes, and conditions.* Subjects were asked to study a target object from one point of observation. They were then blindfolded and asked to aim the pointer at the target from the study position. This showed that subjects could remember the target location and also allowed us to obtain baseline levels of error. The children all pointed accurately to within 15° of the target during the study-position tests, except for one child on one trial who was shown the target again and for whom the test was repeated. Subjects then viewed the target again to refresh their memories of its location and were blindfolded, guided to a novel point of observation, and asked to localize the target from the novel point. The experimenter guided subjects to the novel point by holding their arm near the elbow and walking with them to it. Children were rewarded with small prizes for completing each trial. The rewards were contingent on completing a trial, not on accuracy of performance.

Altogether, the children participated in eight study-position trials and eight novel-position trials, four after walking a one-turn route away from the study position and four after walking a three-turn route. The simple routes each consisted of one 90° turn, averaged 4 m in distance, and averaged 6 s in duration. The complex routes each consisted of three 90° turns, averaged 11 m in distance, and took an average of 16 s to complete. The route segments were approximately equal in distance, and half of the turns were to the left and half to the right.

To keep the study task simple for the young children, each child needed to learn the name and location of just one familiar target object. Different subjects studied the target in different locations, randomly selected from the set of five possible locations depicted in Figure 1. Different novel test positions were used for the four one-turn routes and the same four were used for the three-turn routes. Each of the novel points of observation was about 3.5 m from the study position. Two were located about 15° to the left and right of the study position, and two were located about 40° to the left and right, as depicted in Figure 1.

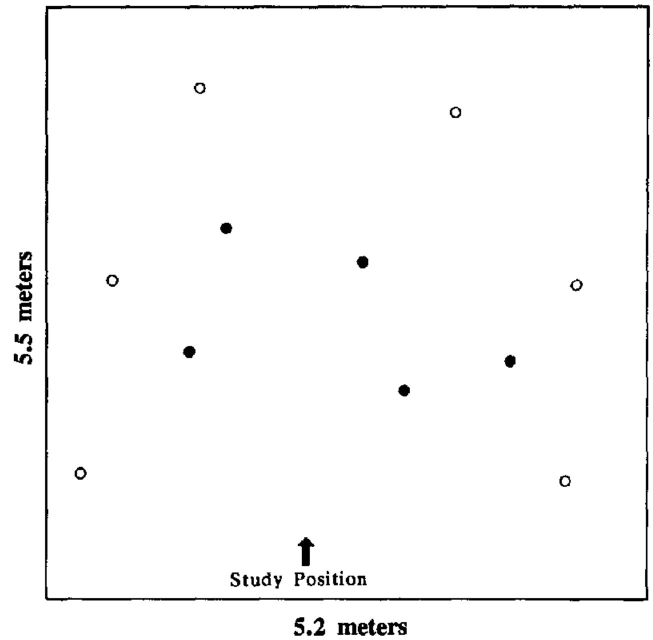


*Figure 1.* Location of the study position, six novel places of observation (open circles), and five target locations (filled circles).

## Results and Discussion

Unsigned errors might be misleading measures of accuracy. Given that the repeated trials in the present task involved collections of turns to the left and right, a systematic bias to err in one direction would likely reflect a motor response bias. Instead of averaged unsigned errors, variable errors were computed to assess the precision of subjects' spatial orientation independent of the possibility of a directional response bias. These variable errors were calculated for each condition as the standard deviation of each subject's four signed errors. Empirically, the variable errors were very highly correlated with the averaged unsigned errors. Constant errors were computed to assess the magnitude of the left or right response bias and were calculated as the mean of each subject's four signed errors in each of the conditions of the experiment.

For the study-position trials, the average magnitude of the constant errors was 10° for the children and 8° for the adults; in the novel-position trials they averaged 25° and 22°, respectively. Statistical analyses showed that the magnitudes of the constant errors were not significantly related to the subjects' ages or to the number of turns in the routes, but they were significantly larger for the novel-position tests than for the study-position tests.

