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Navigation System for the Blind:

Auditory Display Modes and Guidance

Abstract

The research we are reporting here is part of our effort to develop a navigation system for the blind. Our long-term goal is to create a portable, self-contained system that will allow visually impaired individuals to travel through familiar and unfamiliar environments without the assistance of guides. The system, as it exists now, consists of the following functional components: (1) a module for determining the traveler's position and orientation in space, (2) a Geographic Information System comprising a detailed database of our test site and software for route planning and for obtaining information from the database, and (3) the user interface. The experiment reported here is concerned with one function of the navigation system: guiding the traveler along a predefined route. We evaluate guidance performance as a function of four different display modes: one involving spatialized sound from a virtual acoustic display, and three involving verbal commands issued by a synthetic speech display. The virtual display mode fared best in terms of both guidance performance and user preferences.

1 Introduction

Human wayfinding consists of two distinct components: sensing of the immediate environment for impediments to travel (e.g., obstacles and hazards) and navigating to remote destinations beyond the immediately perceptible environment (Golledge et al., 1991; Golledge, Klatzky, and Loomis, 1996; Rieser, Guth, and Hill, 1982; Strelow, 1985; Welsh and Blasch, 1980). Navigation, in turn, involves updating one's position and orientation during travel with respect to the intended route or desired destination and, in the event of becoming lost, reorienting and reestablishing travel toward the destination. Methods of updating position and orientation can be classified on the basis of kinematic order. Position-based navigation (called *pilotage* or *piloting*) relies on external signals indicating the traveler's position and orientation (often in conjunction with an external or internal map). Velocity-based navigation (called *dead reckoning* or *path integration*) relies on external or proprioceptive signals indicating the traveler's velocity; displacement and heading change from the origin of travel are obtained by integrating the velocity vector. Acceleration-based navigation (called *inertial navigation* or *path integration*) involves double integration of the traveler's linear and rotary accelerations to obtain displacement and heading change from the origin; no external signals are required.

The visually impaired are at a considerable disadvantage, for they often lack the needed information for bypassing obstacles and hazards and have relatively

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little information about landmarks, heading, and self-velocity—information that is essential to sighted individuals navigating through familiar environments who have knowledge of these environments or who are navigating through unfamiliar environments on the basis of external maps and verbal directions.

2 Assistive Technology for Wayfinding

Efforts to develop using technology to assist the visually impaired with wayfinding have, until very recently, been limited to development of devices that help individuals avoid obstacles. Following adoption of the long cane by the blind community as the primary means of detecting obstacles, much effort has been expended to supplement or supplant the long cane with electronic travel aids such as the Laser Cane and ultrasonic obstacle avoiders (Brabyn, 1985). Even with these devices, however, the blind traveler has lacked the freedom to travel without assistance, for efficient navigation through unfamiliar environments relies on information that goes beyond the sensing range of these devices.

Within the last decade, development of wayfinding aids has been directed more frequently to the navigation component. One approach has been to put location identifiers throughout the environments traveled by blind persons. Tactual identifiers are not suitable, for the blind traveler would need to tactually scan the environment just to know of their existence. Instead, developers have come up with identifiers that can be remotely sensed by the blind traveler using special equipment. One such system of remote signage currently being deployed in demonstration projects is what is known as Talking Signs (Crandall, Gerry, and Alden, 1993; Loughborough, 1979). In the Talking Signs system, infrared transmitters are installed throughout the travel environment (e.g., subway station or airport). These highly directional transmitters continuously transmit digital speech indicating what is at the location of the transmitter (e.g., phone booth); within a range of 15 m or 40 m (depending upon battery size), a blind traveler with an infrared receiver can pick up the signal from the transmitter and hear the digital utterance; directional localization of the transmitter is possible by aiming the hand-held receiver to obtain maximum signal strength.

A disadvantage of placing a network of location identifiers within the environment is the cost of installing and maintaining the network relative to the coverage achieved. One alternative 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.

There are a multitude of methods for determining the traveler's current location. These vary in the extent to which they require sensing of the environment or reception of signals provided by external positioning systems. At one extreme, there is inertial navigation, which requires no external sensing. At the other extreme are methods involving the matching of perspective video images of the environment to 3D models stored in computer memory. In between are methods employing dead reckoning and a variety of local and global positioning systems (e.g., GPS, Loran, VOR-DME) in which the navigator determines current position using signals from transmitters at known locations. Because of the high degree of accuracy of its position fixes, the Global Positioning System (GPS) or its Russian equivalent (GLONASS) is the preferred choice for travel within terrestial environments where obstructions of the sky and multipath distortion do not interfere with satellite reception. For environments in which GPS signals are only intermittently available, 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 (analogous to GPS or Loran) or a network of location identifiers (e.g., Talking Signs) will be needed to assist blind persons with navigation.

