Journal of Experimental Psychology: General
1992, Vol. 121, No. 2, 210-221

0096-3445/92/$3.00

Visual Experience, Visual Field Size, and the Development of Nonvisual Sensitivity to the Spatial Structure of Outdoor Neighborhoods Explored by Walking

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When places are explored without vision, observers go from temporally sequenced, circuitous inputs available along walks to knowledge of spatial structure (i.e., straight-line distances and directions characterizing the simultaneous arrangement of the objects passed along the way). Studies show that a life history of vision helps develop nonvisual sensitivity, but they are unspecific on the formative experiences or the underlying processes. This study compared judgments of straight-line distances and directions among landmarks in a familiar area of town by partially sighted persons who varied in types and ages of visual impairment. Those with early childhood loss of broad-field vision and those blind from birth performed significantly worse than those with early or late acuity loss and those with late field loss. Broad-field visual experience facilitates perceptual development by providing a basis for proprioceptive and efferent information from locomotion against distances and directions relative to the surrounding environment. Differences in the perception of walking, in turn, cause the observed differences in sensitivity to spatial structure.

When observers explore a place, they often come to know the distances and directions relating its objects, features, and events. Knowledge of spatial structure such as this is useful, providing a basis for launching actions from novel points of observation and for planning actions before reaching the intended launching points. How is it that observers go from the temporally sequenced, circuitous inputs available along walks to knowledge of the simultaneous spatial arrangement of the objects passed along the way? Is visual input along the walk critical to the acquisition of such knowledge? Does a life history of visual experience play an important role in the development of the underlying capacities?

The research and preparation of the report were supported by grants from the National Institute of Handicapped Research, Vanderbilt University Research Council, and the National Institute of Disability and Rehabilitation Research.

We thank Terry Deniston for help testing the participants; Mark Appelbaum and Howard Sandler for help thinking about the statistical analyses; Anne Garing for help editing the manuscript; Daniel Ashmead, Emerson Foulke, and Herbert Pick for critiquing the theory; and anonymous reviewers for sharpening our presentation. Thanks also to the participants and to the many orientation and mobility instructors throughout the southeastern and midwestern United States who helped identify participants and worked to define test areas.

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Studies indicate that blind persons often come to know the spatial structure of a place they have explored by walking, without vision (e.g., Haber & Haber, 1990; Hollyfield & Foulke, 1983; Klatzky, Loomis, Golledge, Fujita, & Pellegrino, 1990; Lockman, Rieser, & Pick, 1981; Worchel, 1951). However, a life history of visual experience appears to facilitate the development of such nonvisual sensitivity to the spatial structure of places visited along circuitous paths walked without vision. For example, studies show deficits in the accuracy of spatial knowledge of adults who were blinded early in life compared with those blinded later in life (Casey, 1978; Dodds, Howarth, & Carter, 1982; Fletcher, 1980; Herman, Chatman, & Roth, 1983; Rieser, Lockman, & Pick, 1980; Rossano & Warren, 1989).

Two things are important to note about this developmental effect. First, early- and late-blinded groups may differ in either type or accuracy of spatial knowledge, or both. Second, the deficit appears to be consistent across groups of early-blinded persons, but it is not evident in the performance of every early-blinded individual. This indicates that visual experience facilitates the rate of development or the speed of learning but that it is not necessary to induce the capacity for learning (Gottlieb, 1976).

Given that life histories of visual experience facilitate the development of nonvisual sensitivity, what is the nature of the formative visual information and what are the processes by which it influences development? To address these issues we assessed the knowledge of spatial structure of partially sighted persons who varied in the age of onset of visual impairment and in the nature of their remaining vision. For some, remaining vision consisted of poor acuity combined with visual fields that were intact. For others, remaining vision consisted of small fields combined with varying degrees of acuity. For about half, vision loss occurred near the time of birth, whereas for the others it occurred later in childhood.

There were practical and theoretical reasons to investigate the spatial learning and orientation of persons with low amounts of vision. Practically, the results of a survey of 94 low-vision persons by Genensky, Berry, Bikson, and Bikson (1979) indicated that many reported disabling difficulties with spatial orientation and others did not. However, the causes of the difficulties are not understood, and the degree to which they vary systematically with the type of visual impairment is not known. Theoretically, the study of the spatial knowledge of persons who vary in age of onset of vision loss and type of remaining vision provides a method to investigate the contributions of life histories of specific classes of visual experience to spatial development.

Perception of Spatial Structure While Navigating Without Vision

Newcomers to an area typically explore it via circuitous routes around buildings and other obstacles to vision and direct travel, and yet they acquire knowledge of the straight-line distances and directions relating some of the objects passed at different times along the way. Whether walking, driving, or operating a wheelchair to explore, observers could come to know the spatiotemporal integration of the different, mutually occluded regions of the place that were explored along circuitous routes by using environmental information, biomechanical information, or both. In some situations, many observers can see directly how two or more objects that are mutually occluded from view are related spatially to a common set of landmarks and use those landmarks as a frame of reference to know the spatial relations of the mutually occluded objects.

However, when walking with or without vision, observers could integrate biomechanical input associated with the biomechanical activity of walking with their memories of objects encountered earlier along a path to know the spatial structure of the objects (Rieser, 1990). Little is known about the processes that underlie such path integration and that link the biomechanical input from one's own actions to one's knowledge of objects encountered along the way. However, studies show that some primate and nonprimate species (e.g. Gallistel, 1989; Mittelstaedt & Mittelstaedt, 1982) use such path integration strategies to maintain spatial orientation. Levine, Jankovic, and Palij (1982) proposed a *cognitive map* description and computer simulation of the processes. In their scheme, a map would be created when biomechanical input is read into the mind's coordinate system; knowledge of a region's spatial structure would then be accessed from the cognitive map by processes that read off the object-to-object distances and directions from it.

Still needed, however, is a theory about the "read into" processes through which observers might know the spatiotemporal integration of biomechanical input from their actions with their memories of objects passed along the way. Logically, observers need to be sensitive to information that specifies the changing self-to-object distances and directions as they walk from object to object. To do this, the underlying system needs access to the calibration of biomechanical input from locomotion against the distances and directions relating objects encountered along the path.