The averaged variable errors appear in Figure 2. From the study position, the children averaged 11° of variable error ($SD$ = 4) and the adults averaged 6° ($SD$ = 2). Thus, children and adults alike understood the task and were able to aim the pointer with good precision when they knew the target location well. From the novel positions, the children averaged 51° ($SD$ = 22) and the adults 26° ($SD$ = 18). The precision of both groups was much better than chance levels. In this situation, the signed errors of a person responding randomly from the 360 degrees of possible response would form a rectangular distribution ranging from −180 to +180 whose mean is 0° and whose standard deviation (the measure of variable error used here) is 90°. Each group's

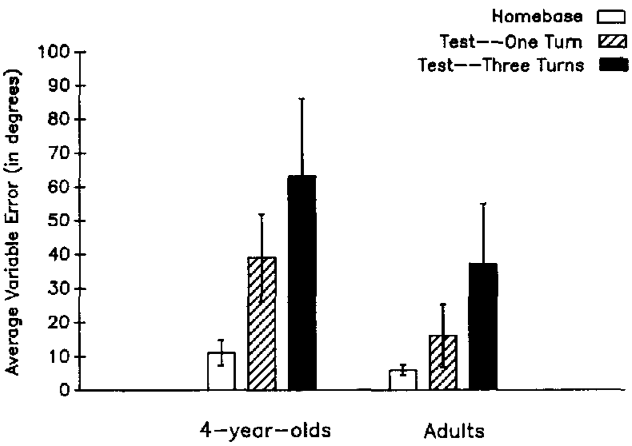


*Figure 2.* Average degree of variable error in Experiment 1 for the 4-year-olds and adults as a function of test location route complexity. (Bars around each mean show the standard deviations.)

error was significantly better than this, the $t(7)$ values ranging from 4.49 to 14.53, all $ps < .001$.

Route complexity and test position were not crossed in the design, so we conducted separate analyses of variance (ANOVAs) to assess the possible interactions of age with test position and route complexity. The Age × Test Position ANOVA showed significant main effects of age, $F(1, 14) = 15.16$, $p < .01$, and of test position, $F(1, 14) = 72.08$, $p < .01$, and a significant Age × Test Position interaction, $F(1, 14) = 5.77$, $p < .05$. This significant interaction could not be due to response factors. It shows that the children and adults localized the targets with similar levels of error at the study position, where subjects knew the targets well, but that the children were significantly worse at the novel test positions. The Age × Route ANOVA showed significant main effects of age, $F(1, 28) = 17.32$, $p < .01$, and of route $F(1, 28) = 15.26$, $p < .01$. The Age × Route interaction did not approach significance. These results indicate that spatial orientation was more difficult for children and adults alike after the more complex routes.

These more complex routes involved more steps and more turns than the simple routes. Either sensory factors or more central processes involved in the spatiotemporal integration of the elements of the complex routes with each other or with the remembered target may account for the main effect of route complexity. What might cause the main effect of age on performance? It cannot be attributed to response factors because the same response factors were involved in performance at the study position and yet the children and adults did not significantly differ there. The age differences may be due to differences in visual perception, forgetting, or spatiotemporal integration.

## Experiment 2

When observers walk, their network of self-to-object distances and directions changes, and the rate of change depends on four variables: the observer-to-target distance, the observer-to-target direction relative to the direction of locomotion, the distance translated, and the distance rotated. With vision, spatial orientation may be more precise when exploring places consisting of many discrete features than when exploring places with few features, because the gradients of flow would be more highly differentiated. If spatial orientation when walking without vision is analogous to orientation when walking with vision, the same pattern may be true. On the other hand, because the self-to-object distances and directions change at different rates for objects located in different parts of the field, it may be computationally more complex to maintain spatial orientation relative to multiple targets than to a single target. Experiment 2 was designed to evaluate this issue.

Logically, whether keeping up-to-date on spatial orientation is more difficult for multiple targets than for single targets depends on the processes and representations used. For example, observers may tend to encode targets individually: To keep up-to-date on their spatial orientation while walking without vision, they may follow the strategy of focusing attention on a single target, keeping track of it, and neglecting the others (e.g., Acredolo, Adams, & Goodwyn, 1984). If this is the case, then observers should perform better when responding to single-object arrays than to multiple-object arrays. Alternatively, observers may encode the space wholistically and keep up-to-date on their position relative to all of the elements of the array in a parallel fashion while walking (Huttenlocher & Newcombe, 1984). If this is the case, then observers should perform similarly well when responding to single-object and multiple-object arrays.

