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Navigating without Vision: Basic and Applied Research

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ABSTRACT: We describe some of the results of our program of basic and applied research on navigating without vision. One basic research topic that we have studied extensively is path integration, a form of navigation in which perceived self-motion is integrated over time to obtain an estimate of current position and orientation. In experiments on pathway completion, one test of path integration ability, we have found that subjects who are passively guided over the outbound path without vision exhibit significant errors when attempting to return to the origin but are nevertheless sensitive to turns and segment lengths in the stimulus path. We have also found no major differences in path integration ability among blind and sighted populations. A model we have developed that attributes errors in path integration to errors in encoding the stimulus path is a good beginning toward understanding path integration performance. In otber research on path integration, in which optic flow information was manipulated in addition to the proprioceptive and vestibular information of nonvisual locomotion, we have found that optic flow is a weak input to the path integration process. In other basic research, our studies of auditory distance perception in outdoor environments show systematic underestimation of sound source distance. Our applied research has been concerned with developing and evaluating a navigation system for the visually impaired that uses three recent technologies: the Global Positioning System, Geographic Information Systems, and virtual acoustics. Our work shows that there is considerable promise of these three technologies in allowing visually impaired individuals to navigate and learn about unfamiliar environments without the assistance of human guides. (Optom Vis Sci 2001;78:282–289)

Key Words: auditory distance perception, blind, GIS, Geographic Information System, GPS, Global Positioning System, navigation, navigation system for the blind, path integration, spatial hearing, virtual sound, visually impaired

Our ongoing project, supported by the National Eye Institute, is a combination of basic and applied research. A major impetus for the project was the loss of sight in 1984 by one of us (Golledge), a geographer specializing in the areas of human spatial cognition, behavioral geography (research relating to urban activity and transportation), and Geographic Information Systems (GIS). Another of us (Loomis), a psychologist specializing in perception with side interests in computing and displays, came up with the idea in 1985 of a navigation system for the visually impaired and approached Golledge and others at the University of California, Santa Barbara about the idea. The result of the initial discussions was the formation of a research group, the core of which consisted of the three authors. Klatzky, then a professor at the University of California, Santa Barbara, brought to the project her expertise in memory, cognitive processes, and haptic perception. From the beginning, the primary goal of the group has been to do basic research on spatial perception and spatial cognition relevant to understanding navigation by the visually impaired and to the development of an effective navigation system. This article describes the highlights of our research.

BASIC RESEARCH ON NAVIGATION, SPATIAL COGNITION, AND SPATIAL HEARING

Path Integration in Humans with and without Vision

An emerging view of navigation in humans and other species is that there are two distinct means of keeping track of position and orientation during travel: landmark-based navigation and path integration.[1] In landmark-based navigation, visual, auditory, tactual, and olfactory landmarks provide the traveler with direct sensory information about current position and orientation, often in conjunction with an external map or a cognitive map. In path integration, the traveler uses sensed motion to update current position and orientation relative to some starting point. Path integration constitutes a reliable means for venturing beyond the environment for which one has an internal or external map and facilitates the integration of fragmentary landmark information into a coherent representation of the environment.[1]

Our research on path integration in humans has been primarily concerned with the vestibular and proprioceptive information (including efference copy) that is associated with normal walking. We have focused on these inputs because of our interest in the ability of blind and blindfolded sighted observers to perform path integration without external reference. In real travel, however, the blind have access to much richer information for path integration—for example, environmental sound sources often provide acoustic flow information, and tactually sensed solar radiation, prevailing winds, and general slope of the ground surface often provide directional information that facilitates path integration. Furthermore, for navigation in general, they also have access to various auditory, tactual, and olfactory signals that are informative about specific locations in the environment.