The theory presented here is framed within a perceptual learning model for the underlying processes (J. J. Gibson, 1958, 1966). The model stems from the observation that when observers locomote, the flow of biomechanical input from their locomotion covaries with the flow of the environment relative to them. For humans, environmental flow is specified visually with the most precision and across the most differentiated range of distances, but information is also available from other modalities if the environment provides objects that emit sounds or radiate heat, wind, or odorant.

The covariation of the environmental flow and biomechanical flow created by an individual's action is typically invariant with respect to types and directions of locomotion, whereas it varies across individuals and situations in terms of the relative rates of environmental and biomechanical flow. For example, physical rotations and physical translations result in characteristically different patterns of environmental flow, and the differences are invariant across situations and individuals. Physical translation movements always result in changing self-to-object distances and directions, and the rates of change vary from object to object, depending jointly on the self-to-object distance and the object's directions relative to the direction of locomotion. Physical rotations, on the other hand, typically result in no change in the self-to-object distances and changes in self-to-object directions that are the same for all objects (Rieser, 1989). As another example, the direction of physical actions typically covaries with the resulting direction of environmental flow in an unvarying way. Forward locomotion typically results in radially expanding environmental flow, whereas backward locomotion results in radially contracting flow; leftward locomotion typically results in rightward flow; clockwise rotation typically results in counterclockwise flow; and so forth.

The covariation of the relative rates of biomechanical flow and environmental flow, on the other hand, would show some situation, age and individual specificity. For example, the energy needed to locomote against the wind is greater than with the wind, and the energy needed to locomote uphill is greater than downhill. In addition, the number of steps needed to translate a given distance varies as a function of limb length. Access to knowledge of such regular covariations relating environmental and biomechanical flow could mediate observers' sensitivity to the changing self-to-environment relations when walking without information about the resulting environmental flow per se.

This theory was recently evaluated experimentally by pretesting walking without vision, giving observers experience with rearranged relations of visual-environmental and biomechanical flow, and then posttesting walking without vision (Rieser, Ashmead, & Pick, 1988). If the calibration of walking without vision is influenced by the correlation of visual-environmental and biomechanical input while walking with vision, then observers should err in predictable ways. In one set of conditions, observers were exposed to visual-environmental flow that specified a faster rate of locomotion than their proprioceptive rate. The result was that during the posttests all observers consistently undershot the targets, as if they had recalibrated the distance of each stride. In the other set of conditions, observers were exposed to visual-environmental flow that specified a slower rate of locomotion than their biomechanical rate, and all observers consistently overshot the targets during the posttests.

Views of Spatial Knowledge and Its Development

Nativist and empiricist philosophers have long debated different models of how people come to know spatial structure and how they develop the capacity to know it. Descartes (1637/1965) developed the example of a blind person tactually exploring the features of large objects to learn their shapes. His view was that sequences of tactual impressions were compiled within a single, unifying spatial framework embodying the metric properties of Euclidean geometry. The capacity for such a mental representational framework, he theorized, was an innate property of human minds, not a residue of experience. Berkeley (1709/1965), on the other hand, wrote about the problem of visual distance perception and argued that the capacity resulted from perceptual learning and experience. He theorized that the visual cues themselves could not give rise to knowledge of distances, except through learned associations relating visual cues for distances with tactual cues for the same distances. Tactual input enriches vision, according to this view, and knowledge of spatial structure originates in perceptual learning, whereby observers notice the correlations of different streams of input.

The implication is that age- and handicap-related deficits in spatial knowledge are caused by deficits in the underlying representational capacities. Some contemporary developmentalists follow Descartes and argue that the capacity for such mental representations is innate (Gelman & Baillargeon, 1983; Landau, Gleitman, & Spelke, 1981), whereas others follow Berkeley, arguing that the capacity unfolds during early childhood (Piaget & Inhelder, 1967; Siegel & White, 1975). Framed within a perceptual learning view, whereby observers come to know the covariance of visual-environmental flow during locomotion and the corresponding flow of biomechanical input, development would consist of the onset of sensitivity to the covariance, followed by increases in sensitivity and precision (E. J. Gibson, 1969). According to this view, deficits in knowledge of spatial structure stem from deficits in perception of the changes in self-to-object relations during locomotion.

Gradients of sound, wind, odor, and temperature could specify environmental flow during locomotion. However, unlike the other modalities, vision provides large, highly differentiated views of the structure of space, and mathematical models of the processes through which knowledge of spatial structure could be extracted from optic flow during locomotion have been proposed (Banks, 1988; Cutting, 1986; Koenderink & Van Doorn, 1977; Lee, 1980; Nakayama & Loomis, 1974; Prazdny, 1980). Theoretically, it is important that the environmental flow elements be sampled from across a range of the field and processed in parallel. The reason for this is that the self-to-object distances and directions change at different rates across the different portions of the field, depending on each object's distance from the observer and its direction relative to the observer's locomotion. Because of this, one might suppose that a critical feature of the visual input is that it have a large field. Persons born with small visual fields might tend, according to this perceptual learning view, to be deficient in their knowledge of spatial structure and similar to congenitally totally blind persons. Low levels of acuity, on the other hand, do provide optic flow fields under high-contrast conditions, and congenital deficits in acuity should not lead to deficits in the development of knowledge of spatial structure. This model of development is focused on processes of perceptual learning like those espoused by Berkeley (1709/1965). However, unlike Berkeley, vision is thought to enrich proprioception, not to be enriched by it.

Design

The theory presented here is developmental: It implies that a life history of broad-field vision early in life, not high-resolution vision, facilitates the development of sensitivity to spatial structure of locales explored by walking. This theory was tested using naturally occurring groups of subjects who varied in type of partial vision and age of onset of partial vision loss. The resulting four groups consisted of persons with early- versus late-onset poor acuity (with normal fields) and early- versus late-onset small fields (with varying degrees of acuity). We predicted a significant onset by vision type interaction in which the early-onset poor-field group's performance would be deficient compared with the other groups.