Nothing is known about the effects of the number of targets on young children's spatial orientation when walking without vision. Earlier research has indicated that number of targets does not influence adult performance under similar conditions using similar methods. For example, Lindberg and Garling (1981) asked adults to localize a single target or three targets after walking without vision and found that the number of targets did not significantly affect their error, which averaged about 14°. Similarly, in work conducted across different experiments, adults walked simple routes without vision and localized items from single-target sets (Rieser, Guth, & Weatherford, 1987) and five-target sets (Rieser, Guth, & Hill, 1986); the errors in both cases averaged only about 15°. However, it may be the case that adults discover and use strategies that enable them to keep track of multiple targets and that young children, lacking such strategies, show an effect of environmental complexity.

### *Method*

*Subjects and design.* The subjects were 24 four-year-old children (mean age = 4.5 years, range = 4 to 5 years) and 24 college students, all recruited as in Experiment 1. In addition to age, the experimental design included number of target objects (one, three, and five) and test position (study position and novel position, with repeated measures on test position). All subjects were tested at the study positions and then again after walking one-turn routes to the novel positions. Subjects were randomly assigned to participate in either the one-, three-, or five-target condition so that equal numbers of male and female subjects were in each condition. Each subject completed six trials each at the study and the novel test positions.

*Experimental space and procedures.* Subjects were tested at their respective schools in quiet rooms that were unfamiliar to them, and they were asked to learn and localize either one, three, or five target objects. Altogether, a single study location, six novel test locations, and five target locations were defined in each test room. Common household objects served as the target objects, which were located on waist-high tables scattered throughout the room. During the study phase, subjects could see all of the target objects to be included in their condition, but the novel test locations were not identifiable.

Subjects were individually tested in study and test phases like the subjects in Experiment 1. During the study phase, subjects studied the target(s) from the single study position and were then tested from the study position while blindfolded. Two of the 4-year-olds each produced one error larger than 15° and so were asked to study the target location(s) again. The routes walked all had one 90° turn, varied from 1.8 to 4.9 m in distance, and averaged 6 s in temporal duration.

Subjects in the one-target condition were asked to aim the pointer when the single target was named. Subjects in the three- and five-target conditions were asked to aim the pointer when one of the targets was named; the particular target was not predictable until it was named after the walk. After localizing a single target on each trial, the still-blindfolded subjects were guided back to the study position, and the tests were repeated as in Experiment 1. In the one-target condition, the same single target was named in each of the repeated trials. In the three- and five-target conditions, the to-be-named target was randomly selected from the set, with the constraint that the same target was not named on two consecutive trials.

### *Results and Discussion*

Constant errors were calculated across the six repeated trials for each subject in each condition, and their absolute values were analyzed to assess differences in magnitude of left versus right bias in aiming the pointer. For the study-position trials, the children averaged 6.9° of error and the adults averaged 3.6° of error, and at the novel position, the children averaged 13° and the adults 5.8°. ANOVAs on the absolute values of the constant errors showed that the children's 10° overall average constant error was significantly larger than the adults' 5°, $F(1, 42) = 8.14$, $p < .01$, and that the average 9° constant error for all subjects at the novel positions was significantly larger than the 5° bias at the study position $F(1, 42) = 4.69$, $p < .01$. Neither the main effect of number of targets nor its possible interactions approached significance.

The average variable errors produced by the children and by the adults appear as a function of the number of targets in Figure 3. The averaged errors ranged from 5° to 46°; all were significantly better than the 90° error expected by chance, $t(7)$ values ranging from 5.28 to 110.22, $ps < .001$. Thus, both groups localized the targets with better than chance levels of performance in all conditions.

An Age × Test Position × Number of Targets ANOVA revealed three significant effects: age, $F(1, 42) = 50.76$, $p < .001$; test position, $F(1, 42) = 111.62$, $p < .001$; and the Age × Test Position interaction, $F(1, 42) = 30.90$, $p < .001$. As in Experiment 1, the significant Age × Test Position interaction indicates that the adults were more accurate in keeping informed of their changing spatial orientation than were the young children and that this is due to sensory–perceptual–cognitive factors and not to response factors.

It is important to note that neither the number of targets main effect nor its possible interactions with other variables approached significance. This is not consistent with the possibility that observers tend to keep up-to-date on their changing spatial orientation relative to only a single target while walking without vision. Instead, this result is consistent with the idea that observers tend to encode their surroundings wholistically and to keep up-to-date on their spatial orientation relative to the whole array. Alternatively, it may be that the design was not sensitive to the possible effects of the number of targets. For example, because the adults' performance was very good, their near-ceiling performance may have masked an effect of number of targets. To evaluate this possibility, the task was made more difficult in Experiment 3 by increasing the complexity of the routes walked.