A prototypical task for studying path integration, used in both animal and human studies, is that of traveling from an origin along an outbound path of varying direction and then, at some point on the path, attempting to return directly to the origin. A wide variety of species, among them the desert ant,[2] the dog,[3] the funnel-web spider,[4] the golden hamster,[5, 6] and the rat,[7] have exhibited the impressive ability of returning to the origin of travel solely on the basis of path integration. An organism performing this task might, at a minimum, simply maintain a representation of current orientation and position relative to the origin.[1, 4, 8–11]

Among the major published studies of human path integration,[12–16] the most systematic is one of ours.[14] In the return-to-origin task reported in this study, subjects were passively guided along two legs of a triangle. Upon reaching the end of the second leg, subjects attempted to return unaided to the origin. Vision and hearing were blocked by blindfold and earphones. Twenty-seven triangular pathways were completed by each of 37 subjects; these 27 triangles (Fig. 1, left panel) represent factorial combinations of three values each of the first and second legs (2, 4, and 6 m), and three values of the stimulus turn (60°, 90°, and 120°). The walking trajectories back toward the origin were measured by a computer tracking system; the right panel of Fig. 1 gives the results for an adventitiously blind subject. The failure of the trajectories to converge on the origin (marked by the "X") is typical of the data for the other 36 subjects. Even so, the return responses of the average subject show good sensitivity to variations in the lengths of each leg and in the magnitude of the intervening turn.

Several aspects of the data from this and other experiments reported in the cited study[14] indicate that subjects were not continuously updating position and orientation with respect to the origin but were instead storing in memory the leg lengths and turn angles of the outbound path and then using these stored values to determine the return path. A model based on the configural properties of the outbound path was subsequently fit to the data of the above experiment.[17] This "encoding-error" model makes the assumption that all of the systematic error pattern observed in the data is the result of errors made while encoding the leg lengths and turn magnitude in the outbound path. In particular, the model assumes that the smallest legs and turns are overestimated, the largest legs and turns are underestimated, and the middle values are encoded without systematic error. Leg length and turn are both encoded by linear functions, each characterized by two parameters (slope and intercept). Fig. 2 shows the predicted terminal points for all 27 triangles along with the average terminal points of all 37 subjects, based on the initial response direction and walked distance. With just four parameters, the model is quite successful in accounting for the pattern of average responses for the 27 triangles.

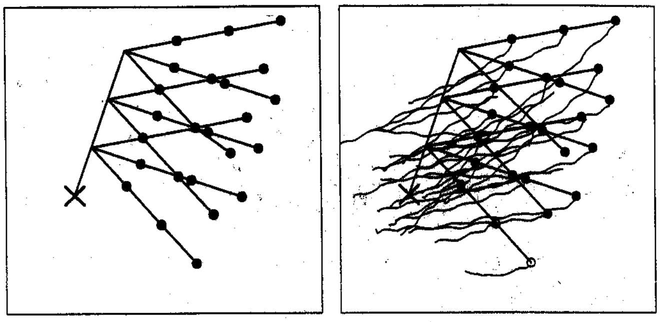

FIGURE 1.

Left panel: The 27 triangles used in a pathway completion experiment[14]. They were created by crossing three lengths of leg 1 (2, 4, and 6 m), three turn angles (60°, 90°, and 120°), and three lengths of leg 2 (2, 4, and 6 m). The solid circles represent the drop off points, at which the subject attempted to walk back to the origin (indicated by the X). Right panel: The computer-measured trajectories of a typical subject attempting to walk back to the origin. All trajectories were complete except for the two associated with the open circles, which were truncated because of loss of camera information. Adapted with permission from Loomis et al.[14]

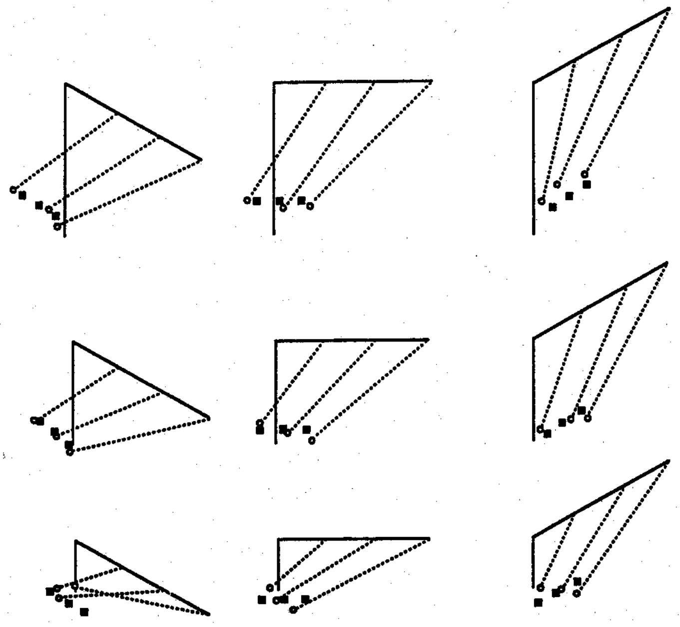

FIGURE 2.

