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GPS-Based Navigation Systems for the Visually Impaired

Jack M. Loomis, Reginald G. Golledge
University of California Santa Barbara

Roberta L. Klatzky
Carnegie Mellon University

INTRODUCTION

According to the 1990 U.S. Census of Population, there are approximately 1.1 million individuals registered as legally blind and up to 3 million reporting severe vision impairment. Yet another 3 to 4 million are visually impaired to the degree that they cannot drive and/or have difficulty reading signs or printed material. The most fundamental needs of visually impaired or blind populations include access to information (particularly that presented in written format), accessibility to the environment, and independence of movement. Our focus here is on the latter two needs.

Accessibility to the environment is important for all individuals. Access includes not only physical mobility, such as making a trip to a store by a selected transportation mode, but also being able to recognize key choice points or decision points in the environment (e.g., landmarks, streets, or neighborhoods). Accessibility therefore involves the ability to interpret, recognize, and understand the layout of features in the environment as well as being able to travel in as obstacle-free a manner as possible.

For many blind people the loss of sight is paralleled by a loss of independence. Of the 1.1 million legally blind persons in the United States, approximately 10,000 use guide dogs and 100,000 are able to travel somewhat independently using a long cane. This leaves approximately 1 million people who are dependent on other humans for movement, information processing, and environmental interpretation and use. Loss of independence is probably the most humbling of all the disadvantages associated with the loss of sight. A wearable device that can reduce dependence in all manners of interaction with the local environment is of the utmost importance to increasing the quality of life for the blind or visually impaired individual.

This chapter details the current state of research and development on GPS-based navigation systems for the visually impaired, most of which are portable, verging on wearable. It begins with a consideration of the need for such systems by the visually impaired, distinguishing between two different aspects of wayfinding—obstacle avoidance and navigation. It then reviews a number of efforts aimed at developing navigation aids for the visually impaired and then focuses first on other projects dealing with GPS-based navigation systems and then on our own project. It then briefly describes some research we have done on the display of information for route guidance and for conveying the spatial layout of important off-route entities (e.g., landmarks) and ends with a consideration of the obstacles to be overcome in implementing effective practical systems.

NAVIGATION VERSUS OBSTACLE AVOIDANCE

Human wayfinding consists of two very different functions: sensing of the immediate environment for obstacles and hazards and navigating to remote destinations beyond the immediately perceptible environment (Golledge, Loomis, Klatzky, Flury, & Yang, 1991; Golledge, Klatzky, & Loomis, 1996; Rieser, Guth, & Hill, 1982; Strelow, 1985; Welsh & Blasch, 1980). Navigation, in turn, involves updating one's position and orientation during travel with respect to the desired destination, usually along some intended route. Methods of updating position and orientation can be classified on the basis of kinematic order. Position-based navigation relies on external signals indicating the traveler's position and orientation (generally in conjunction with an external or internal map). Velocity-based navigation (usually referred to as "dead reckoning") relies on external or internal signals indicating the traveler's velocity vector; displacement and heading change from the origin of travel are obtained by integrating the velocity vector. Acceleration-based navigation (usually referred to as "inertial navigation") involves double integration of the traveler's linear and rotary accelerations to obtain displacement and heading change from the origin; external signals are not required. Most navigation, whether by animal, human, or machine, involves a combination of two or more of these methods.

The visually impaired are at a huge disadvantage, especially in unfamiliar environments, for they lack much of the information needed for planning detours around obstacles and hazards and have little information about distant landmarks, heading, and self-velocity, information that is essential when traveling through unfamiliar environments on the basis of maps and verbal directions.

ELECTRONIC TRAVEL AIDS

Following adoption of the long cane by the blind community as the primary mobility aid in the 1940s (Farmer, 1980), considerable effort has been expended to supplement or replace the long cane with electronic travel aids (ETAs) to assist with obstacle avoidance and navigation. Electronic obstacle avoiders, such as the Laser Cane and ultrasonic-based Binaural Sonic Aid, inform the traveler of nearby barriers to free and safe movement and are used to find paths that circumvent such obstacles (Brabyn, 1985; Farmer, 1980). Even with these devices, however, the visually impaired traveler has lacked the freedom to travel without assistance, for efficient navigation through unfamiliar environments relies on information beyond the limited sensing range of these devices.