## Experiment 3

### *Method*

Number of targets was varied between subjects, whereas test position and number of turns were varied across each subject's repeated trials. To complete part of the design, the Experiment 1 data were used. These data consisted of the eight 4-year-olds and 8 college students who studied single targets and were then tested after following either one- or three-turn routes. To complete the rest of the design, 8 additional 4-year-olds (mean age = 4.5 years) and 8 additional college students participated, all selected through procedures described for Experiment 1. Three additional children were tested but complained about the blindfold and refused to complete the trials. These new groups underwent four repeated tests with the target objects at both the study and novel positions after following one- and three-turn routes. The procedures were identical to those described for Experiment 1, with the only exception being that the new subjects learned the locations of five target objects instead of single targets.

### *Results and Discussion*

Like the results of the previous experiments, the ANOVA of the absolute values of the constant errors showed significant main effects of age and of test position ($p < .05$), indicating that the responses of the younger children showed a larger directional bias than those of the adults and that the responses from the novel position showed a larger directional bias than those from the study position. Furthermore, there were no systematic effects of route complexity or of environmental complexity on the magnitudes of the constant errors.

The averaged variable errors appear as a function of the number of targets and the number of turns in Figure 4. The accuracy of both groups of subjects was consistently better in all conditions than the 90° error expected by chance, as determined by $t$ tests, $ps < .001$. The Age × Test Location ANOVA on the variable errors showed the same significant interaction as in the previous two experiments. In addition, the variable errors were submitted to an Age × Number of Turns × Number of Targets ANOVA: Like the results of Experiments 1 and 2, the main effect of age was significant, $F(1, 28) = 36.14$, $p < .001$, showing that the adults were more accurate than the children. As in the results of Experiment 1, the main effect of turns was significant, $F(1, 28) = 57.52$, $p < .001$, showing that the errors after the three-turn routes were significantly larger than those after the

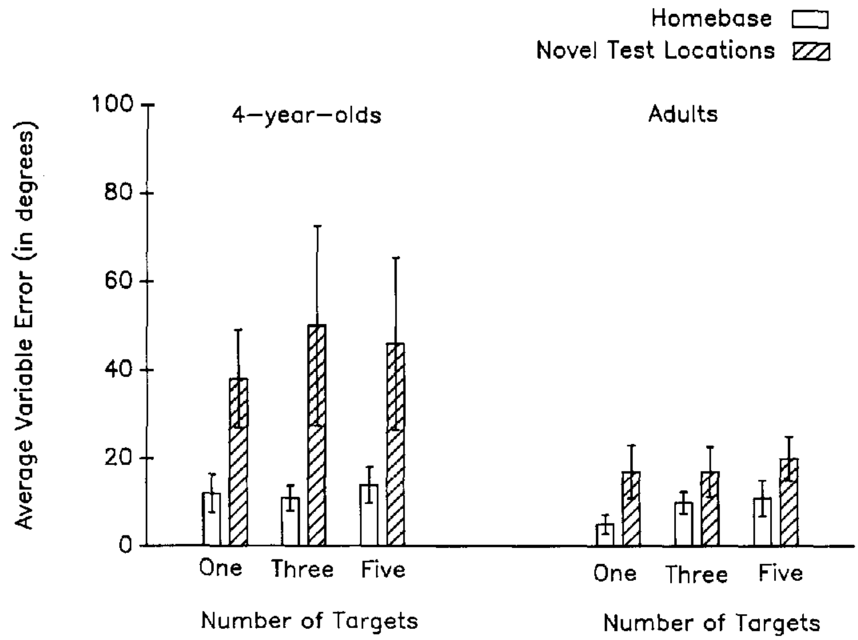


*Figure 3.* Average degree of variable error in Experiment 2 for the 4-year-olds and adults as a function of test location and number of targets. (Bars around each mean show the standard deviations.)

one-turn routes. The magnitude of the effect of turns did not interact with the subjects' ages.

Like the results of Experiment 2, neither the main effect of number of targets nor its possible interactions with the other variables approached significance. Because the means and standard deviations of the variable errors were proportional, a log transformation was applied. However, the ANOVA of the transformed scores yielded the same patterns of effects.