Results of the encoding error model.[17] Each of the panels represents a particular value of leg one (2, 4, or 6 m) and a particular value of turn (60°, 90°, or 120°). The three lengths of leg 2 (the solid horizontal or oblique line) are indicated in each panel. The origin of locomotion corresponds to the lower point of the vertical line (leg 1) in each panel. The open circles correspond to the stopping points of the average subject after the attempted return to the origin (after correction for any veering). The solid squares are the stopping points predicted by the model. Reprinted from Fujita et al.[17]

Other work, however, indicates that the same model fails to predict average performance in pathway completion tasks where the paths have more legs or where the distributions of path parameters are quite different from what they were here.[12, 13] Moreover, it appears that a model like this, in which the path segments and turns are separately encoded in memory, is not appropriate for modeling path integration when the outbound path is continuously turning and hence indivisible into straight segments. Given the restricted applicability of the encoding error model, its main value seems to be in constituting a good initial model, from which more general models might be induced and developed.

In our most recent work on path integration, we have turned to evaluating the informational inputs to the path integration process. In this work, our interest has broadened to include visual input as well. Thus, we have been most interested in these inputs: optic flow, proprioception (including signals from the brain to the musculature), and vestibular signals. In our first experiment,[18] subjects performed triangle completion; auditory information was blocked by the use of earphones. For this work, we used a virtual visual display, which provided binocular optic flow by means of a head-mounted display. In conditions involving visual stimulation, the subject visually experienced movement through a virtual environment consisting of identical vertical posts distributed over the surface plane; this display provided optic flow information about self-motion but no landmark information to permit the return to the origin. In two conditions, the subject walked, while being guided by the experimenter, along the two outbound legs of the triangle; in one of these, the visual display was turned on during the outbound traverse whereas, in the other, it was turned off. Two other conditions (with and without vision) were like the first two except that the subject was moved in a wheelchair over the two outbound legs. Finally, in the fifth condition, the subject remained seated in the stationary wheelchair while receiving only optic flow. In all conditions, the subject then attempted to walk without further sensory input back to the origin (as specified by the sensory information signifying self-motion along the outbound path). The only effect of these manipulations was poorer performance in the vision only condition—subjects showed much greater error in aiming toward the origin.

This result prompted our second experiment on this topic.[19] We hypothesized that although the subject could use optic flow to apprehend the outbound path, the subject's perceived terminal orientation (heading) was the same as it was before the turn because of the dominant influence of vestibular and proprioceptive signals specifying stationarity. This last experiment involved a variant of triangle completion, in which the subject responded simply by facing the direction of the origin. The first leg was 3 m, the second leg was 2 m, and the intervening turn varied from 10° to 170°. Here, we describe the results of three of the conditions in the experiment, all of which excluded auditory information. In the Walk condition, the subjects walked while being passively guided without vision over the first leg, the turn, and then the second leg. The other two conditions were performed with a virtual visual display system while the subject was seated in a swivel chair. Binocular optic flow corresponded to simulated movement through a world of vertical posts, as in the previously described experiment. In the Real Turn condition, the subject was appropriately rotated in the chair while undergoing the stimulus turn, thus receiving vestibular information about the turn along with optic flow. In the Visual Turn condition, the subject remained physically stationary while experiencing the stimulus turn only by way of optic flow. We predicted that in the Walk and Real Turn conditions, both of which involved physical turning of the body, the subject would respond without significant systematic error. For the Visual Turn condition, we predicted that the subjects would fail to update their headings during the turn in the absence of vestibular information and thus would make a directional response (turning to face the origin) with an error equal to the stimulus turn (turn 1). We obtained results very close to our predictions (Fig. 3). Thus, optic flow by itself does not induce automatic updating of heading in the way that vestibular and proprioceptive information does, a conclusion supported by other recent research.[20–23] For reviews of research on path integration in humans, the reader is referred to two book chapters by the authors.[24, 25]