3 GPS-based Navigation Aids for the Visually Impaired

The idea of using GPS to assist the visually impaired with navigation goes back over a decade, when Collins (1985) and Loomis (1985) independently pro-

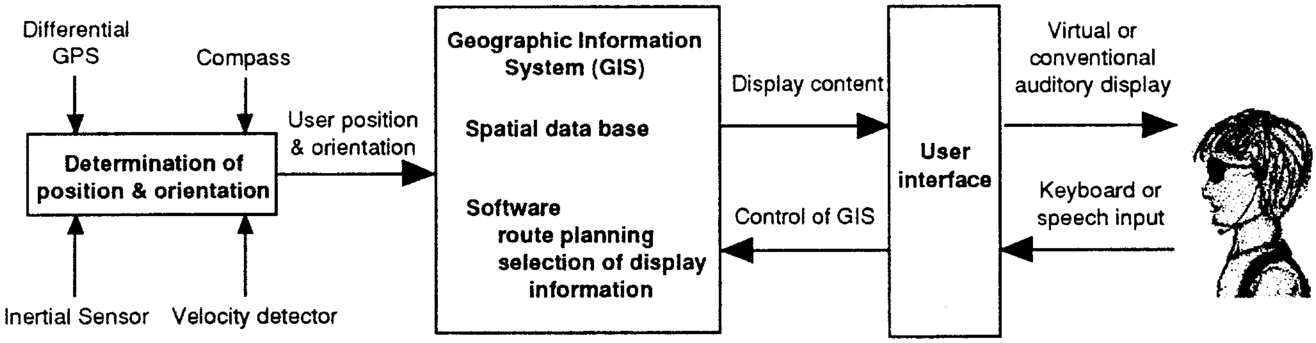

Figure 1. *The functional components of any navigation system for the blind. (from Loomis, Golledge, Klatzky, Speigle, and Tietz {1994}. {©} 1994 Association for Computing Machinery, Inc. Reprinted by permission.)*

posed it. The first evaluation of GPS for this purpose was carried out by Strauss and his colleagues (Brusnighan et al., 1989); because their research was conducted at an early stage of GPS development, the poor positioning accuracy they obtained precluded practical studies with blind subjects. Nowadays, most GPS applications requiring real-time positioning accuracy better than 25 m use differential correction (DGPS)—correction signals from a GPS receiver at a known fixed location are transmitted by radio link to the mobile receiver, allowing the mobile receiver to determine its position with an absolute positional accuracy on the order of 1 m or better.

All GPS-based navigation systems for the blind consist of these functional components (Figure 1): a module for determining the traveler's position and orientation, a Geographic Information System (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.

There are now a number of research and commercial endeavors around the world utilizing GPS or DGPS for determining the position of a blind traveler. They differ in terms of the three functional modules mentioned above, as well as in terms of physical configuration, weight, cosmetic acceptability, etc.

One commercial GPS-based system, which is about to be marketed, is the Strider product from Arkenstone of Sunnyvale, California (Fruchterman, 1996). A key feature of the product is its inclusion of detailed digital maps that cover most of the cities and towns in the United States. A synthetic speech display provides information about the spatial disposition of nearby streets and points of interest, as well as instructions for traveling to desired destinations. The current version uses neither a compass nor differential correction for GPS localization and, thus, affords only approximate information for orientation and route guidance.

A similar research and development effort is the Mobility of Blind and Elderly People Interacting with Computers (MoBIC) project being carried out by a UK/Swedish/German consortium (Petrie et al., 1996). The MoBIC Outdoor System (MoODS) is quite similar to Strider, but it also includes differential correction (by mobile phone link) and a compass worn on the body for heading information. A commercial product is in the development stage.