Two additional groups were included to identify baseline levels of performance obtainable under the extreme range of conditions. A group of sighted persons was included to identify the optimal level of performance, obtained from individuals with life histories of normal vision who received normal visual input while exploring the test space. The life histories of the late-onset groups included normal vision, but the groups had only partial vision of the test spaces. It may be that either high-resolution or broad-field views while exploring the test spaces, or both, facilitate the acquisition of spatial knowledge, even over the long-term course of learning home neighborhoods. This possibility was addressed by comparing the performance of the late-onset partially sighted groups with that of the sighted group. At the other extreme, a group of congenitally totally blind persons was included to identify the level of performance expected in the absence of all visual input and experience. It may be that life experience consisting exclusively of either low-acuity or small-field partial vision, or both, facilitates development of nonvisual sensitivity compared with life experience without vision. This was addressed by comparing the performance of the early-onset partially sighted groups with that of the congenitally blind group.

This naturally occurring-groups design is one where the levels of the independent variables, type of partial vision and age of onset of vision loss, were selected, not randomly assigned. A general limit of such designs is that the individuals in some groups may differ systematically from those in others beyond the intended nominal differences in type and onset of partial vision. We attempted to control for this by selecting subjects who were roughly equivalent in terms of numerous criteria and by measuring other potentially relevant characteristics and analyzing statistically their effects. For example, individuals were assessed on their knowledge of their own neighborhoods, which were relatively large, complex, and navigated regularly in the course of regular activities. The individual neighborhoods varied somewhat in size and complexity, and the individual subjects varied somewhat in the frequencies with which they navigated their respective neighborhoods. Logically, size, complexity, and familiarity could influence spatial knowledge and potentially confound group differences in age-of-onset and type of vision loss. We controlled for such possibilities statistically by assessing size, complexity, and familiarity and investigating their possible effects through analysis of covariance.

By knowledge of the *spatial structure* of place we mean the accuracy with which observers can judge either the straight-line directions or distances relating the different features of place, or both. To assess subjects' knowledge of spatial structure, they were asked to judge the straight-line distances and directions relating well-known landmarks in their neighborhoods. Directions were judged via two methods to help control for their respective advantages and disadvantages. One method was for subjects to aim a pointer in the judged direction; the response requirements of this method per se seem to involve relatively little cognitive load but a great deal of manual coordination. The other method was for subjects to judge the direction in terms of an imagined clockface; this method per se seems to involve more cognitive load (to keep the imagined clockface in mind) but requires no manual coordination. Straight-line distances were judged via the method of triadic comparisons. Because some subjects could see and others could not, we elected to assess knowledge in a neutral context. Subjects sat in an office and were asked to bring to mind their knowledge of the test neighborhood and judge the distances and directions relating the landmarks in the remote neighborhood.

Method

Subjects

The participants were 72 adults (42 men and 30 women) tested in their communities in different towns scattered throughout the southeastern and midwestern United States. They included 60 persons with partial vision (39 with early onset) and 6 congenitally blind and 6 normally sighted persons. Participants were selected who (a) ranged in age from 16 to 59 years at the time of the test (M = 26 years, SD = 9 years); (b) matriculated with at least a high school education (all but one, who was progressing satisfactorily while enrolled as a junior in high school); (c) were described by rehabilitation counselors as within normal or high levels of intellectual functioning; (d) showed no handicaps except for vision loss; and (e) could be identified as functionally knowledgeable of an appropriate test area for which city plans were available, having traveled there for about 1 year or longer.

Information about visual impairment was obtained from medical records and confirmed by interviews with the participants and their orientation and mobility instructors (educators specializing in teaching spatial orientation and mobility skills to visually impaired persons). Etiologies varied widely and multiple causes of vision loss were often indicated, including accidental trauma, pediatric disease, retrolental fibroplasia, juvenile diabetes, cataracts, macular degeneration, detached retina, glaucoma, optic nerve atrophy, albinism, and congenital toxoplasmosis. The medical records indicated the age of onset of visual impairment for each participant as well as their tested acuities and visual-field sizes. The low-vision participants were classified in terms of two dimensions of visual experience. One dimension was age of onset of visual loss, which ranged from birth to 37 years. The 39 early-onset partially sighted subjects lost partial vision before 3 years of age. (For 37 of these subjects, the onset was listed as at birth, and for 2 subjects, at 2 years.) The 21 late-onset subjects lost partial vision after 5 years of age. (For 17, the onset was listed as after 10 years of age.) It is important to note that different individuals may first report vision difficulties at differing levels of severity and that vision loss is often progressive in severity.

The vision of 40 participants showed deficits in acuity combined with normal visual fields. For the early-onset acuity loss group (n = 31), the average acuity was 20/322 (SD = 187) and for the late-onset group (n = 9), average acuity was 20/293 (SD = 211). The vision of 20 participants showed deficits in visual fields combined, in many cases, with deficits in acuity. The early-onset field and acuity loss participants (n = 8) had an average acuity of 20/176 (SD = 152) and a visual field of 20° (SD = 14). The late-onset field and acuity loss participants (n = 12) had an average acuity of 20/282 (SD = 368) and a visual field of 16° (SD = 8). In addition to the partially sighted participants, 6 congenitally totally blind and 6 normally sighted observers participated.

Procedures and Experimental Spaces

Participation was enlisted with the aid of many agencies providing services to blind and visually impaired persons throughout the southeastern and midwestern regions of the United States.[1] A sample experimental space is depicted in Figure 1. Orientation and mobility instructors who at the time were providing services to each individual participant were asked to select as a test area a rectilinear outdoor neighborhood that ranged in size from 4 × 6 to 6 × 6 blocks and that served as a major regular travel space for each participant. Instructors identified nine familiar landmarks scattered throughout each area that each participant could travel to independently. City plans for each neighborhood were obtained, and the true angles and distances among the centers of the landmarks were measured from the plans. Measures of the complexity of the test neighborhoods included size and number of intersections. To estimate participants' familiarity with the test space and landmarks, they were asked to estimate the frequency with which they traveled between each of the 36 pairs of landmarks. These scores were summed to identify the rate of monthly visits to the nine landmarks. The result was that participants averaged weekly visits to each of the nine locations used as landmarks. In

[1] The following agencies helped identify participants: Tennessee Rehabilitation Center for the Blind, Nashville; Georgia Academy for the Blind, Macon; Tennessee School for the Blind, Nashville; Arkansas Enterprises for the Blind, Little Rock; Minneapolis Society for the Blind, Minneapolis, Minnesota; Miami Lighthouse for the Blind, Miami, Florida; North Carolina Mecklenberg Association for the Blind, Charlotte; Hillsborough Lighthouse for the Blind, Tampa, Florida; West Palm Beach Lighthouse for the Blind, West Palm Beach, Florida; Kentucky School for the Blind, Louisville; and State of Indiana Services for the Blind, Indianapolis.