## Experiment 4

Good performance depends on accurately remembering the target locations, and decay in the precision of the underlying mental representation of the targets would thus lead to poor spatial orientation. Experiment 4 was designed to assess the simple effects of time on precision of spatial orientation. In one condition, subjects studied a target, put on the blindfold, and

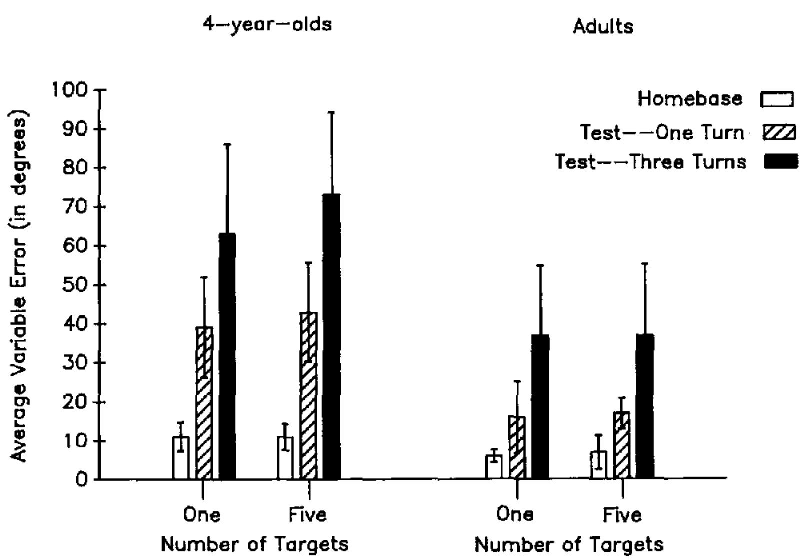


*Figure 4.* Average degree of variable error in Experiment 3 for the 4-year-olds and adults as a function of the test location, route complexity, and number of targets. (Bars around each mean show the standard deviations.)

walked immediately to the novel position and responded, whereas in the other condition they studied the target, put on the blindfold, waited 10 s, and then walked to the novel position and responded.

We had two purposes in mind for running the delay condition: to help clarify the effects of both age and of route complexity on performance in the previous experiments. Regarding the effects of age, consider that children's performance might have been worse than that of adults' simply because of the passage of time from last viewing the target(s) until responding, not because of the walking activity from the study position to the novel test position. This possibility makes sense if one supposes that the children might not have paid attention during the trials and had thus forgotten the target locations or if the children's memories underwent a decay in precision over time. Regarding effects of route complexity, consider that performance was worse on the longer routes than on the shorter ones. Because the longer routes involved more time from last viewing the target at the study position until responding to it at the novel test position, the longer time interval itself may have caused the decline.

### *Method*

The tests were added to the end of the trials from Experiments 1 and 3. From Experiment 1, all 8 of the adults and 5 of the children agreed to participate on simple one-turn routes following a 10-s delay after putting on the blindfold at the study location. Each subject was tested with a single target. From Experiment 3, all 8 of the adults and 5 of the children agreed to participate in the same conditions but with five targets.

### *Results and Discussion*

To compare performances on the no-delay versus delay conditions, $t$ tests were used. For children, the average score of 44° ($SD$ = 12) for the no-delay condition did not significantly differ from the 46° ($SD$ = 11) average for the delay condition. For the adults, the 17° ($SD$ = 7) no-delay average did not differ significantly from the 19° ($SD$ = 8) Delay average. Thus, an unfilled time interval per se (from last viewing the targets until walking to a new point of observation and pointing at them) did not significantly influence the children's or the adults' performance.

We should note that the test of spatial orientation required subjects to walk from a study position to a novel test position. The time interval from last viewing the targets until responding was filled with the activity of walking, whereas the time-delay condition in the present experiment was unfilled. This experiment did not evaluate the possible effects of filled intervals on spatial orientation.

## General Discussion

The children and adults maintained their spatial orientation while walking without vision and without other sources of environmental reference information. Both groups exceeded chance levels of accuracy in each condition across the walks, which ranged from about 3 m to 11 m in distance and involved one or three 90° turns. This level of performance was possible only if subjects knew how far (and in what direction) they had walked relative to the remembered visual perceptions of self-to-object distances and directions. The findings across the set of four experiments provide a consistent picture of the effects of the various independent variables and their possible interactions. The meanings of these are discussed below.