Another GPS-based system is the system being developed in Japan as part of a research project by Makino and his colleagues (Makino, Ishii, and Nakashizuka, 1996; Makino, Ogata, and Ishii, 1992). A unique feature of this system is its use of a digital mobile phone as the communication link between the traveler and the GIS. The mobile phone transmits the traveler's GPS coordinates to the GIS computer at a central facility. The GIS then outputs synthetic speech that is transmitted back to the traveler, providing information on his/her position. Use of a mobile phone link has the advantages of minimizing the weight and computing power that must be carried by the traveler and of simplifying the updating of the spatial database. A similar system is the "Electronic Guide Dog" project (Talkenberg, 1996) being undertaken by a European consortium. It, too, uses a mobile phone link between the traveler and a central facility. However, this project differs in its use of a human agent at the central facility, who communicates by voice to give the traveler positional and other information.

4 The Personal Guidance System

The system our group has developed, the Personal Guidance System, is being used as a research test bed (Loomis et al., 1994). Our long-term goal has been and continues to be to contribute to the development of a portable, self-contained 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 representations of the environment through which they are traveling than is currently the case without information about what lies off-route. As conceived, our system, like other navigation systems, is not intended to provide the blind person with detailed information about the most immediate environment (e.g., obstacles); thus, the blind traveler will still have to rely on the long cane, the seeing-eye dog, or ultrasonic sensing devices for this information.

In support of this project, we have been engaged for over 10 years in basic research dealing with the ability of humans to navigate in small-scale space without vision (Fujita et al., 1993; Klatzky et al., 1990; Loomis et al., 1993) and with human auditory distance perception (Loomis et al., in press; Speigle and Loomis, 1993).

The first module of our system (Figure 1) is concerned with determining the position and orientation of the traveler. For positioning, we have used a number of DGPS configurations over the last three years. The configuration used in the experiment below consisted of a Trimble 12-channel GPS receiver (Model DSP 4000SE) with differential correction from a base station located 20 km away (Accqpoint Wide Area DGPS service). DGPS fixes are provided at the rate of 0.67 Hz. Under the requisite conditions of satellite availability, geometry of available satellites, and signal-to-noise ratio, the DGPS hardware and software localized the traveler with an rms absolute error of close to 1 m.[1] For orientation sensing, we used a fluxgate compass (Etak 02 0022) attached either to the strap of the earphones worn on the head (for one condition of the experiment) or to the backpack carrying the rest of the equipment (for two of the other conditions).

The second module of our system (Figure 1) is the computer containing the GIS. Our system is built around a 486 subnotebook computer (Sager 486SLC 33 with expansion chassis) that contains the campus database and system software. Our test site is the University of California, Santa Barbara campus, for which we have developed a spatial database containing all buildings, roads, walkways, bikeways, trees, and other details (Golledge et al., 1991). Our main development efforts have gone into creating a reliable system, developing the database of the campus (Golledge et al., 1991), and developing the GIS software that provides the traveler with the desired functionality.

The third module of our system (Figure 1) is the user interface. For user input, we currently use a keypad, but almost all of our development effort has gone into the display component. From the beginning (Loomis, 1985), our plan has been to use spatialized sound from a virtual acoustic display to convey information about the surrounding environment to the blind traveler. A virtual acoustic display takes a monaural audio signal (e.g., speech or sound effect) and transforms it into a binaural signal (heard by way of earphones) so that the sound appears to emanate from a given direction and distance (Begault, 1994; Carlile, 1996; Gilkey and Anderson, 1997; Loomis, Hebert, and Cicinelli, 1990; Wenzel, 1992; Wightman and Kistler, 1989). (The "head tracker" in our system consists of the DGPS receiver subsystem for position sensing and the fluxgate compass mounted on the earphone strap for sensing head orientation.) In this conception, as the blind person moves through the environment, he/she would hear the names of buildings, street intersections, and so on, "spoken"

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[1] Although the absolute error of a given DGPS fix may exceed 1 m, two successive DGPS fixes generally exhibit little relative error, for the various signals used in differential positioning are quite stable over the short term (on the order of seconds or even minutes). Thus, even in the presence of significant absolute error, a brief straight traverse by the traveler is measured as a nearly straight line, with wavering of less than 10 cm.

by speech synthesizer, coming from the appropriate locations in auditory space as if they were emanating from loudspeakers at those locations.

Our display subsystem consists of several components. Synthetic speech is generated by an RC Systems V8600 synthesizer. Its monaural output is then rendered binaural by the virtual acoustic display hardware. Initially we used our own analog implementation (Loomis et al., 1990), but then substituted this with a commercially available DSP implementation (the Alphatron from Crystal River Engineering) because of its greater hardware reliability. We also use a DSP reverberation unit (Zoom 2000) to provide reverberation, which adds to the realism of the sound. The last component of the display subsystem is the pair of stereo earphones worn by the traveler; the different models we have tried have not been discernibly different in auditory effectiveness.