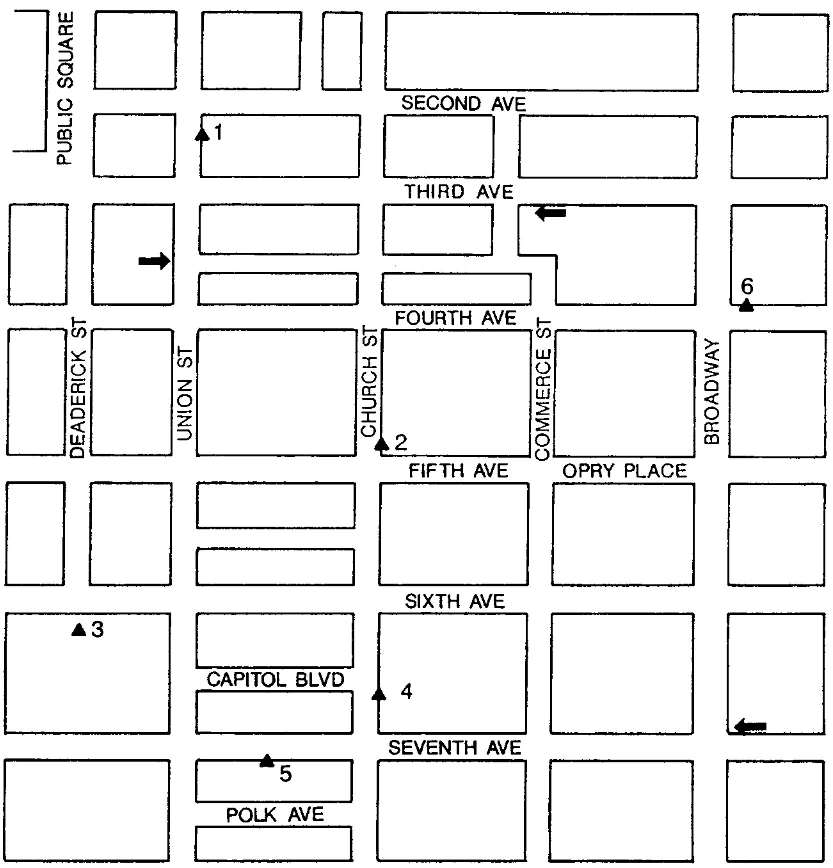

Figure 1. A typical test area. (The large arrows identify the station points. The numbers 1 through 6 identify the target locations [they include a parking ramp, cookie shop, plaza, pedestrian tunnel, restaurant, and arcade]. AVE = avenue; BLVD = boulevard; ST = street.)

addition, ratings of subjects' educational levels and levels of work experience were estimated through interviews and subjects' files. Educational level was rated in these categories: some high school, high school graduate, some college, college graduate, master's degree, and post-master's graduate work. Level of work experience was rated in these categories: never employed, unskilled, semiskilled or clerical, technical, and professional or managerial.

The Pointer Method of Assessing Knowledge of Directions

The tests were conducted by an experimenter in an office located in a local agency or school. During the warm-up phase, the experimental space and the nine landmarks were described verbally, and subjects were encouraged to ask for clarification if needed. In addition, subjects were introduced to a pointer mounted to swivel like a game spinner above a 360° protractor and asked to practice aiming it at objects in the office where they were seated. To practice before the tests, subjects were instructed to imagine standing at a particular point of observation and to aim the pointer at nearby objects in the room. These instructions were delivered verbally, and subjects tried them by imagining they occupied a neighboring room and aiming the pointer at nearby objects. The tester continued to provide feedback and instruction until subjects were satisfied they understood the instruction and aimed the pointer appropriately in the office.

During the test phase, subjects stayed in the office, were asked to call the experimental space to mind, and were asked to imagine standing at a particular landmark while facing in a particular direction within the experimental space. For example, a subject was asked to imagine standing at the entrance to the post office, facing north so that his or her back was against the front door. Facing directions were described redundantly, both in terms of their relation to a physical feature and their compass direction. Three of the nine landmarks were used as points of observation, and the other six were used as target locations. While imagining standing at each of the three station points, subjects were asked to aim the pointer at the six target landmarks in the test area, for a total of 18 test trials. The trials were blocked by imagined point of observation, and the landmarks were randomly interspersed within each block. The angles were recorded to the nearest 2° from the protractor.

The precision with which observers localize the radial direction of a target can be characterized in terms of the unsigned errors, that is, the average magnitude of the errors regardless of their direction. However, others have shown (Attneave & Pierce, 1978; Schutz & Roy, 1973) that unsigned errors can, in some cases, provide misleading estimates of a subject's knowledge of location. The difficulty arises in situations where subjects are biased to err by a constant amount in a constant direction and yet respond with great precision within this constant error. Consider, for example, a hypothetical subject in the present situation who bends his or her wrist while aiming the pointer, throwing it off by a constant amount of 20° to the left.

Supposing the hypothetical subject had exact knowledge of the target locations, the magnitude of his or her unsigned error averaged across trials would be 20°, because of this constant response bias. Now consider a second hypothetical subject, one who used the pointer accurately but whose knowledge of the relative target locations was imprecise, averaging 20° of error distributed to the left and right of the actual locations. Both hypothetical subjects would average 20° of unsigned error, despite the fact that the first had exact knowledge of the spatial structure of the targets, whereas the other had imprecise knowledge.