### *Number of Targets*

When people walk with vision, optical flow specifies the changing network of self-to-object distances and directions simultaneously throughout the field. Adults seem sensitive to their changing position relative to the surroundings as a whole when walking with vision. However, spatial orientation while walking without vision might be mediated by using a strategy of mentally tracking individual targets. If this were the case, then errors in spatial orientation would be expected to increase as a function of the number of targets. The number of targets did not exert a statistically significant effect. This suggests that both groups perceived their changing spatial orientation with respect to their surroundings as a whole when walking without vision, without needing to focus their attention on individual target objects.

The experiments may have been insensitive, masking a true effect. We have four arguments against this. First, the presence of other large and statistically significant main effects and interactions (involving test position, route complexity, and age) shows that the design was sensitive to many of the possible effects. Second, null findings were obtained in Experiment 2 in the context of one-turn routes and then replicated and extended in Experiment 3 with both one- and three-turn routes. Third, the same results were found after increasing the power of the statistical analyses by combining data from Experiments 2 and 3; in this analysis, we combined the one-target and five-target scores from the one-turn routes in Experiment 2 with those from Experiment 3. The resulting difference did not approach significance at the $p$ = .20 level, and the power of the analysis was about .78. And fourth, the lack of an effect of number of targets on adult performance replicates previous research findings of similar levels of error and latency for varying numbers of targets (Lindberg & Garling, 1981; cf. five-target situations in Rieser, Guth, & Hill, 1986, and one-target situations in Rieser, Guth & Weatherford, 1987).

These results do not imply that attention is not involved in spatial orientation while walking without vision. Indeed, one of the present authors often loses his way even while walking with vision when deep in conversation. The implication of the present study is that attention is typically invested in the task of spatial orientation relative to the surroundings as a whole, not relative to single target objects. One's changes in spatial orientation seem to be updated wholistically across the multiple features of the immediate surroundings. This model, involving perception of simultaneous changes in the network of self-to-object distances and directions, is consistent with the present perceptual learning view of spatial orientation while walking without vision and with computational models of the information provided by optical flow.

### *Number of Turns in Route*

The errors of children and adults alike were greater after walking the three-turn routes compared with the one-turn routes in both Experiments 2 and 3. We can rule out visual perception as a possible cause of this effect because the conditions for visual perception were identical for the one- and three-turn-route trials. The three-turn walks involved longer temporal durations than the one-turn walks; if one supposes that the mental representation mediating performance undergoes significant, time-based decay, then the time difference might have caused the effect of number of turns. The results of Experiment 4 showed no effect of an empty delay period on the children's or the adults' performance.

However, the longer delay during the three-turn walks was filled with the activity of walking while being guided without vision. The walking activity may have caused a faster rate of decay than would occur in the unfilled time interval used in Experiment 4. Suppose, for example, that subjects attended to their surroundings during the unfilled interval and thereby maintained their memories of them, whereas they attended to the walk (and not to their surroundings) during the filled interval and failed to maintain a sharp memory of their surroundings. If this is the case, then the effect of route complexity may be due to decay in working memory.

The results of other research with adults can be used to rule out this possibility. The possibility that time- and activity-based decay in mental representations accounts for variations in adult walking without vision has been evaluated in several recent studies. An earlier study by Thomson (1983) indicated that for adults, there is an abrupt decay in the precision of walking without vision about 8 s after last viewing the target. However, a number of recent studies have failed to find this pattern, which is apparently unreliable (Elliott, 1987; Loomis, DaSilva, Marques, & Fukusima, 1988; Rieser, et al., in press; Steenhuis & Goodale, 1988).

For example, to investigate this issue, Rieser et al. (in press) asked adults to stand in an open field, view a target located 2 to 22 m straight ahead, and attempt to walk to its position without vision or other sources of feedback. The precision of their responding was a linear function of the target distance. To evaluate whether the greater error associated with the greater distances was associated with time or with the distance traveled, an empty delay interval was added in one condition, and, in another, subjects were asked to walk faster (thus reducing the time needed to walk the same distances). Like the present study, the results indicated that distance, not time, influenced the precision of responding.

The effect of route complexity could be due to proprioception or to the calibration of vision with proprioception. Suppose that error is a consistent proportion of distances turned, distances translated, or both. If this is the case, then observers' perceptions of their paths of walking will show increasing levels of error as a linear function of increasing distances of turn, or translation, or both, consistent with the results of the present experiments. The present experiments do not let us independently evaluate the degree to which proprioception or the calibration of proprioception with vision contributed to the effect of route complexity. In addition, we do not know the degree to which the effect of route complexity was due to the differences in total distance rotated or translated.

