Evaluation of Spatial Displays for Navigation without Sight

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We report on two route guidance tasks using a highly accurate GPS receiver. Eight participants who were visually impaired or blind traveled two routes, one on a city sidewalk, and one in a city park. We tested and compared two types of spatial output devices that give route guidance information. One output display used a hand-held pointer, using a standard Talking Signs receiver that integrated the GPS signal information with the Talking Signs® signal information. This device gave travel instructions and on-course confirmation when pointed in the proper direction. The other spatial display used auditory virtual reality that presented the audible spatial information (waypoint direction and distance) through small air-tubes inserted into the ear. Travel times, distance, and errors were recorded. In addition, we tested users' ability to find precise locations, such as the intersections of small paths and a bus stop pole. Various subjective ratings were collected about blind participants' needs and perception of the various display and output options that they used. All subjects completed the tasks with both output displays, found all the waypoints and locations, and rated the two displays highly. The virtual sound display produced superior times overall and received slightly higher favorable ratings.

Categories and Subject Descriptors: H.5.1 [**Information Systems**]: Information Interfaces and Presentation—*Multimedia Information Systems*; H.5.2 [**Information Systems**]: Information Interfaces and Presentation—*User interfaces*

General Terms: Artificial, augmented, and virtual realities, Evaluation/methodology; Ergonomics, Auditory I/O, User-Centered Design, Voice I/O, Haptic I/O

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1. INTRODUCTION

The Global Positioning System (GPS) has a myriad of uses beyond those originally intended by the U. S. Department of Defense. Current uses include aircraft navigation, car navigation, tracking and scheduling of fleets of commercial vehicles, and animal tracking in scientific research. For car navigation

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systems, visual map displays allow users to see where they are, where the destination is, and the street network for reaching the destination. In addition, such systems can provide textual route directions when desired.

Two decades ago, Loomis [1985] and Collins [1985] independently proposed using GPS to provide blind and visually impaired people with the ability to navigate through unfamiliar territory. Since then, much research and development has been devoted to this goal [e.g., Brusnighan et al. 1989; Golledge et al. 1991, 1998; Helal et al. 2001; LaPierre 1998; Loomis et al. 1994, 1998, 2005; Makino et al. 1996; Petrie et al. 1996; Talkenberg 1996; Walker and Lindsay 2004]. [Loomis et al. in press] provides a comprehensive review of electronic travel aids and wayfinding assistance for visually impaired travelers.

There are now three accessible GPS products for blind users including StreetTalk from Freedom Scientific, Trekker from HumanWare, and the BrailleNote GPS from Sendero Group (see evaluation by [Denham et al. 2004]), and more are sure to be introduced.

With most of the designs above, the display interface uses synthesized speech. While quite effective, speech presents the user with additional cognitive and memory loads relative to direct spatial perception [Klatzky et al. 2002, 2003]. An alternative is to use some sort of spatial display that provides the user with more direct perceptual information about the spatial layout of the environment, including the destination. The original idea of Loomis [1985] was to provide this perceptual information by means of a virtual sound display. Computer-generated sound incorporating auditory cues for distance and direction would allow the user to hear important locations in the environment, with their labels spoken by a speech synthesizer, coming from the appropriate locations within the user's auditory space. Experiments on route guidance have shown that blind travelers are able to travel more efficiently with a virtual sound display than with nonvirtual displays [Loomis et al. 1998, 2005]. A recent survey conducted with 30 blind travelers indicated that the respondents saw promise in other types of spatial displays that conveyed directional information using a body, hand, or head-oriented directional display [Golledge et al. 2004]. One such display might be an array of tactile stimulators arranged around the torso or neck, with one of the stimulators signaling at any moment the direction of the next waypoint along a route [Ertan et al. 1998]. Another such display is the Haptic Pointer Interface or HPI [Loomis et al. 2001]. The HPI mimics the functioning of a Talking Signs receiver, which is used in conjunction with the Talking Signs system of Remote Infrared Audible Signage (RIAS) [Crandall et al. 1999; Hatakeyama et al. 2004; Loughborough 1979; Marston and Golledge 2003]. Just as a traveler hears an utterance when pointing the RIAS receiver toward a RIAS transmitter, the person holding an HPI device would hear an utterance issued by the computer when the device is aimed toward an environmental location represented in the computer's database.