The entire navigation system (computer, speech synthesizer, acoustic display hardware, and batteries) is carried in a backpack worn by the user. The total weight of the backpack and hardware is 11.4 kg.

5 Some Issues Relating To Use of a Virtual Acoustic Display

One of the challenges to using virtual sound in the user interface is achieving adequate perceptual realism and localization accuracy for the two navigational functions of most interest: guidance of the traveler along a predefined route and providing the traveler with knowledge of the off-route environment. The guidance function is easy to accomplish, for as long as the traveler can localize the next waypoint along the route in front and within the median plane, he/she can walk to it just by keeping it centered within the median plane. This level of directional localization is readily accomplished with the simplest of virtual displays, provided that head rotations produce concomitant changes in the binaural signal. Acquisition of environmental knowledge is much more demanding, for the traveler must be able to localize off-route landmarks with reasonable precision. Achieving adequate directional localization is a solved problem—the virtual acoustic display synthesizes the binaural signals by convolving the monaural source signal with the listener's own head-related transfer function (HRTF), the mathematical description of the spectral filtering and time delays of the head, pinnae, and ear canals (Wenzel et al., 1993; Wightman and Kistler, 1989). Even a fair approximation to the person's HRTF is probably sufficient, provided that the head rotations of the traveler are tracked and used to modify the binaural signal. The real challenge is achieving realistic auditory distance perception. Just obtaining extracranial localization of virtual sound has proven to be a much more complex issue than originally thought (Durlach et al., 1992; Loomis and Soule, 1996), but some success has been reported (Begault, 1991; Loomis et al., 1990; Wenzel et al., 1993; Wightman and Kistler, 1989); it remains to be seen whether virtual acoustic displays will be able to produce large and reliable changes in perceived distance.

At the moment, the virtual acoustics display in our system makes use of earphones that partially occlude external sounds, including those high frequencies important to echolocation. We realize that if a virtual acoustic display is to be used in a practical system, it will be necessary to use transducers that minimally block external sounds (e.g., earphones that are nearly acoustically transparent, miniature speakers for bone conduction, or miniature speakers located several centimeters distal to the external ears). Even so, the masking of external sounds by virtual sounds and the additional attentional demands of the constant navigation signal will continue to be detriments to the avoidance of obstacles, but our hope is that the benefits of navigational information to the blind traveler will far outweigh them. If indeed the virtual sound display proves effective for navigation, there is also the distinct possibility of using these same transducers to present an augmented echolocation signal, like that used in many ultrasonic avoidance devices (Brabyn, 1985).

6 Experiment on Guidance

The experiment we report is concerned with the guidance function: leading a blind traveler along a route of predefined waypoints (turn points). At the outset, we define a couple of important navigational concepts.

Heading is the facing direction of the traveler's body (or head) with respect to a reference direction (e.g., true north) and is defined even when the traveler is stationary. In our experiment, heading is provided by the fluxgate compass. *Course* is the traveler's direction of travel with respect to the reference direction and is defined only when the person is in motion. In our experiment, course is obtained from two successive DGPS fixes. *Bearing* is the direction from the traveler to another point in space, as measured with respect to the reference direction. A traveler wishing to proceed directly to a location, sets his/her course equal to the bearing of that location. *Relative bearing* is the bearing of a location with respect to the heading of the traveler, and *course-relative* bearing is the bearing of a location with respect to the course of the traveler (Beall and Loomis, 1996).

Our experiment is concerned with the display of information to the blind traveler for the purpose of guidance. Our primary interest was in determining whether spatialized sound from a virtual acoustic display resulted in better or worse route-following performance than verbal guidance commands provided by a synthetic speech display. Of secondary interest was a comparison of guidance with and without heading information, as provided by the fluxgate compass, and the effect of varying the frequency with which guidance information was provided to the traveler.

6.1 Method

In the experiment, we used four different routes comprising nine linear segments defined by 10 waypoints (specified by their DGPS coordinates). These were situated within a large open grassy field on campus. In Figure 2, true north is indicated by the top of the figure. The north-south and east-west legs were either 6.1 m (20 ft) or 12.2 m in length, and the diagonal legs were always 8.6 m. The four paths were equal in length. Turns were 45, 90, or 135 degrees. The start point was always the western-most waypoint.