Possible Deficits in Spatial Processing in the Early Blind

For decades, researchers have been interested in whether visual experience is necessary for the development of normal spatial ability; several reviews of this work have been published.[26–29] To address this issue, researchers have typically compared early-blind subjects with late-blind or blindfolded sighted subjects on a variety of spatial tasks. The research indicates that on locomotor tasks involving some spatial inference, early-blind subjects generally perform more poorly than the other groups.[28] Our study[14] is one of the few to find no difference between the early-blind group and the other two groups in such tasks. We performed the comparison

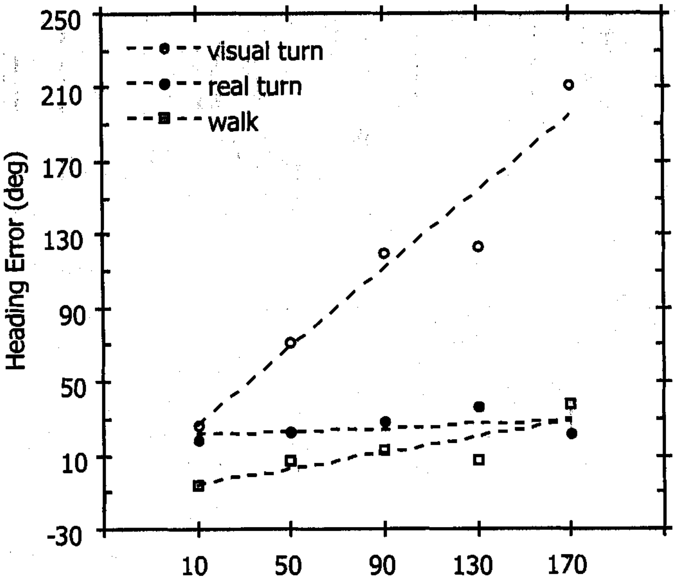

FIGURE 3.

Results of an experiment on path integration.[19] Subjects were guided along the first leg of a triangle, then through the turn indicated on the abscissa (turn-1), and then along a second leg. After completing the second leg, the subject turned through an angle to face the origin. Heading (facing) error is plotted as a function of the magnitude of turn-1. The three conditions are described in the text. Adapted from Klatzky et al.[19]

using two tasks. The first was triangle completion, as mentioned in the previous section. We compared the performance of 12 sighted adults, 12 early-blind adults, and 13 late-blind adults, all of whom wore blindfolds. No differences in performance were observed. The second task, based on one by Rieser et al.,[30] was a more complex spatial task in which subjects had to infer the spatial relationship of six objects. They learned the location of each object in relation to a fixed origin in the room, by walking between the origin and each object while blindfolded. Subsequently, they moved to one of the objects while still blindfolded and had to point to each of the other objects, a response that required spatial inference. Two early-blind subjects showed greater pointing errors than the remaining eight subjects (five sighted and three other early-blind subjects), but these remaining eight subjects performed at comparable levels.

In conjunction with the locomotor tasks of the study[14] described above, we conducted a battery of additional tests with the same blind and sighted populations.[31] Several tasks were performed on the scale of a tabletop. They included estimating the length of the third leg of a triangle after manually exploring the first two legs, assembling a set of tiles to make a simple shape (e.g., making a chevron from two diamonds), and mental rotation (i.e., determining whether two cut-out shapes were congruent within a rotation on the plane of the table). Other tasks involved locomotion, including maintaining a heading while walking in a straight line, estimating or replicating a walked distance, estimating or replicating a physical turn, and retracing a pathway of two or three segments. Across the tabletop tests, early-blind, late-blind, and sighted subjects performed similarly, except that in mental rotation, the blind were more accurate than the sighted. The groups also performed similarly in the locomotion tasks. Although the performance levels for both the locomotion and tabletop tasks were very similar, a multivariate discriminant analysis, based on just two measures, was able to classify subjects into groups (sighted, early blind, and late blind) with above-chance accuracy. However, because only two measures out of many contributed to the classification and because these particular measures seemed rather arbitrary, the analysis gives little support to the idea of systematic differences in spatial ability as a function of visual status. Thus, the fact remains that direct comparisons among groups differing in visual experience, across a wide variety of spatial measures, yielded few differences in our research. Our having selected blind subjects who were independent and mobile in everyday life may have contributed to the nearly equivalent performances of blind and sighted. In their review of the literature,[28] Thinus-Blanc and Gaunet have suggested that strategic differences, potentially modifiable by experience, may underlie at least some of the effects of blindness that have been observed. The selection process in our experiments may have been one that favored blind persons who had developed highly effective spatial strategies.