We wished to assess the precision of subjects' knowledge of spatial structure, not constant biases caused by the method of direction judgment. To accomplish this, the signed error of each response was calculated by subtracting the response angles from the true angles as measured from the blueprints. Constant error and variable error scores were computed from the signed errors for each individual's set of direction judgments. Constant errors indicate a subject's bias to err consistently to the left or right, and scores were computed by taking the median of the signed errors in the judged headings. The absolute values of each individual's constant errors were submitted to further analyses to identify possible group-related variations in the magnitude of leftward or rightward bias in the responding. High constant errors would indicate that subjects tended to err in their aim toward all of the different targets from the three station points in a consistent direction. This could happen, for example, if a person consistently misjudged his or her hand position on the pointer and therefore misjudged the actual direction in which he or she aimed the pointer by a constant.

The precision of knowledge of spatial structure can be directly assessed through the variable errors. They reflect the precision with which the observers judged target directions relative to each other, with the constant error or bias to respond more in one direction than another removed. Variable error scores were computed by taking the standard deviation of the signed errors in the judged headings. In addition, global scores reflecting the averaged unsigned errors were submitted to the same analyses simply to show that the significant patterns of overall error agreed with those found for the variable errors, our measure of knowledge of spatial structure.

The Clockface Method of Assessing Knowledge of Directions

The clockface method is an alternative method of assessing knowledge of spatial structure. It involves a greater cognitive load than the pointer method and was designed to control for the possibility of vision-related differences in skill at the perceptual-motor task of aiming a pointer, independent of differences in knowledge of the directions among the landmarks. The 18 trials conducted using this method were the same as those described for the pointer method, but the response method differed. During the warm-up phase, subjects were asked to think of themselves as centered within a horizontal clockface, facing 12 o'clock so that 3 o'clock lay directly to the right and 9 o'clock directly to the left, and to identify the direction of various objects in their immediate surroundings to the nearest hour on the imaginary clockface. The use of a clockface like this was familiar to most subjects who had experience using it as part of their orientation and mobility training. Subjects practiced this until they responded well and understood the instructions.

Straight-line Distance Judgments by the Method of Triadic Comparisons

Subjects were asked to identify the closest together and the farthest apart pairs for each of the 84 possible triads of the nine landmarks from their test areas, for a total of 168 judgments. Each judgment was scored as correct or incorrect against the actual comparative distances assessed by measuring the city plans, and the error frequencies were tallied.

Results and Discussion

Descriptive statistics for the groups' errors in judging spatial structure appear in Table 1. There were sufficient numbers of repeated trials to compute the odd–even item correlation as an estimate of the reliability of the variable errors of judged directions, the constant errors of judged directions, and the errors of judged distances. The resulting correlations were .82 for the pointer-method variable errors, .82 for the clockface-method variable errors, and .73 for the triadic-comparison method of straight-line distance-judgment errors. The odd–even item correlations for the constant errors, measures of response bias in the direction judgments, were .55 for the pointer method and .45 for the clockface method. In addition, the three measures of knowledge of spatial structure correlated well with each other: .70 for the variable errors from the pointer and the clockface methods and .51 and .54 for the respective variable errors correlated with the distance errors.

Although the subjects were selected to meet general criteria, there were uncontrolled variations in their vision, their familiarity with the respective experimental spaces, and the complexity of the respective spaces. Statistical analyses were conducted to determine whether these uncontrolled variations may have influenced the group differences predicted as a function of vision type and onset. The major prediction is of a significant Vision × Onset interaction in which the early-onset field loss subjects will show less accurate knowledge of spatial structure than the late-onset field loss, early-onset acuity loss, and late-onset acuity loss subjects. It is important to note that all partially sighted subjects had usable amounts of vision while exploring their test neighborhoods. If the early-onset field loss group had the poorest level of visual input while exploring, then this might account for poorer performance. However, this was not the case, as is apparent from the data describing the subjects' levels of vision. The average visual field and acuity scores of the early-onset field loss group were even slightly better, though nonsignificantly, than those of the late-onset field loss group. Similarly, the average acuity of the early-onset field loss group was slightly, though nonsignificantly, better than that of the early-onset acuity loss group.

The uncontrolled variations in the size and complexity of the individually selected experimental spaces and in subjects' familiarity with them could likewise confound group differences. These were assessed empirically, and the groups' scores appear in Table 2. To control statistically for their possible effects, the analysis of the errors in judging spatial structure included a series of analyses of covariance, in which the size scores, complexity scores, and familiarity scores were treated as covariates in the ordinary Vision × Onset × Gender design. In no case did the covariates confound the interpretation of the predicted effects. The remainder of the statistical analyses reported are the results of the Vision × Onset × Gender analyses of variance (ANOVAs) of the partially sighted subjects and appropriate planned comparisons with the blind and sighted baseline groups.

Table 1
Group Means and Standard Deviations for Errors in Judging Spatial Structure by Three Methods

Group	Pointing error: Variable	Pointing error: Unsigned	Clockface error: Variable	Clockface error: Unsigned	Triadic comparison distance error
Early-onset loss					
Field loss					
M	81	74	81	67	63
SD	25	35	28	22	15
Acuity loss					
M	33	29	33	26	43
SD	19	22	16	13	17
Blind					
M	55	42	60	50	51
SD	18	15	20	22	7
Late-onset loss and normal vision					
Field loss					
M	29	23	27	25	46
SD	11	8	13	9	12
Acuity loss					
M	35	34	27	30	39
SD	21	25	24	17	11
Normal vision					
M	21	17	20	18	33
SD	6	6	5	3	7

Note. Errors for the pointing and clockface methods are in degrees; triadic comparison distance errors are in frequency.