Within the past decade, development of ETAs has been directed much more to the navigation function. One approach has been to put location identifiers throughout the environments traveled by visually impaired persons. Tactual identifiers are not effective, for the visually impaired traveler needs 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 visually impaired traveler using special equipment. Two such systems of remote signage are Talking Signs and Verbal Landmark (Bentzen & Mitchell, 1995; Crandall, Gerry, & Alden, 1993; Loughborough, 1979). In the Talking Signs system, currently being deployed around the world, infrared transmitters are installed throughout the

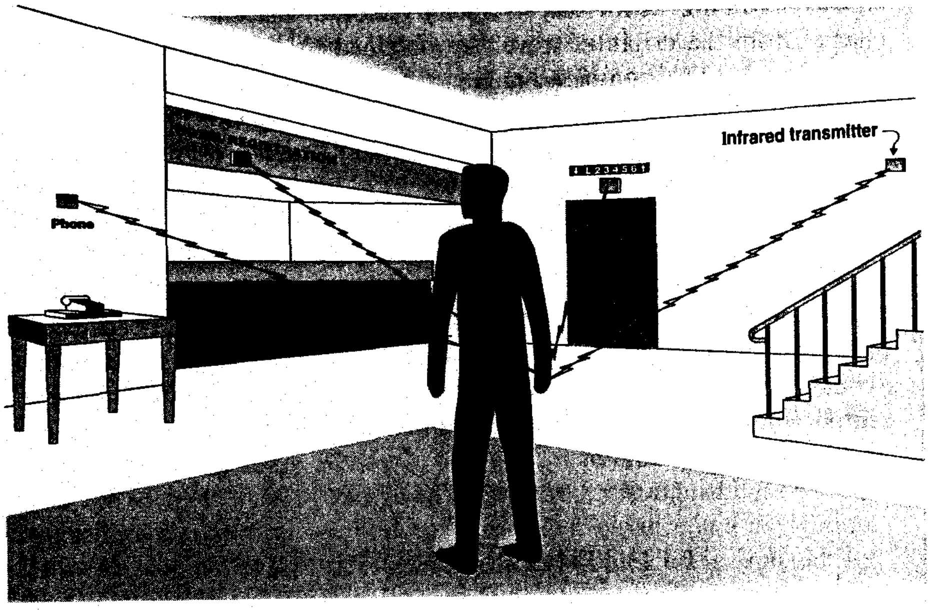

FIG. 13.1. The Talking Signs system of remote signage. Infrared transmitters are installed near important environmental entities. Each transmitter continuously sends out a digitally encoded utterance about the nearby entity. A person holding a Talking Signs receiver hears the utterance when pointing the receiver in the direction of the transmitter. (Adapted from Figure 1 in: Crandall, W., Bentzen, B. L., Myers, L., & Mitchell, P (1995). *Transit accessibility improvement through Talking Signs remote infrared signage: A demonstration and evaluation.* Document #95-0050, Project ACTION, 700 Thirteenth St. NW, Suite 200, Washington, DC.)

travel environment, such as in airports, shopping centers, and hotels (see Figure 13.1). These highly directional transmitters continuously transmit digital speech indicating their location; within a range of 20 m, a visually impaired traveler with an infrared receiver can pick up the signal from the transmitter and hear the digitally encoded utterance; directional localization of the transmitter is sensed by aiming the hand-held receiver to obtain maximum signal strength. The Verbal Landmark system is of similar design, but differs in significant ways (Bentzen & Mitchell, 1995). The RF transmitter has a more limited range (2 m) and is omnidirectional, making precise localization impossible. A visually impaired traveler within reception range receives verbal instructions for travel to other locations within the environment.

The obvious 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. An alternative is to use computer technology to locate the traveler, there being a multitude of methods. These vary in the extent to which they require sensing of the environment, reception of signals provided by external positioning systems, and stored information about the environment. Inertial navigation is attractive, for it requires neither external sensing nor stored information about the environment; unfortunately, the unavailability of accelerometers of sufficiently high sensitivity and low noise rules out inertial navigation as the primary basis for pedestrian travel. A very different approach is to use map correlation, whereby video images of the environment are matched to 3-D models of the environment stored in memory. More common, however, are methods that rely on positional signals received by the traveler and processed by computer. Ogata, Makino, Ishii, and Nakashizuka (1997) have experimented with infrared barcode labels that appear as uniformly colored strips and can be attached to objects and wall surfaces within a building; infrared video sensing and computer processing provide the traveler with locational speech information encoded on the labels. Local positioning systems based on low-power high-frequency transmitters are another approach. However, the method that is most frequently considered because of its high positional accuracy, wide signal coverage, and ready availability is that based on satellite signals. The Global Positioning System (GPS) and its Russian equivalent (GLONASS) are now widely used for many positioning applications, including navigation (for details on GPS, see Parkinson & Spilker, 1996).