Auditory Distance Perception

One of our goals for the navigation system for the visually impaired (to be described later) is to help the user develop a mental representation of the spatial layout of buildings and other objects in the environment. Our plan all along has been to convey the necessary information by way of 3-dimensional sound created by a virtual sound display and delivered by earphones. As we conducted research on virtual sound,[32] we became interested in how well people are able to perceive the distances of real sound sources in natural outdoor environments. Until now, very little research has been done on this topic. Thus, we performed research on distance perception using real sounds produced by loudspeakers. In the first of our two studies,[33] we varied the distance of the source from 2 to 6 m (measured from the response location). In one condition, subjects listened to the stimulus (a pulsetrain) and then attempted to walk to its location without further information from the source (the loudspeaker was silently moved out of the way). In other conditions, subjects walked 1 or 2 m toward the response location while being exposed to the pulsetrain; these conditions provided subjects with dynamic information about the source. Although there were small effects of the dynamic cues, the walked distances of the subjects in all conditions were compressed by a factor of two relative to the variation in source distance. In the more extensive second study,[34] we conducted three experiments comparing the perceptual localization of auditory targets and visual targets. In all three experiments, we used two different responses to assess perceived distance to a target: verbal report and walking. For the former response, the subject simply gave a verbal estimate of the distance (in feet) of the target or a verbal estimate of its direction (in degrees). For the latter response, the subject viewed or listened to a target and then, as in the earlier study,[33] attempted to walk to its location with vision and audition occluded. The results of the more precise walking response are shown in Fig. 4. The three experiments confirmed earlier studies by showing that the locations of visual targets up to 15 m away are quite accurately perceived under full-cue viewing. They also confirmed the stationary listening results of two earlier studies[33, 35]—the range of perceived auditory distance is compressed about twofold relative to the physical range.

APPLIED RESEARCH: NAVIGATION SYSTEM FOR THE VISUALLY IMPAIRED

Efforts at using technology to assist the visually impaired with wayfinding have, until recently, focused on the development of electronic devices for avoiding obstacles, like ultrasonic sensors.[36] Even with these devices, however, the blind traveler has lacked the freedom to travel without assistance because efficient navigation through unfamiliar environments relies on information well beyond the sensing range of these devices. Within the last decade, development of wayfinding aids has shifted more to assisting with navigation. One approach is to place electronic location identifiers (e.g., Talking Signs) throughout the environments.[37] The expanding installation of Talking Signs, accompanied by their ready acceptance by blind travelers, is one of the success stories of assistive technology for the blind. However, an alternative and complementary approach is to use computer technology to locate the traveler and then make use of a spatial database of the environment to display to the traveler his/her location relative to the environment. Here we focus on the satellite-based Global Positioning System (GPS). Today, 12-channel GPS receivers provide an absolute accuracy on the order of 5 to 20 m. Still, positional error can be reduced to submeter accuracy by means of a differential correction signal transmitted by radio link from a "base station" (Differential GPS or DGPS). GPS (or DGPS) is the preferred choice for pedes-