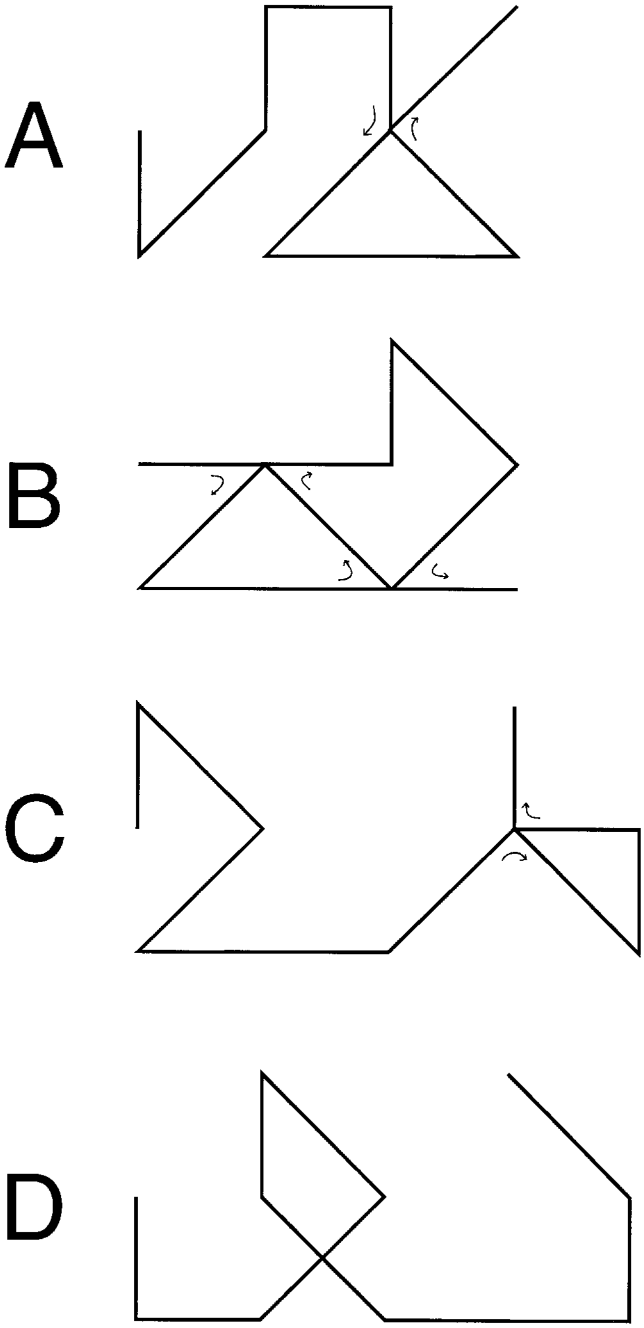

Figure 2. *The four paths used in the experiment. They were equal in length, with diagonal legs of 8.6 m. The starting location of each path was always the waypoint depicted at left-center.*

We evaluated four display modes in the experiment, three involving a conventional speech display and the fourth involving spatialized (virtual) sound. The four modes are depicted in Figure 3, with the next waypoint (waypoint 1) being off to the traveler's left. In the Virtual mode, the fluxgate compass was mounted on the earphone strap, providing the heading of the person's head; the relative bearing of the waypoint is depicted as 80 degrees left. The navigation system computer con-