Pedestrian use of GPS for positioning has three shortcomings. The first is that the accuracy of stand-alone commercially available GPS receivers is limited to 20 m or so. Much higher accuracy is afforded by differential correction (DGPS), in which correction signals from a GPS receiver at a known fixed location are transmitted by radio link to the mobile receiver, allowing the latter to determine its position with an absolute positional accuracy on the order of 1 m or better; however, differential correction requires a separate receiver, and service is not available in many locations. The second shortcoming is the possible loss of satellite visibility when nearby buildings or dense foliage block a substantial part of the sky. Signal loss is most noticeable in the downtown areas of moderate to large cities where a concentration of tall buildings at times occludes much of the sky from a street-level location. The third shortcoming involves multipath distortion resulting from reflections of the GPS signal from nearby structures. Because distance to a satellite is computed from the time delay of signal transmission and signal reception, positions derived from reflected signals are in error.

For environments in which GPS signals are only intermittently available or degraded by multipath distortion, GPS needs to be supplemented by dead reckoning (based on measurements of travel velocity) or inertial navigation (based on measurements of travel acceleration). When GPS signals are unavailable (e.g., indoor environments), either some form of local positioning system or a network of location identifiers, such as Talking Signs, will be needed in assisting visually impaired persons with navigation.

GPS-BASED NAVIGATION AIDS FOR THE VISUALLY IMPAIRED

The idea of using GPS to assist with navigation by the visually impaired goes back over a decade (Collins, 1985; Loomis, 1985). The first evaluation of GPS for this purpose was carried out by Strauss and his colleagues (Brusnighan, Strauss, Floyd, & Wheeler, 1989). Because their research was conducted during early deployment of GPS, the poor positioning accuracy available to them precluded practical studies with visually impaired subjects.

There are now a number of research and commercial endeavors around the world utilizing GPS or DGPS for determining the position of a visually impaired traveler. One commercial GPS-based system has been under development by Arkenstone of Sunnyvale, California for several years (Fruchterman, 1996). It makes use of detailed digital street maps covering the United States as well as selected locations in other countries. A synthetic speech display provides both information about the locations of nearby streets and points of interest and instructions for traveling to desired destinations. The system 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 that has been conducted by a UK/Swedish/German consortium (Petrie, Johnson, Strothotte, Raab, Fritz, & Michel, 1996). The MoBIC Outdoor System (MoODS) is similar to the Arkenstone system but includes differential correction and a compass worn on the body for heading information.

Another GPS-based system is that being developed as part of a research project in Japan by Makino and his colleagues (Makino, Ishii, and Nakashizuka, 1996; Makino, Ogata, & Ishii, 1992). A distinguishing feature of this system is its use of a digital mobile phone for communication between the traveler and the computer that contains the spatial database. The mobile phone transmits the traveler's GPS coordinates to the computer at a central facility, which in turn outputs synthetic speech, which is transmitted back to the traveler, providing information on his/her position. Use of a mobile phone link has the advantages of minimizing the cost, weight, and computing power of the unit carried by the traveler and of simplifying the updating of the spatial database. A related system is the "Electronic Guide Dog" project in Europe (Talkenberg, 1996). It too uses a mobile phone link between the traveler and a central facility, but, in contrast to the Makino design, uses a human agent at the central facility, who communicates by voice to give the traveler positional and other information.