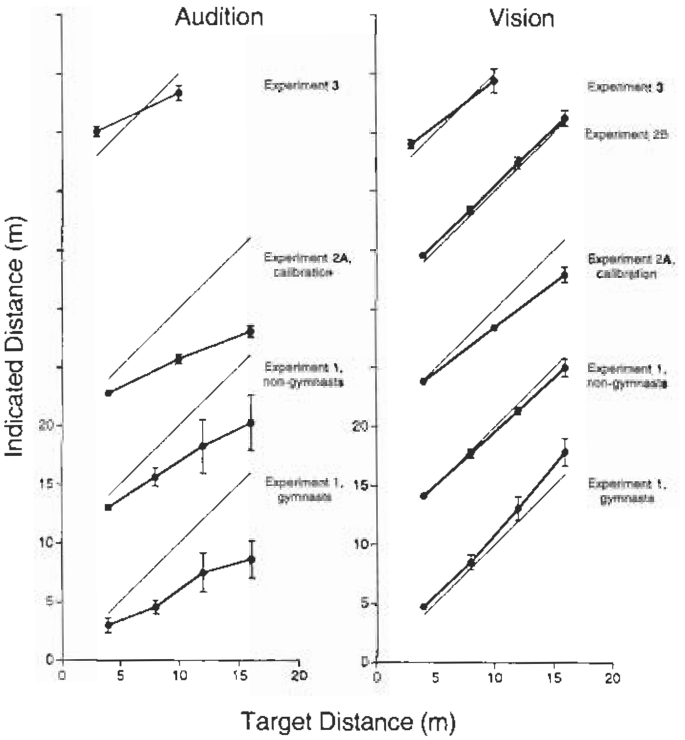

FIGURE 4.

Results of a study comparing auditory distance perception and visual distance perception in an open field[34]; both types of stimuli were tested with the same set of subjects in same-numbered experiments. Subjects viewed a visual target or heard a sound from a loudspeaker. After termination of the stimulus, the subject attempted to walk to its location without further information about the target. On average, the visual results show very accurate responding, confirming other results in the literature. On average, the auditory results showed that perceived auditory distance is compressed by about a factor of two relative to physical source distance. Reprinted from Loomis et al.[34]

trian travel within open environments where signal obstruction and multipath distortion (due to reflections) pose no problem. For environments in which GPS signals are subject to obstruction or multipath distortion, such as in downtown areas near tall buildings or under trees, GPS needs to be supplemented by inertial navigation or dead reckoning. When GPS signals are unavailable (e.g., indoor environments), either some form of local positioning system or a network of location identifiers, like Talking Signs, will be required to assist blind persons with navigation.

All GPS-based navigation systems for the blind consist of these functional components: a module for determining the traveler's position and orientation, a GIS comprising the system software and the spatial database for relating the traveler's orientation and GPS coordinates to the surrounding environment, and the user interface. A number of projects have explored the use of GPS for navigation by the blind,[38–42] and one company, Sendero Group, is about to market a product.

The system our group has developed, the Personal Guidance System, is being used as a research test bed.[43–45] Our long-term goal has been to contribute to the development of a portable system that will allow visually impaired individuals to travel through familiar and unfamiliar environments without the assistance of guides. We also hope that such a system will allow blind travelers to develop much better cognitive representations of their surroundings than is currently the case.

The first component of our system consists of a 12-channel DGPS receiver for locating the user in space and an electronic compass for providing heading information. Our GIS is implemented within a portable computer. The user interface is designed around a virtual sound display. From the outset, the idea has been to use 3-dimensional ("spatialized") sound to convey information about the surrounding environment to the blind traveler (Loomis JM, unpublished data). In this conception, as the blind person moves through the environment, he/she would hear the names of buildings, street intersections, etc., spoken by speech synthesizer. The resulting spatialized utterances come from the appropriate locations in auditory space as if they were emanating from loudspeakers at those locations.

The left panel of Fig. 5 shows the third author wearing the version of the system developed during the period from 1992 to 1995, and the right panel shows him wearing the version developed during 1999 to 2000 using miniaturized hardware. Details of the system design and implementation are available in several sources.[43–45]

An issue that has interested us for more than a decade is the perceptual realism of virtual sound.[32, 46] Although virtual acoustic displays have been effective at accurately conveying the direction of a simulated sound source, they have been far less successful at conveying distance information. Our experience with a variety of commercially available virtual acoustic displays has been that it is rare to hear a virtual sound presented through earphones as appearing more than a meter away. Because the problem is not with earphone listening per se,[46] the difficulty in rendering distance of virtual sound appears to be that distance cues are not being simulated properly, with reverberation likely being the most important cue[47, 48] We are optimistic that this problem will eventually be solved and commercially available displays will be able to render virtual sounds to seem to come from a great distance.