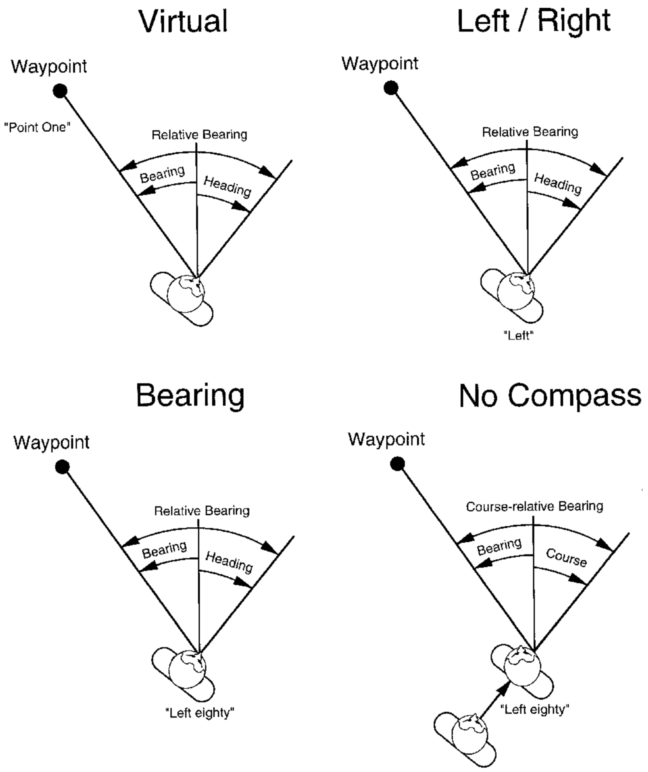

Figure 3. *The four display modes used in the experiment. For all modes, audio information was conveyed by earphones. In the Virtual mode (upper left), Left/Right mode (upper right), and Bearing mode (lower left) conditions, the traveler's heading was sensed by a fiuxgate compass, allowing relative bearing information about the next waypoint (here Waypoint 1) to be displayed to the traveler. In the Virtual condition, the traveler heard the number of the waypoint, spoken by speech synthesizer, as spatialized sound; thus the utterance "one" was heard as coming from a relative bearing (re the median plane of the head) of about 80 degrees left and from several meters away. In the Left/Right mode, the traveler received only ternary speech information ("left," "right," or "straight") about the relative bearing of the waypoint (re the median plane of the torso). (Because the synthesized speech signal was the same for both ears, the traveler localized the speech within the head.) In the Bearing mode, the traveler received more detailed speech information (e.g., "left eighty") about the relative bearing of the waypoint (re the median plane of the torso). Finally, in the No Compass mode (lower right), heading information was unavailable. To provide directional information to the next waypoint, the traveler's course was computed from two successive DGPS fixes; the traveler then received speech information (e.g., "left eighty") about the course-relative bearing of the waypoint.*

stantly updated (at 58 Hz) the distance and relative bearing of the waypoint with respect to the traveler's head. The waypoint number was spoken by the speech synthesizer, the output of which was then rendered binaural by the virtual acoustic hardware. The depicted traveler heard the utterance "one" coming from a relative bearing of approximately 80 degrees left, as if emanating from a sound beacon at the location of the waypoint. By turning his/her head in its direction, the traveler could center the perceived sound within the median plane. As the traveler approached the computer-defined waypoint, the sound level of the utterance increased appropriately. The traveler could gauge when he/she was near the "virtual beacon" on the basis of the increased sound level and on the rapidly changing motion parallax of the virtual sound due to lateral translations of the head (Loomis et al., 1990). When the traveler approached within 1.5 m of the waypoint, the computer took this as being at the waypoint and then began activating the next waypoint in sequence.

In the Left/Right mode (Figure 3), the fluxgate compass was mounted on the backpack worn by the subject to indicate the heading of the traveler's torso. The speech synthesizer provided ternary information about the relative bearing of the next waypoint. If the waypoint had a relative bearing between 5 degrees left and 5 degrees right, the computer issued, by way of the speech synthesizer, the verbal command of "straight," indicating that the traveler should walk in the direction of his/her current heading. If the relative bearing was between 5 degrees left and 179 degrees left, the verbal command "left" was issued; if the relative bearing was to the right, the command issued was "right." The best strategy for the subject was to pivot while stopped until receiving "straight" and then walking in that direction.

The Bearing mode (Figure 3) was like the Left/Right mode except that more information about relative bearing was provided. Here, the relative bearing between the torso and the next waypoint, rounded to the nearest 10 degrees, was spoken (e.g., "left 80"). As in the previous mode, if the relative bearing was between 5 degrees left and 5 degrees right, the command "straight" was issued.

Finally, the No Compass mode (Figure 3) was like the Bearing mode, in that the subject received the same type of verbal command from the computer (e.g., "left 80"). However, a course-relative bearing of the next waypoint, rounded to the nearest 10 degrees, was spoken instead of relative bearing. The course of the traveler was computed from two successive DGPS fixes. With differential correction, the relative accuracy of two successive fixes was sufficient to provide quite accurate route guidance. If the traveler stopped moving, however, course was not defined, and the computer stopped issuing commands. Thus, the traveler had to keep walking in order to obtain guidance information.