THE PERSONAL GUIDANCE SYSTEM

The system our group has developed, the Personal Guidance System, is being used as a research test bed (Golledge, Klatzky, Loomis, Speigle, & Tietz, 1998; Loomis, Golledge, Klatzky, Speigle, & Tietz, 1994; Loomis, Golledge, & Klatzky, 1998). Our long-term goal is 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. The basic conception that has guided us from the beginning (Loomis, 1985) relies on a virtual acoustic display as part of the user interface. A virtual acoustic display takes a monaural audio signal (e.g., speech or environmental sound) and transforms it into a binaural signal delivered by earphones, the result being a sound that appears to emanate from a given environmental location (Begault, 1994; Carlile, 1996; Gilkey & Anderson, 1997; Loomis, Hebert, & Cicinelli, 1990; Wenzel, 1992; Wightman & Kistler, 1989). In our conception, as the visually impaired person moves through the environment, he/she would hear the names of buildings, street intersections, etc. spoken by a speech synthesizer, coming from the appropriate locations in auditory space (Figure 13.2), as if they were emanating from loudspeakers at those locations, in analogy with the Talking Signs system. Besides leading the visually impaired person along a desired route, the system would hopefully allow the person to develop a much better representation of the environment than has been the case so far. Our system is not intended to provide the visually impaired person with detailed information

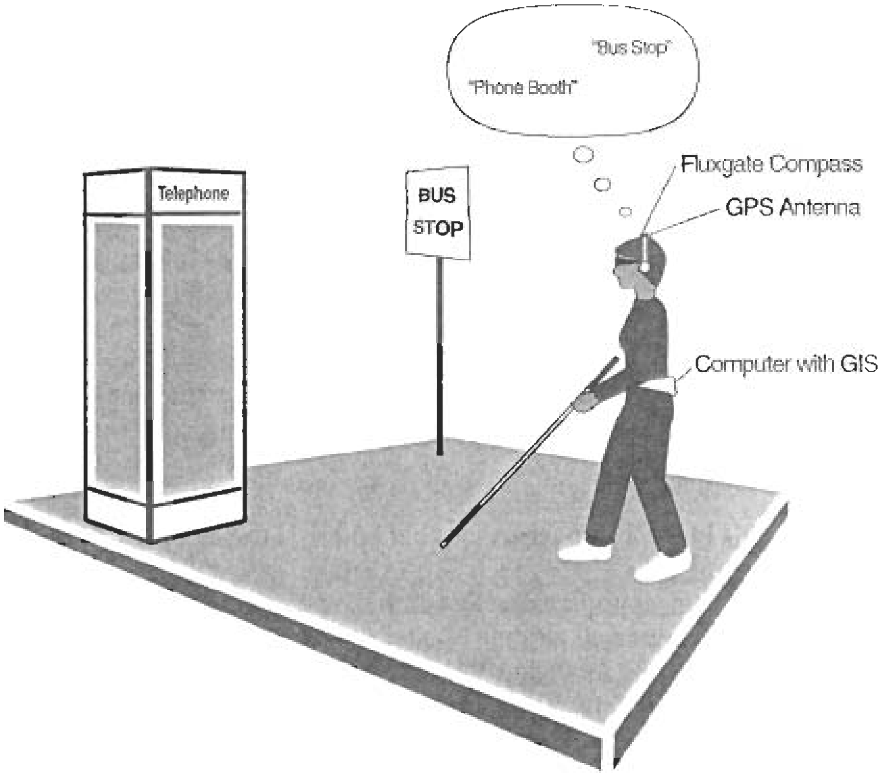

FIG. 13.2. Artist's conception of a future implementation of the Personal Guidance System. The GPS receiver locates the traveler with respect to the surrounding environment, represented in a spatial database that is part of the Geographic Information System within the computer. The fluxgate compass provides the computer with orientation of the traveler's head. Wearing earphones, the traveler hears spatialized virtual sound spoken by a speech synthesizer, with the spoken labels of entities appearing to come from their locations in the environment. (Adapted from Figure 1 from Loomis, Golledge, Klatzky, Speigle, and Tietz [1994]. © 1994 Association for Computing Machinery, Inc. Reprinted by permission.)

about the most immediate environment (e.g., obstacles); thus, the blind traveler will still have to rely on the long cane, seeing-eye dog, or ultrasonic sensing devices for this information. The current implementation of our system weighs 11 kg and is carried in a backpack worn by the user (Figure 13.3), but the version being developed will be truly wearable.

FIG. 13.3. Current implementation of the Personal Guidance System being worn by author Reginald Golledge. Miniaturization will eventually result in a wearable system like that depicted in Figure 13.2.