Our evaluation research on our navigation system has been exclusively concerned with the effectiveness of the display interface.[49, 50] Using the technology current at the time, we had to

FIGURE 5.

Left panel: One of the authors (Golledge) wearing the version of the Personal Guidance System developed during 1992 to 1995. Right panel: Golledge wearing the miniaturized version of the system developed during 1999 to 2000.

conduct our research using a virtual acoustic display that did not render distance very well. Even so, a virtual sound interface appears quite effective, based on the two formal experiments, one of which we describe here. This experiment assessed different display modes for controlling route guidance.[49] It was performed in a large open field, which insured good GPS reception. The task of the subject was to walk along a route specified by the computer; each route consisted of ten 7-m segments. The subject wore the system in a backpack and received guidance information by earphones, either spatialized synthetic speech in one mode (Virtual) or conventional synthetic speech in the other three modes. In the Virtual mode, route waypoints were specified as virtual beacons; on each segment, the subject walked toward the perceived synthetic speech giving the number of the next waypoint. After reaching a waypoint, the computer then activated the next waypoint. This mode required an electronic compass mounted on the headphone strap. In the Left/Right mode, the computer gave the subject course information by way of the conventional synthetic speech; the speech information was the same for both ears, causing the speech to appear to come from inside the head. Commands of "left," "right," and "straight" were issued to keep the subject on course toward the next waypoint; when reaching it, the computer then began issuing commands for the next waypoint in sequence. For this mode, the compass was mounted on the subject's torso. The Bearing mode was very much like the Left/Right mode except that the subject received synthetic speech telling the turn magnitude in number of degrees required for the subject to be facing the next waypoint (e.g., "left forty-five"); here, too, the compass was mounted on the torso. The issued commands in the fourth and last mode (No Compass) were similar to those of the third except that no compass was used. In this case, the computer could only give directional instructions (e.g., "right thirty") by computing the subject's course (direction of travel) on the basis of two successive DGPS fixes. If the subject stopped walking, course was undefined and no instructions could be issued.

Fig. 6 gives the results obtained with one dependent measure of performance: time to complete the route. We also manipulated the rate at which guidance information was issued (every second or every 5 s). We ran 10 blind subjects using a within-subject design; with proper counterbalancing, each subject performed under each display mode and display rate (along a different path). As can be seen in the figure, performance was poorest in the condition without the compass, whereas the best performance scores were obtained in the Virtual mode. Furthermore, subjective ratings by the subjects (5 = best and 1 = worst) averaged 4.4, 4.1, 3.8, and 2.5 for Virtual, Bearing, Left/Right, and No Compass, respectively. The performance data and subjective ratings indicate that the Virtual mode is the best of the four modes. Because it has the additional advantage of being able to communicate off-route information more efficiently than the other modes, the Virtual mode has considerable promise as part of the interface for a navigation system.

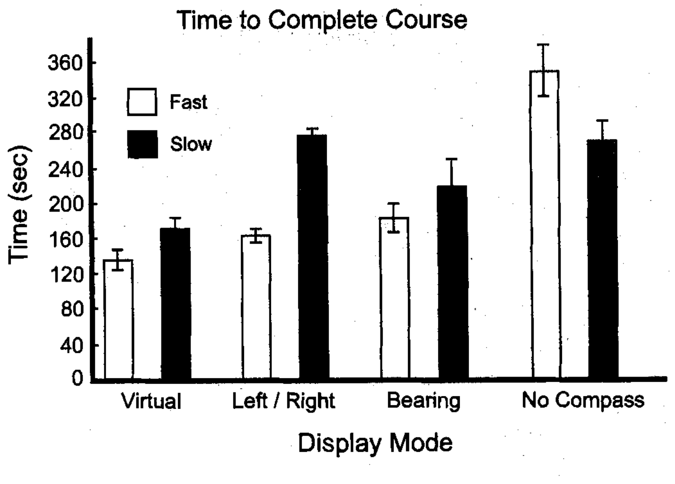

FIGURE 6.