Knowledge of Directions Assessed by the Pointer Method

Consider first the overall accuracy of subjects' responses, and then consider variations in accuracy of their knowledge of spatial structure as a function of vision type, age of onset, and gender. Overall, the subjects judged the landmark-to-landmark directions with much better than chance levels of accuracy, although some individuals did not. Observers with no knowledge of the test area would select their responses at random. The best single measure of the accuracy of the subjects' responses is the unsigned error averaged across the repeated trials. Randomly generated responses would average 90° in overall, unsigned error. The partially sighted subjects' 35° average response error ($SD = 28$) was significantly more accurate than the responses expected by chance according to t test; this was the case for each of the groups as well ($ps < .02$). The best measure of subjects' knowledge of spatial structure is the variable error, which averaged 39° ($SD = 25$) over all partially sighted subjects, and the constant errors averaged 16° ($SD = 26$). Group means for the variable errors appear in Table 1.

Table 2
Means and Standard Deviations as a Function of Vision and Onset for Features of the Experimental Spaces

Group	Surface area (in 100,000 ft^2 [12,321 m^2])	Complexity (no. of intersections)	Familiarity (frequency of visits per landmark per month) *M*	*SD*
Early onset				
Field loss	29.5	28	11.0	7.5
Acuity loss	42.5	27	8.7	6.7
Late onset				
Field loss	56.0	37	4.4	5.7
Acuity loss	45.9	29	3.9	5.0

To assess the Vision × Onset interaction on the accuracy of participants' knowledge of the spatial structure of their respective test neighborhoods, the variable errors were submitted to a Vision × Onset × Gender ANOVA. The constant error scores were submitted to the same analysis for evidence of possible group differences in bias when judging directions. As a check, the averaged unsigned errors were analyzed as well; because the patterns of significant effects for the unsigned errors and the variable errors were the same, only analyses of the latter are reported.

For the variable errors, the Vision × Onset interaction was statistically significant, $F(1, 52) = 17.41$, $p < .001$. None of the possible effects of gender approached significance at the $p < .10$ level; the main effects of onset and vision were both significant at the $p < .01$ level. Follow-up t tests showed that the source of the interaction was the poor performance of the early-onset field loss group, which was significantly worse than that of the other groups ($ps < .001$), which did not significantly differ. In addition, t tests were used to compare the baseline performance of the sighted subjects ($M = 21°$, $SD = 6$) and the congenitally blind subjects ($M = 49°$, $SD = 15$) with that of the partially sighted groups, all at the $p < .05$ level. The early-onset field loss group was significantly worse than the sighted group, and none of the other partially sighted groups significantly differed from the sighted group. On the other hand, all of the partially sighted groups significantly differed from the congenitally blind group. Of these, the late-onset field, early-onset acuity, and late-onset acuity groups all performed significantly better than the congenitally blind group. The early-onset field loss group performed significantly worse than the congenitally blind group. This effect was unexpected; its reliability and alternative explanations are presented in the General Discussion section.

The degree to which individuals tended to err across their repeated trials by pointing consistently to the left (or right) of the target is assessed by the constant-error scores. There was no systematic tendency to err toward the left or right across the members of any group. To assess whether the magnitude of the errors, regardless of their direction, varied across the groups, the unsigned value of each individual's constant error score was analyzed statistically. The main effect of gender was statistically significant, $F(1, 52) = 4.17$, $p = .04$, showing that the 8° ($SD = 7$) average unsigned error of the men was significantly smaller than the 25° (SD = 35) average of the women. None of the other effects on the constant errors approached significance.

Knowledge of Directions Assessed by the Clockface Method

The partially sighted subjects' clockface direction responses averaged 32° ($SD = 20$) of overall unsigned error, which was significantly better than the 90° average expected of a random responder according to *t*-test results; this was the case for each of the groups as well ($ps < .01$). Their variable errors (which appear in Table 1) averaged 39° ($SD = 25$), and their constant errors averaged 8° ($SD = 6$). The variable errors and constant errors for the partially sighted groups were submitted to a Vision × Onset × Gender ANOVA. As a check, the unsigned errors were submitted to the same analysis; because the pattern of significant effects was the same as the pattern for the variable errors, only the latter are reported.

For the variable errors, the Vision × Onset interaction was statistically significant, $F(1, 52) = 24.07$, $p < .001$. In addition, the main effects of vision ($p = .007$), onset ($p < .001$), and gender ($p = .033$) were significant, and none of the other possible effects approached significance at the $p < .20$ level. The main effect of gender showed that the average 32° ($SD = 20$) variable error by men was significantly better than the average 50° ($SD = 28$) error by women. The pattern of results of *t* tests used to compare the partially sighted groups' performance to that of the baseline groups was the same as the pattern for the pointer-method errors. For the constant errors, the Vision × Onset × Gender interaction was significant, $F(1, 52) = 4.56$, $p = .04$. The groups' averages were similar, ranging from 3° to 10°. The *t* tests used to explore the simple effects showed that the interaction resulted from the fact that the 10° average constant error produced by early-onset field loss women was significantly worse than the 3° average produced by the men; the other groups ranged from 6° to 9° average constant errors, and there were no significant differences as a function of gender, vision, or onset.

Knowledge of Straight-Line Distances Assessed by the Method of Triadic Comparisons

Group means for the errors appear in Table 2. The errors were submitted to an Onset × Vision Type × Gender ANOVA. The main effect of onset was statistically significant, $F(1, 52) = 4.26$, $p = .041$, and the major effect of vision type was significant, $F(1, 52) = 6.22$, $p = .015$. The Onset × Vision Type interaction approached significance, $F(2, 52) = 2.07$, $p = .15$, sharing the same general pattern as the direction-judgment errors. None of the other effects approached significance.

General Discussion

The perceptual learning theory presented here is not about the development of the capacity to know and imagine spatial structure. Instead, it is about the capacity to extract knowledge of the spatial structure of places explored without vision from variation in the self-to-object relations while walking. The theory is that experience of broad-field vision facilitates the development of nonvisual sensitivity, increasing the precision of what is known and possibly the rate at which it comes to be known. The theory is supported by the present group-related variations in precision of spatial knowledge shown by the groups of partially sighted subjects.

Visual impairment per se did not significantly influence the precision of observers' knowledge of spatial structure, nor did early-onset visual impairment per se influence precision. The significant Vision × Onset interaction resulted from the significantly poorer performance by the early-onset field loss group relative to the late-onset field loss, early-onset acuity loss, and late-onset acuity loss groups. The pattern of results was very consistent across various measures of error, across the partially sighted men and women, and across various measures of spatial knowledge.