The first module of our system (Figure 13.4) determines the position and orientation of the traveler. For positioning, we have used a number of DGPS configurations. The configuration used in the experiments mentioned below consisted of a Trimble 12-channel GPS receiver with differential correction from a base station located 20 km away (Accqpoint Wide Area DGPS service). DGPS fixes, with absolute errors of about 1 m and much better relative accuracy, were provided at the rate of 0.67 Hz. Although GPS can indicate the traveler's course (direction of travel over the ground) on the basis of successive position fixes, navigation systems are more effective when heading is independently available, for travel instructions are usually expressed relative to the traveler's heading rather than course, and course is not defined for a stationary traveler. For the sensing of heading (of either the head or of the body), we have used a fluxgate compass attached either

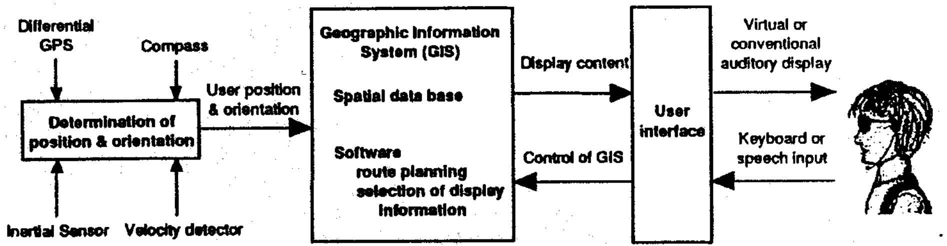

FIG. 13.4. Functional components of a GPS-based navigation system for the visually impaired. (From Loomis, Golledge, Klatzky, Speigle, and Tietz [1994]. © 1994 Association for Computing Machinery, Inc. Reprinted by permission.)

to the strap of the earphones worn on the head or to the backpack carrying the rest of the equipment.

The second module of our system (Figure 13.4) is the subnotebook computer containing the Geographic Information System (GIS), which comprises the environmental 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. Our main development efforts have gone into creating a reliable system, developing the database of campus and developing the GIS software that provides the traveler with the desired functionality (Golledge, Loomis, Klatzky, Flury, & Yang, 1991; Golledge, Klatzky, Speigle, Loomis, & Tietz, 1998).

The third module of our system (Figure 13.4) is the user interface. For user input, we currently use a 24-button keypad, but in the version being developed we will use a lapel microphone and speech-recognition software. Almost all of our development effort has gone into the display component. Our approach of using virtual sound contrasts with all other projects on GPS-based navigation systems for the visually impaired, for these others use conventional synthesized speech to convey information to the traveler. Research and user preferences will ultimately determine which approach is better.

The system provides information for route guidance as well as about the spatial disposition of important off-route entities (e.g., buildings, well-known landmarks). Route guidance information is provided by a succession of virtual beacons placed at significant choice points (waypoints) along that path. The virtual beacons are activated in sequence as a path is followed, and each beacon in turn becomes more intense as the traveler approaches it. Homing occurs by turning one's head until the sound source appears

directly in front of the head and then orienting the body in that direction and walking toward the source. Additional information can be provided about off-route entities, also using virtual sound. Here, the traveler is informed about some subset of the surrounding environmental entities by having their names spoken by a speech synthesizer and then rendered as spatialized sound by the virtual display. The traveler can activate this additional layer of information whenever it is desired.

We have conducted a number of informal demonstrations of the system at our test site, the UCSB campus. With these demonstrations, we have shown the capability of the system to guide an unsighted person with normal binaural hearing to some specified destination using a sequence of virtual beacons; under conditions of good satellite availability, the DGPS component functions well enough to keep the traveler within sidewalks about 5 m in width.

RESEARCH ON AUDITORY DISPLAY MODES

The formal research we have done with the current system has been concerned with comparing the effectiveness of spatialized speech from a virtual acoustic display with nonspatialized speech that conveyed the spatial information in words. The first of two experiments we have conducted was concerned with route guidance (Loomis, Golledge, & Klatzky, 1998). Our primary interest was in determining whether spatialized speech 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.

In the experiment, the subject was led along one of four paths, each comprising 9 linear segments defined by 10 waypoints (specified by their DGPS coordinates). These were situated within a large open grassy field on campus. Each path was 71 m long. We evaluated four display modes in the experiment, three involving a conventional speech display and the fourth involving spatialized (virtual) sound (Figure 13.5). Auditory guidance information was given at two intermittency rates: fast (once every 1.5 s) or slow (once every 5.0 s).