Besides display mode, we were interested in the rate at which the traveler received guidance information. Thus, in all four modes, we employed two display rates: once every 1.5 sec ("fast") or once every 5.0 sec ("slow").

Ten visually impaired male subjects were recruited from the local community. Their ages ranged from 30 to 63 years (mean = 43.4). They were given a simple test for directional hearing prior to the experiment proper. All were blindfolded. Because the test field was free of obstacles, subjects had no need for either a cane or a guide dog while performing the guidance task. Each was paid for participating in the single session, which lasted about two hours.

For each subject, each of the four guidance modes was used twice, once with the slow display rate and once with the fast display rate. Display rate was blocked within guidance mode; two of the modes used the order fast/slow and the others used the order slow/fast. The four paths were randomly assigned to each successive block of four trials. The order of the four methods was randomly determined for each observer. Prior to the eight experimental trials were four practice trials, one for each of the guidance modes (but in the opposite order of that used in the experiment proper). During each trial, the subject's trajectory was recorded, so that the time to complete the route and total distance traveled could be determined. Figure 4 shows two such recorded trajectories on path D (Figure 2), illustrating the huge variability in observed guidance performance.

After performing each of the eight experimental trials, the subject was asked to rate the ease of performing the task on a scale from 5 (easy) to 1 (difficult). After completing the experiment, the subject gave a preference ordering (4 being best). Two subjects did not give these preference orderings.

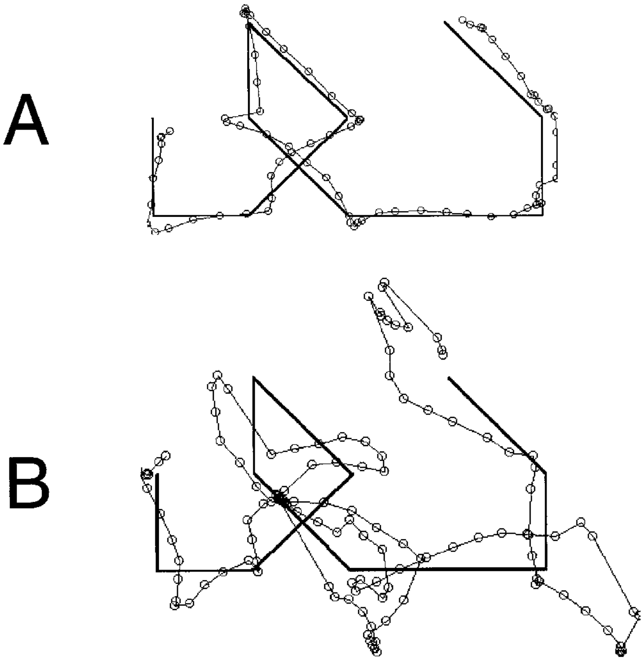

Figure 4. *Illustrative examples of very good (A) and very poor (B) guidance performance on path D from Figure 2, obtained in the Bearing and No Compass modes, respectively. The diagonal leg is 8.6 m long.*

Prior to the practice trials, each subject was screened for directional hearing by using the virtual acoustic display in the same way it was to be used in the experiment. On five successive trials, a single virtual source speaking "point 1" was activated at one of five widely separated bearings. The subject had to turn his or her head and face the source. Prompt and accurate changes in heading were used as criteria to permit inclusion of the subject in the experiment; out of 13 candidates screened for the experiment and for pilot testing, only one was excluded by using this screening procedure.

6.2 Results

The mean performance measures, averaged across subjects, are given in Figure 5 as a function of display mode and display rate. The error bars represent one standard error of the mean.