Error in judging directions can reflect error due to imprecision in knowledge of the to-be-judged directions mixed with error due to a bias in use of the response method. The major analyses were based on the variable-error scores, which reflect imprecision in spatial knowledge independent of possible constant bias. However, exactly the same pattern of significant effects was obtained for the averaged overall (unsigned) errors.

In addition, the Vision × Onset interaction was significant for both the pointer and clockface methods of direction judgments, and the errors showed the same pattern, though nonsignificant, for the straight-line distance judgments. The findings did not interact with gender, and the Vision × Onset interaction was consistent for the partially sighted men and women. The findings reflect weak, at most, gender-related differences in performance. Although the men were significantly more accurate on one measure of spatial knowledge (the clockface direction judgments), the differences did not approach statistical significance on the other two measures (i.e., the pointer method direction judgments or the triadic straight-line distance comparisons).

Partial Vision of the Experimental Spaces Resulted in Normal Levels of Sensitivity to Spatial Structure

The late-onset field loss, early-onset acuity loss, and late-onset acuity loss groups performed with levels of precision similar to that of the sighted group. The present results show that neither large field vision nor high resolution vision while exploring a neighborhood on foot is a necessary basis for coming to know the neighborhood's spatial structure with the levels of accuracy typical of normally sighted explorers. It may be important to note that we assessed people's knowledge of the neighborhood after they were already very experienced at traveling independently within it; therefore, although large-field vision, high-resolution vision, or both, do not appear to facilitate the level of knowledge achieved after great familiarization, they may facilitate the rate of learning.

Early-Onset Small-Field Vision Resulted in Deficient Sensitivity to Nonvisual Information for Spatial Structure

The early-onset field loss group, like the congenitally blind group, showed significantly less precise knowledge of spatial structure than the other groups. Their deficient visual input per se could not have caused the deficit, given the relatively good performance of the late-onset small-field group, whose vision at the time of test was comparable. Instead, we believe this result reflects a developmental phenomenon: The history of normal vision experienced by the late-onset individuals apparently facilitated the development of sensitivity either to nonvisual information or to information available to those with small visual fields.

Most of the small-field individuals also had below-normal levels of visual acuity, creating the possibility that individuals born with small fields of vision combined with good acuity may typically develop normal levels of sensitivity. Because the levels of acuity among the members of the early-onset small field group ranged from 20/25 to 20/480, we were able to investigate this possibility empirically by correlating their acuities with performance on the tasks. There was no evidence to support this possibility. For example, the individual with 20/25 acuity showed the seventh (out of a possible 8) lowest score on the pointer-method measure of direction judgments and the fourth lowest on the clockface-method. The simple correlations were below .15. Furthermore, the covariate analyses show that their poor performance was not due to uncontrolled variations in the size, complexity, or subject familiarity with the experimental space (assessed through frequency of travel to the landmarks).

We selected subjects who were all judged by rehabilitation workers to be of average or above-average intelligence; nonetheless, it might be the case that the early-onset field loss group had the lowest level of intelligence. Analysis of the ratings of educational level and work experience showed that this was not the case. The critical comparison was made between the early-onset acuity loss and early-onset field loss groups, which showed nearly identical distributions. The late-onset groups showed somewhat higher ratings on educational level and work experience, but contingency table analysis showed that the difference was nonsignificant. Thus, we could find no ways in which the members of the early-onset small field group differed from the members of the other groups, except for the differences in either onset or type of visual impairment, or both.

Does the deficient performance of the early-onset small-field group reflect a lack of sensitivity to the information available within the small-field visual input or to that available in the nonvisual input while walking? Consider the support for each alternative in turn. Impoverished visual input per se might provide a sufficient basis for coming to know spatial structure while walking. For example, we know from observing and interviewing low-vision persons with acuity below 20/1,000 that under high-contrast conditions they detect large surfaces and experience compelling flow fields while walking (Long, Rieser, & Hill, 1990). In addition, people with small fields of vision can systematically scan regions of their surroundings to see how their different parts relate spatially. Given this, it may be the case that the life history of normal vision earlier in life improves the processing of the small-field, poor-acuity input.

Although this is possible, we believe the present findings, together with earlier findings about the sensitivity of totally blind persons, reflect differences in sensitivity to the nonvisual information. The argument depends on the comparability of the differences between the early- versus late-onset small-field subjects in the present study and the differences between early- versus late-blinded persons in the present study and earlier ones (these are briefly reviewed in the introduction). Like the early-onset small-field subjects in the present study, the early-onset blind subjects in the present study and those in earlier studies tended to perform poorly when judging the structure of large places. In addition, like the late-onset small-field subjects in the present study, late-onset blind subjects in earlier studies tended to perform well on similar tasks. Neither the poor performance often produced by early-onset blind persons nor the good performance often produced by late-onset blind persons could be mediated by sensitivity to visual information. We assume that the similar patterns of early- versus late-onset performance for visually impaired persons who are totally blind and for those with small fields of vision reflect the effects of similar processes, namely, those involved in sensitivity to nonvisual information.

The early-onset field loss group produced significantly larger errors than the congenitally blind group when judging directions via both the pointer and the clock face methods. Although unexpected, these results indicate that the different levels of error may reflect true differences in sensitivity, because they cannot be explained in terms of corresponding differences in the uncontrolled variables: The groups were very similar in age, levels of work experience, educational levels, and frequencies of visiting the landmarks, and the experimental spaces were very similar in size and complexity.

Although our perceptual learning model of the processes underlying good performance did not lead to the prediction of worse performance by the early-onset small-field group compared with the early-onset blind group, this finding is not inconsistent with the model. Why might early-onset small-field vision interfere with the development of nonvisual sensitivity? It would make sense if one makes three working assumptions. One assumption is that small-field visual input does not provide a sufficient basis for calibrating the environmental consequences of locomotion. A second assumption is that in the absence of vision the system may attempt to calibrate locomotion on the basis of nonvisual information about the rate of environmental flow. A third assumption is that the system may be biased to calibrate locomotion against visual input, even if it consists of small-field input that is insufficient.