In the Virtual mode, the fluxgate compass was mounted on the earphone strap and thus provided the heading of the person's head. The navigation system computer constantly updated the distance and relative bearing of

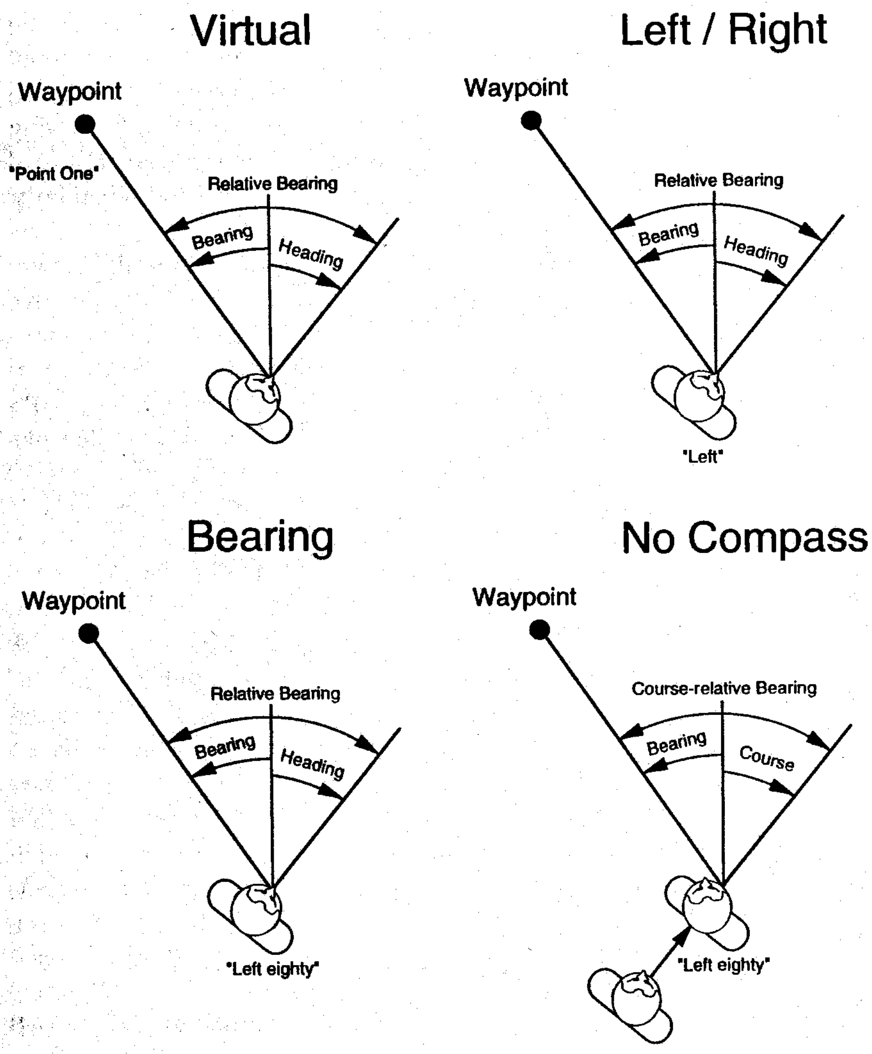

FIG. 13.5. Auditory display modes used in the experiment by Loomis, Golledge, and Klatzky (1998). See text for details. (© MIT Press. Reprinted by permission.)

the waypoint (here, Point 1) with respect to the subject's head. By turning his/her head in its direction, the subject could center the perceived sound within the median plane and then walk in that direction. As the subject approached the computer-defined waypoint, the sound level of the utterance increased appropriately. When the subject approached within 1.5 m of the waypoint, the computer took this as being at the waypoint and then activated the next waypoint in sequence. In the Left/Right mode, the fluxgate compass was mounted on the backpack worn by the subject and indicated heading of the subject's torso. The speech synthesizer provided information about the bearing of the next waypoint ("left"/"straight"/"right") relative to the subject's heading. The Bearing mode was like the Left/Right mode except that more information about relative bearing was provided. Here, the relative bearing between the body and the next waypoint, rounded to the nearest 10 deg, was spoken (e.g., "left 80"). Finally, the No Compass mode was like the Bearing mode, in that the subject received the same type of verbal command from the computer (e.g., "left 80"). However, the bearing of the next waypoint relative to the subject's course (based on two successive DGPS fixes) was spoken by the synthesizer. If the subject stopped moving, however, course was not defined, and the computer stopped issuing commands.