Results of an experiment[49] on route guidance using different auditory display modes (see text for details). Time to finish the 71-m path is given as a function of display mode and rate at which information was supplied to the subject (once every 1.5 or 5.0 s). Reprinted from Loomis et al.[49]

CONCLUSIONS AND FUTURE PROSPECTS

For well over a decade, we have been conducting parallel streams of basic and applied research. Where possible, we use the knowledge gained from our basic research in informing the design of the navigation system that we are continuing to develop.

Our basic research on navigation without vision so far has focused only on one of the two types of navigation—path integration. The other, landmark-based navigation, is probably the more important and will be a topic of our future research. Our laboratory-based research on path integration has demonstrated that subjects performing pathway completion tasks are sensitive to the parameters of the outbound path, as reflected in their return paths, but they do make systematic errors. The encoding-error model accounts well for the systematic errors observed in our large study on triangle completion but fails to account for performance involving more complex paths. Its primary value is in providing a starting point for the modeling of human path integration without vision. Future experimental work will assess whether the systematic errors we have seen in triangle completion "scale up" as we increase the scale of the outbound path.

More recently, our research on path integration has focused on the informational inputs to path integration. Using a visual virtual display, we have studied the role of optic flow in pathway completion. Our two studies, along with those of other researchers, indicate that optic flow is a relatively poor input to the path integration process, especially in connection with the updating of heading (facing direction).

Two of our studies have been concerned with whether nonvisual spatial ability depends on prior visual experience. For the most part, our tabletop and locomotion studies reveal no differences in ability between those with extensive prior visual experience (sighted and late blind) and those with little prior visual experience (early blind). Other studies, however, have indicated that the early blind have some significant deficits in spatial ability. The differences in results may reflect different populations of subjects, based on selection procedures—in particular, those subjects who are independent and mobile in evetyday life may have better spatial abilities than those who are not.

Another line of our basic research has focused on auditory distance perception. Using both verbal report and a motoric response, we have confirmed other research by showing that perceived distance varies about half as much as physical source distance within the same physical environments in which visual distance perception is accurate. Future research will determine whether experienced blind travelers are more accurate at perceiving auditory distance than blindfolded sighted subjects, but some preliminary research we have recently conducted suggests that they are not.

Our applied research with the GPS-based navigation system that we have been developing shows that a virtual acoustic display has promise as the display interface, for it performed best in guiding blind subjects along a short route when compared with three other modes involving spatial language. Other research we have published and are currently conducting shows that virtual sound equals or surpasses spatial language in other ways as well. Moreover, as virtual acoustic displays improve, especially in terms of rendering distance, they will undoubtedly offer further advantages over spatial language. On the other hand, earphones, which are needed to implement virtual sound, are objectionable to some visually impaired individuals, and a virtual acoustic display entails more complexity than a basic speech interface. Thus, it remains to be seen whether virtual sound will be included in future commercial products. Whether it is or is not, the prospects for GPS-based navigation systems are better than ever in light of the improving accuracy of GPS receivers, decreasing size and cost of powerful computers, the emergence of wireless connectivity with the Internet, and the growing availability of digital maps suitable for pedestrian travel. Surely, obstacles remain, such as the development of low-cost alternatives to GPS when GPS coverage is lacking and the creation and maintenance of digital maps appropriate to blind travel. However, because these obstacles are not insurmountable, we believe that it is just a matter of time before many or perhaps most visually impaired travelers will be navigating through outdoor and indoor environments using GPS-based navigation systems and local positioning technology like Talking Signs. Hopefully these navigation systems will provide the visually impaired with much more functionality than simple route guidance. As rich databases for town and cities are developed for the larger population, databases that inform the traveler about nearby restaurants, businesses, etc., there is every reason to expect that the visually impaired population will eventually have as much access to this information as the sighted population. Moreover, we are hopeful that such navigation systems will have the added benefit of allowing the visually impaired to develop more accurate and extensive knowledge of spatial layout than must be the case presently.

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