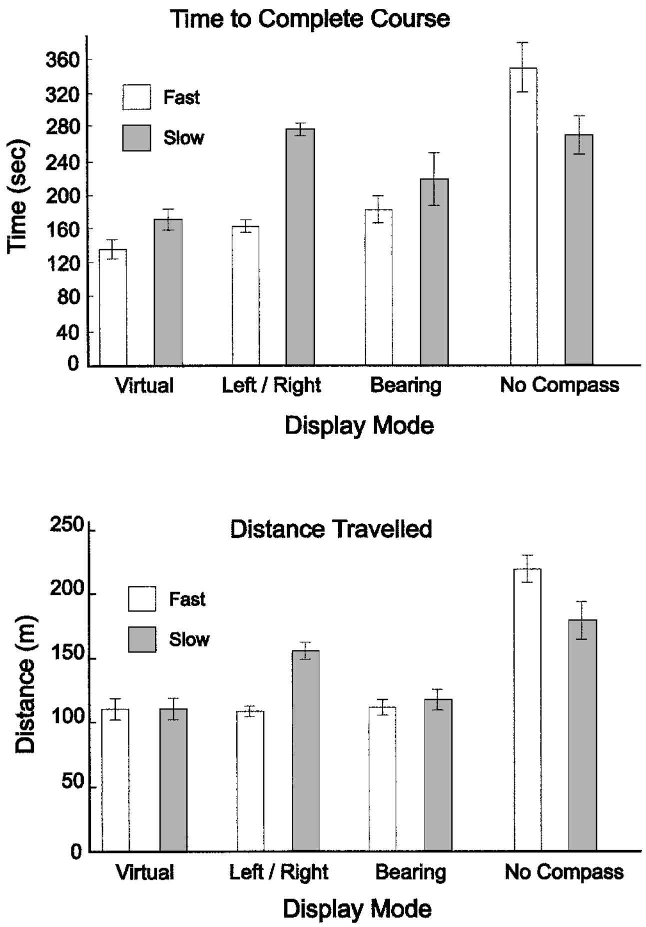

Figure 5. *Performance results of the experiment.*

A within-subjects analysis of variance (ANOVA) on completion time revealed a main effect of display mode, $F(3, 27) = 3.87, p < 0.02$ and an interaction between mode and display rate, $F(3, 27) = 4.81, p < 0.01$. A similar ANOVA on travel distance showed similar effects: a main effect of display mode, $F(3, 27) = 11.23$, $p < 0.001$, and an interaction between mode and display rate, $F(3, 27) = 5.13, p < 0.01$.

The ANOVAs and means noted in Figure 5 do not tell the whole story. Taking the average of a subject's completion times for fast and slow display rates, seven out of the 10 subjects did best with the Virtual mode, two did best with the Bearing mode, and one with the Left/Right mode. In addition, of the six completion times registered in all trials by all subjects that were less than 100 sec, five were in the Virtual mode (the sixth was in the Bearing mode); compare these with the mean times in Figure 5.

The subjective ratings of the different modes were similar for fast and slow display rates, but varied with display mode. Averaging across them and across subjects, the mean ratings (5 is best) were 4.4, 4.1, 3.8, and 2.5 for the Virtual, Bearing, Left/Right, and No Compass modes, respectively. The preference orderings showed that five out of the eight subjects from whom rankings were obtained liked the Virtual mode best, two liked the Bearing mode best, and one judged the Virtual and Bearing modes equal in preference.

6.3 Discussion

The experiment allows the following conclusions to be drawn: First, the performance data, subjective ratings, and preference orderings converge in indicating that the best mode was that employing spatialized sound from a virtual acoustic display (Virtual mode). The Bearing mode was a close second in terms of the performance means and subjective ratings, but the Virtual mode showed a clear advantage in terms of the preference orderings and fastest completion times.

Second, the performance data, subjective ratings, and preference ordering are consistent in indicating the undesirability of providing guidance information without a compass. Navigation systems that use neither differential correction of the GPS fixes nor a compass for heading information will be unable to provide detailed guidance information; furthermore, subjects will need to determine heading on their own using other types of information, such as the direction of the sun or knowledge of the street orientation.

Given that a navigation system will need to convey information other than that needed for guidance, it is not feasible to provide guidance information at high intermittencies. Ideally, guidance information would be provided only every 10 sec or so. In view of this objective, the only display modes that seem to warrant further consideration for providing guidance information are the Virtual and Bearing modes, both of which led to quite good performance at the slower display rate. Besides its leading to the best performance, the Virtual mode has an additional advantage in that relative bearing information is contained within the spatialized sound and thus can be conveyed in a very short utterance. This advantage ought to translate into more time being available for conveying other sorts of information. On the other hand, the disadvantages of using virtual sound are that (1) the traveler must have normal directional hearing, (2) earphones and a compass must be worn on the head, (3) normal spatial hearing of environmental sounds might be occluded by the earphones or masked by the virtual sound, and (4) there is additional cost and system complexity associated with using virtual acoustic hardware.

Guidance, however, is not the only function to be served by such a navigation system. Another important function is providing the blind traveler with information about the surrounding environment, both its content and the spatial disposition of this content. We believe that spatialized sound will be more effective in conveying this information than synthesized speech.

Acknowledgments

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