The two performance measures (time to complete the route and travel distance) as well as the subjective ratings by the ten blind subjects showed a slight superiority of the Virtual mode over the next best mode, Bearing (time to completion is shown in Figure 13.6). The No Compass mode was decidedly worst, both in terms of performance and ratings. The experimental findings show the importance of using a compass to provide heading information for route guidance and the potential benefit of using spatialized virtual sound over conventional speech information.

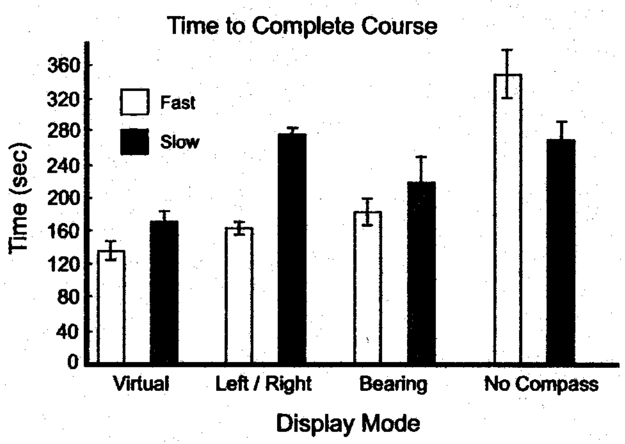

FIG. 13.6. Results of the experiment on guidance using different auditory display modes. Time to finish walking the 71 m path is given as a function of display mode and rate at which information was given to the subject (once every 1.5 s or every 5.0 s). (From Loomis, Golledge, and Klatzky [1998]. © MIT Press. Reprinted by permission.)

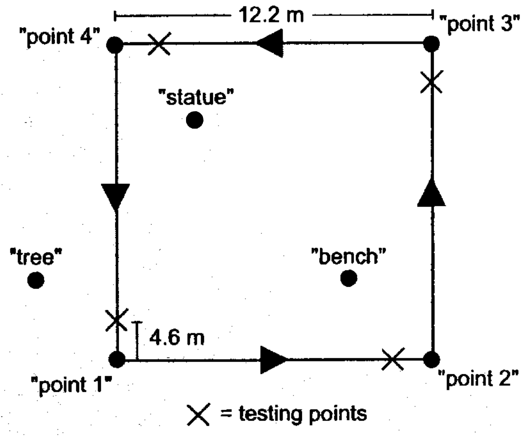

FIG. 13.7. One of the spatial configurations of landmarks along with the walking route used in the experiment on spatial learning. Subjects walked around the square in a counterclockwise direction. They were led to each waypoint (vertex) by means of spatialized speech indicating the next waypoint. Information about the locations of three off-route landmarks using either spatialized virtual speech (e.g., "statue") or nonspatialized speech (e.g., "statue, 4 o'clock") was presented on each leg of the square. After four traverses of the square during the learning phase, the subject was tested at each of the four marked locations.

The second experiment we have conducted on auditory display modes was concerned with the learning of spatial layout. In the training phase, the subject was guided five times around a square (12.2 m on a side) using virtual beacons located at the four vertices (Figure 13.7). Along each side of the square, the subject received information about the location of each of three off-route landmarks, identified by names (e.g., "statue") spoken by a synthesizer. In the Virtual mode, subjects heard the name as spatialized speech from the virtual display, as in the preceding experiment. In the Bearing mode, the subjects heard nonspatialized speech giving the approximate relative bearing to each landmark in terms of a clockface (e.g., "statue, 3 o'clock"). Two different spatial configurations of landmarks were used, with proper counterbalancing of their assignment to the two conditions across subjects. Spatial learning was assessed using both tactual sketch maps and direction estimates. The latter were obtained during a sixth traverse of the square following the training phase. No information about the landmarks was provided during this sixth traverse. Along each leg, the subject was instructed to stop at a testing location (indicated by the "X" in Figure 13.7) and there the subject was given the name of each landmark (without directional information) and responded with its relative bearing (stated in terms of a clockface, such as "ten o'clock" or "eleven thirty"). Absolute error was the primary performance measure; it is the absolute value of the difference between the relative bearing of the target and the subject's estimate.