### *Development of Spatial Orientation When Walking Without Vision*

The children maintained their spatial orientation across walks without vision with less precision than did the adults. The results of Experiments 1, 2, and 3 all showed a significant Age × Test Position interaction, indicating that the children and adults responded similarly when tested at the familiar study location and differed significantly when tested at the novel test position. This shows that the age differences were due to differences in how well the groups maintained their spatial orientation when walking without vision and were not due simply to age differences in how well they could manage the requirements of the task. It is important to note that the age groups did not differ significantly in the effect either of number of targets (no effect) or of route complexity (similar, significant effects for both groups).

In light of the present results, let us consider the degree to which the observed age differences might be due to age-related changes in each of the underlying processes, namely, visual perception, proprioception, calibration of vision with proprioception, and working memory. The age effect on the spatial orientation task could be associated with the development of visual perception. A great deal is known about the early development of sensitivity to monocular and binocular cues specifying the relative distances of objects within reach (see Yonas & Granrud, 1985, for a review), but little is known about children's visual perception of the absolute distances involved in locomotion across the present range of 3- to 11-m distances. If, as suggested by DaSilva's (1985) work, children systematically underestimated distances in this range, then they would err in their initial self-to-target distance perception, and this may contribute to the age difference in performance. We need to know more about how errors and imprecision in children's visual distance perception might limit their perceptual–motor coordination.

The age effect may have been associated with the development of sensory processes involved in proprioception and the calibration of vision with proprioception. If children were less precise than adults in their calibration of vision with proprioception, then adults would perceive how far they had walked/turned relative to their remembered surroundings with more precision than children and would thus aim the pointer more accurately. The age effect in spatial orientation may have thus been due to developmental differences in visual perception, proprioception, or calibration. However, the results of Experiment 4 can be used to rule out the possibility that this age effect was due to different rates of decay and to adults' better memories for self-to-target distances and directions, because neither group's performance was significantly influenced by the addition of the empty, 10-s delay.

### *Conclusions*

Developmentalists have long wondered about the origins of perceptual–motor coordination, seeking to understand what is learned and what is innate. The present experiments showed that young children know the scale of their walking actions relative to the scale of their visible surroundings. The relation of these two scales changes whenever the relevant anatomical systems change. For example, as children's legs grow in length and muscle mass, there are corresponding changes in the efferent and proprioceptive information associated with a given rate of walking. In addition, the eyes grow and change in shape. As Banks (1988) showed, these changes result in changes in the relation of optical flow to the eye's physical movements through space. Thus, the relation of optical flow to leg movements while walking changes with age; the development of perceptual–motor coordination depends on children's sensitivity to these changes.

Our perceptual-learning view is that these changes are specified in the correlation of optical flow when walking with the flow of proprioceptive/efferent information associated with the walking. We assume that children, like adults, are sensitive to these changes and act on them when walking without vision. However, this is not to say that there are not innate bases for these adjustments.

Consider two possibilities. One is that perceptual–motor systems are designed to follow the heuristic of searching for such perception–action correlations and acting on them. A second possibility is that there is a hard-wired, biological basis for perceiving the direction of one's movement, whereas experience determines the perception of the speed and distance of one's movement relative to the surroundings. For example, consider walking forward while looking forward versus walking backward while looking forward. The efferent and proprioceptive information associated with these movements would differ sharply. In addition, the former action results in radially expanding patterns of optical flow, whereas the latter action results in contracting patterns. Developmental changes in the anatomy of the limbs or eyes would not alter this or other directional relations, but they would alter the rate relations. Perceptual–motor systems may be configured innately to take such directional relations into account, and perceptual learning may serve to set the relation of the rate of optical flow to the rate of efferent/proprioceptive information.

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## Call for Nominations for *Developmental Psychology*

The Publications and Communications Board has opened nominations for the editorship of *Developmental Psychology* for the years 1993–1998. Ross D. Parke is the incumbent editor. Candidates must be members of APA and should be available to start receiving manuscripts in early 1992 to prepare for issues published in 1993. Please note that the P&C Board encourages more participation by members of underrepresented groups in the publication process and would particularly welcome such nominees. To nominate candidates, prepare a statement of one page or less in support of each candidate. Submit nominations to

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