2. GOALS OF THE RESEARCH

The present research had three goals. With respect to the first goal, our previous research showed that the UCSB Personal Guidance System (PGS) performed very well in controlled experiments, when people followed paths where no physical structures (such as curbs and sidewalk edges) were available as cues [Loomis et al. 1998, 2005]. In this setting, it is necessary to provide spatial guidance cues frequently, because paths and waypoints are arbitrarily defined and not signaled by the environment. The first goal of the present research was to move from these controlled settings with minimal environmental cues to surroundings that are more characteristic of the blind traveler's everyday activities. The move to everyday environments was made possible in part by the highly accurate GPS receiver (less than 1 m absolute error) we have been using. This GPS receiver allowed for testing with locations like a bus stop pole or intersections within a network of paths located inside a city park.

The second goal of the research was to see how often people would choose to use the spatial display to find the precise direction to the next waypoint. In normal travel on streets and sidewalks, the average blind user has available navigation skills learned over time and through Orientation and Mobility (O & M) training. It is possible that these skills are sufficient for most guidance, so that a Personal Guidance System would be queried only infrequently. We also wanted to test if the directional cues would be used less in a structured space, as when walking along a city sidewalk, than in other, more open situations, where fewer cues are available to guide travel. By allowing people to control the amount of time directional spatial information was received in various locations, we could measure their usage. We further investigated whether more skilled (i.e., faster) blind travelers would use spatial display cues less often. To address these issues, the experiment measured usage by a group of blind travelers in two different environments and also investigated the relationship between total travel time and usage.

The third goal was to compare two different kinds of guidance display: a variant of the HPI and a virtual sound display, which used earphones. We have evaluated these before in our more controlled environments and we wanted to compare them in more realistic travel environments. In addition, we wanted to evaluate a prototype design (first developed at UCSB in 2003) that integrated GPS with RIAS. For the HPI display, we mounted the directional compass used by the HPI directly on top of a RIAS receiver. The traveler could then use the hand-held receiver in HPI mode during large-scale travel, but could also pick up the RIAS signal when close to a RIAS transmitter. For the virtual sound display, the users wore the RIAS receiver around the neck and used it when notified that they were within range. We did not feel the need to design and build a second interface that would work with the virtual sound display; proof of concept was only desired for one of the two spatial displays.

As a final interest, we followed up on an observation from our previous experiments. Although these had shown that the headphones that delivered the spatial information were very effective, some blind users expressed concerns, because the headphones blocked out some important ambient sounds, including echolocation information. In this experiment, we tested a type of earphone (fabricated and tested at UCSB in 2004) that did not block ambient sound.

To summarize, the experiment was principally intended to measure the effectiveness of two display interfaces in two "real-world" environments and to determine the frequency of requests for detailed directional guidance as a function of environment and user's skill. Given the success that had been demonstrated with similar systems in arbitrary environments, we expected excellent performance, including the ability to identify specific locations, such as a bus stop pole and the ability to integrate GPS-based devices with RIAS signals. A final concern was with the acceptability of earphones that did not impede or mask environmental sounds.

3. METHOD

3.1 Participants

Potential participants came from the UCSB campus and contacts with the local Braille Institute. They were contacted by phone and informed of the experiment to determine if they were interested in participating. Eight legally blind people (six male) took part in the experiment. Five had never tried our prototype PGS, three had taken part in a previous experiment. There was a wide range of ages, types of vision loss, and skills. Ages ranged from 19 to 84 with a mean of 43 (SD = 21.3). Three were born blind; the others became blind at 2, 5, 24, 44, and 74 years of age. Four agreed with the statement that they "saw nothing, everything is the same," one reported ability to see shapes, and three said they could identify objects at arm's length. Three of the eight said they could see enough to avoid obstacles while traveling. Etiology of blindness varied widely: retinopathy of prematurity, retinitis pigmentosa, glaucoma, macular degeneration, cataracts, detached retina, and blastoma. Six used a cane as their primary aid, one normally used a guide dog, and one did not usually use a mobility aid. All reported having OsM training and self-ratings on various mobility tasks (1 = well below average and 5 = well