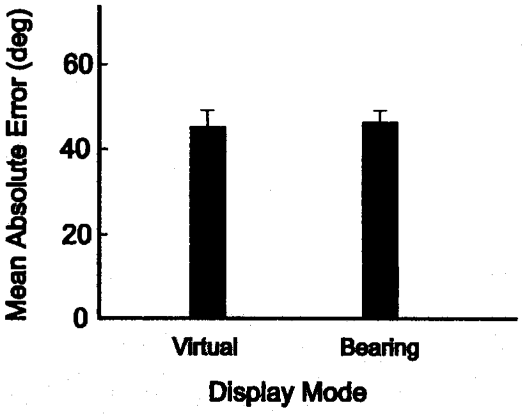

FIG. 13.8. Results of the spatial learning experiment.

Nine blind subjects performed in both conditions of the experiment (with counterbalancing of order and landmark configurations). Even with outlying data excluded, mean absolute error for the direction estimates was large but considerably better than chance performance (90 deg), as shown in Figure 13.8. There were no statistically reliable differences between the two modes. Sketch map performance was similarly unimpressive, with there being no differences between modes. Although performance was disappointing, a brief spatial learning experiment such as this surely does not indicate how well visually impaired travelers could perform following extensive practice with such a system. A visually impaired person using such a system every day while walking to and from work could eventually learn a great deal about the surrounding environment, even if only a small amount of landmark information were acquired each day.

The two experiments together indicate that spatialized speech from a virtual acoustic display has promise as part of the user interface of a blind navigation system. Performance was at least as good as with the other display modes investigated, and spatialized speech has the additional advantage of consuming less time than conventional speech, for the latter must include the spatial information as part of the utterance. On the other hand, there are two difficulties currently associated with the use of spatialized sound. First, present earphone designs attenuate or distort some of the environmental information that is important to visually impaired travelers. This difficulty might be ameliorated, however, by using small transducers mounted a few centimeters from the ears. Second, realistic virtual sound that appears to come from moderate to large distances has been difficult to achieve so far. However, given that the difficulty lies more with current implementations of virtual sound than with the use of earphones per se (Loomis, Klatzky, & Golledge, 1999), it is probably just a matter of time before more effective algorithms for realistic virtual sound are developed.

We should mention, of course, that spatialized speech and nonspatialized speech do not exhaust the possibilities for the display of spatial information. Another promising display technique is based on the Talking Signs system for remote signage. As mentioned earlier, directional localization of the infrared transmitter is obtained by aiming the hand-held receiver to obtain maximum signal strength. The haptic information from the hand, wrist, and arm when the signal is maximal is apparently quite effective in allowing the user to perceive the direction of the transmitter (Bentzen & Mitchell, 1995). Thus, a navigation system interface that uses haptic information in a similar fashion ought to be similarly effective. Such an interface could be readily implemented in the form of a hand-held unit comprising a loudspeaker and an electronic compass. Rotation of the hand would result in a change in the compass signal. Software could then mimic the operation of the Talking Sign receiver so that audible speech from the speech synthesizer is produced only when the hand is pointed in the approximate direction of the virtual beacon or off-route landmark.

PROSPECTS FOR THE FUTURE

In view of the ever improving accuracy of GPS receivers, increasing coverage of differential correction, decreasing size and cost of electronics, increasing sophistication of GIS software, and growing availability of digital maps suitable for pedestrian travel, the prospects are excellent that truly wearable GPS-based navigation systems will someday be used by both the visually impaired and sighted populations (in connection with the latter, see Feiner, MacIntyre, Hollerer, & Webster, 1997). Surely, obstacles remain, such as the development of low-cost alternatives to GPS when GPS coverage is lacking, creation and maintenance of digital maps appropriate to blind travel, fabrication of reliable, affordable, and lightweight systems for all-weather operation, and coping with the inevitable liability issues.

However, because these are not insurmountable obstacles, we are confident that it is just a matter of time before navigation systems using GPS and local positioning technology (e.g., Talking Signs) will be routinely guiding visually impaired travelers through outdoor and indoor environments. 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 access as well. Moreover, we are hopeful that navigation systems with this information will allow the visually impaired to gradually develop more extensive and more coherent mental representations of the environment than they currently have.

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