It is interesting to note that 20 years ago or more, rehabilitation practitioners would often blindfold partially sighted persons when attempting to teach important skills to adapt to their partial vision loss. Barraga (1976) forcefully pointed out that partial vision provides information that is potentially very useful. She demonstrated that individuals with partial vision can learn to use their residual vision effectively and argued that they should be encouraged to do so. The present findings raise the additional possibility that it may be useful to supplement such vision training with opportunities to travel while blindfolded, as a means of encouraging acquisition of sensitivity to nonvisual information while walking.

The Role of Large-Field Visual Experience in Development of Nonvisual Sensitivity

The results of the study reported here indicate that the experiences associated with large-field vision, and not high-resolution vision, influence the development of nonvisual sensitivity to nonvisual information for spatial structure. It is important to note that the role appears to be facilitative. It is clear that experience of broad visual fields is not necessary for the development of nonvisual sensitivity, because the early-onset field loss group, like the congenitally blind group, judged the structure of their neighborhoods with better-than-chance levels of precision. It makes sense that people with no experience of broad-field vision would develop sensitivity because of their access to nonvisual (e.g., acoustic, olfactory, temperature, haptic) information during locomotion for the flow of their surroundings relative to their changing position. On the other hand, it makes sense that visual experience would facilitate precision, given that sensitivity to changes in radial direction and distance is greater for optic flow than for nonvisual modalities.

What are the processes through which broad-field vision facilitates the development of nonvisual sensitivity? This study was conducted to investigate some of the empirical implications of a perceptual learning view of development. Our view is that experience of broad visual fields facilitates the integration of nonvisual biomechanical cues while walking a path with knowledge of the objects encountered along the way. The mechanism involved is simply that broad-field vision provides opportunities to notice the covariation of biomechanical activity associated with locomotion and the visible rates of change in self-to-object relations, rates that differ across different regions of the field.

This perceptual learning view is consistent with some earlier views and inconsistent with others. For example, Pick (1974) suggested that visual experience might provide a necessary experiential basis for visualizing or otherwise imagining space. The possibility that visual experience is necessary does not fit with either the present results or evidence from recent studies of visualization (e.g., De Beni and Cornoldi, 1988; Kennedy, 1982; Sholl & Easton, 1986). However, visual experience may facilitate the precision with which spatial structure can be represented or called to mind.

Others (e.g., Millar, 1985; Warren, 1984; Warren, Anooshian, & Bollinger, 1973) suggested that visual experience influences spatial development by providing a representational framework for integrating inputs from different modalities. This view fits well with both the present findings and perceptual learning theory. Finally, visual experience may facilitate spatial development indirectly. For example, Jones (1975) suggested that sighted children may tend to explore their surroundings earlier, more successfully, and more safely than blind persons. The greater amount of exploratory experience with feedback may provide sighted children with more opportunities to acquire general spatial learning strategies. Because we controlled for amounts of experience in exploring the experimental space, we can rule out the possibility that the groups differed in opportunities to learn about the test space. Nonetheless, the subjects may have differed earlier in life, an important possibility that can be evaluated only through yoked control studies where blind and sighted animals are reared with similar life histories of exploratory experience.

The theory presented here is not that visual experience plays a role in the development of the capacity to know or mentally represent spatial structure. Instead, it is that deficits in spatial knowledge can result from deficits in perceptual learning (Rieser, Guth, & Hill, 1986). This instance of perceptual learning is similar to others where observers have been shown to learn the relation of their own movements and the visible effects of their movements. Well-known demonstrations of this general form of perceptual learning include studies with sighted adults of the recalibration of felt limb position after adapting to distorting prisms (e.g., Hay & Pick, 1966; Held & Hein, 1963), the recalibration of retinal disparity after adapting to distorted mappings of disparity and distance through use of a telestereoscope (Wallach, Moore, & Davidson, 1963), and kittens learning to control paw placements through locomotor experience (Hein & Diamond, 1972).

Conclusions

There is mounting evidence that congenitally totally blind persons can imagine the spatial structure of objects and environments and operate on their images of them. For example, Kennedy (1982) has shown that congenitally blind adults both recognize and draw two-dimensional line drawings of three-dimensional objects and do so with little tutoring. Research has shown comparable levels of spatial learning where blind and sighted observers were asked to learn arrangements of objects or features of objects explored by hand, and without locomotion, from one point of observation (Barber & Lederman, 1988; Juurmaa, 1973; Lederman, Klatsky, & Barber, 1985). In addition, research has shown that visual experience influences performance little or not at all in nonvisual mental rotation tasks where similar levels of performance have been observed across congenitally blind and sighted blindfolded persons asked to imagine objects explored by hand rotated into novel orientations (Carpenter & Eisenberg, 1978; Hollins, 1986; Marmor & Zaback, 1976).

We propose that experience of broad visual fields facilitates the calibration of the biomechanical cues for locomotion against distances and directions moved relative to features fixed in the surrounding environment. The theory implies a facilitative effect of broad-field vision on the development of nonvisual sensitivity. Broad-field visual experience appears to either speed up or increase the precision of sensitivity, or both. Congenitally blind persons come to know the spatial structure of places explored by walking. Although generally with lower levels of precision than those with life experiences of broad-field vision, some show levels of sensitivity comparable to those with normal lifetimes of visual experience. How is it that some "expert" congenitally blind individuals make use of the nonvisual information available while walking to achieve high normal levels of sensitivity to spatial structure whereas others do not? Does their expertise reflect a perceptual learning strategy modified to exploit the nonvisual information specifying environmental flow? Alternatively, does it reflect their discovery and use of alternative strategies?

The results of this study indicate that persons who experienced the onset of blindness or of small-field vision early in life tend to be deficient at learning the spatial structure of a place while exploring it. Orientation and mobility instruction is widely available in the United States to blind persons to a much greater degree than most who are partially sighted. The results of this study indicate that some low-vision persons, especially those who experienced the onset of small visual fields early in life, may need services to a degree comparable to totally blind persons.

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Received April 15, 1991
Revision received August 1, 1991
Accepted August 19, 1991 ■