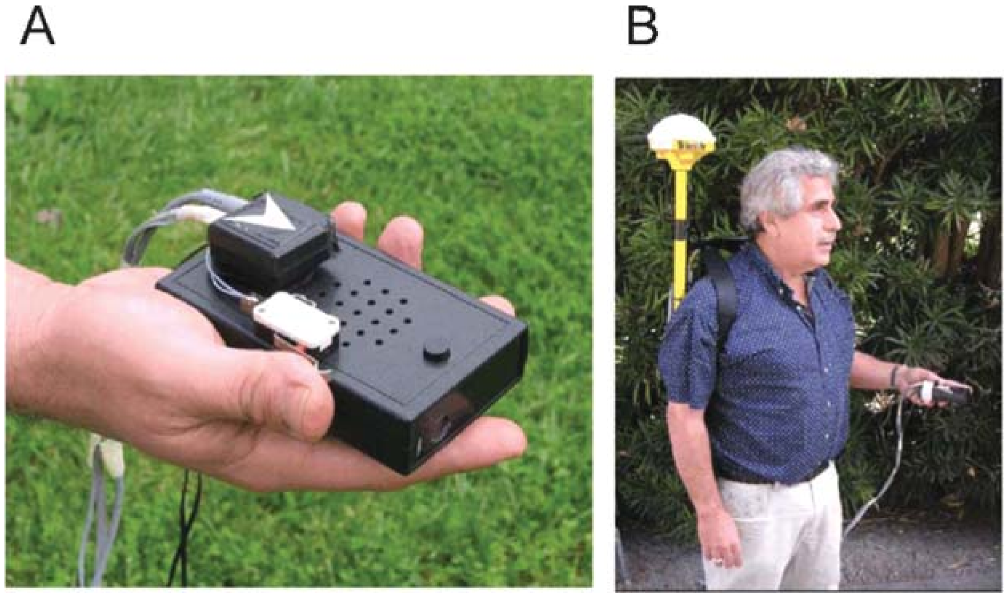

Fig. 1. Some hardware components of the UCSB Personal Guidance System. (A) Shows the Haptic Pointer Interface (HPI) with Talking Signs RIAS interface. At the front is the aperture for receiving the infrared beam, on top is the flux compass, speaker, and a switch to activate the spatial information when desired. (B) Shows the first author with the PGS with HPI spatial display.

above average), provided mean ratings between 2.4 and 3.8, with a group mean of 3.3. None reported a hearing loss, and, since we were testing spatialized sound through earphones, all were tested to make sure they could localize sounds by pointing to the source.

3.2 Hardware and Software

The UCSB PGS for the blind consists of three components: a computer database consisting of geographic and route network information, a GPS receiver to track the location of the user, and a user interface. The computer system, database, GPS receiver, and fluxgate compass that gives heading information were all detailed previously [Loomis et al. 2005]. The experiments reported here used the same system, except for modifications in the spatial displays designed for this research; these modifications are described in the next section.

3.3 Spatial Displays Tested

In this experiment, two spatial displays were used. One was a modified version of the haptic pointer interface (HPI) [Loomis et al. 2001, 2005] that also incorporated a Talking Signs RIAS receiver [Crandall et al. 1999; Marston and Golledge 2003], with a built in speaker. An electronic flux compass was mounted on this receiver so that it could also act as a hand-held pointing device for the GPS (Figure 1A). When the HPI was pointed within 10° of the next waypoint, users heard a fast beeping sound from the speaker in the hand-held unit and walked in that direction.

The other display was a variation of the virtual sound display used in earlier research [Loomis et al. 1998, 2005]. A rapid beeping sound was spatialized by virtual acoustic software so that the beeps appeared to come from the direction of the next waypoint. This beeping sound was delivered through small air tubes in the ear. Air tubes to deliver audible information for the blind were used for an ultrasonic sensing device called the Sonic Torch (renamed the Sonicguide in 1976) [Kay 1964]. The

UCSB acoustic coupling earphones were fabricated and tested in 2004 and made use of pliable air tubes developed for the *hands-free* Talking Signs device designed by Mitsubishi Precision Company.

For both displays, the remaining distance to the next waypoint was announced every 8 s. In addition, there was a button that, when depressed, produced the spatialized beeping sound to provide directional information, but, when released, produced no sound and thus no directional information. Figure 1B shows the PGS with the RIAS receiver-based HPI interface being carried by the first author.

3.4 Interview and Familiarization

After the personal information about blindness and skills was recorded, we familiarized participants with the procedures and use of our PGS. To ensure that they understood bearing degrees and directions, several bearings were spoken (e.g. 45° right) and they were asked to point in that direction relative to straight ahead. They were given a raised line tactile map that they traced with their fingers as an example of a general route following task. Next, they traced the same route that included circles around each waypoint (decision point); it was explained that these circles represented the 2.1 m area they needed to find in order to trigger the next waypoint announcement. Upon arriving within the radius of a waypoint, they would hear synthesized speech that would say "next waypoint x feet at y degrees z" where z would be either left or right, to give them an idea which way to turn for the next path leg.

3.5 Practice Walk

All participants with any residual vision wore a blindfold and all were required to use a cane. Experiments were scheduled only when GPS reliability was determined to be appropriate, based upon a computer almanac and software (Trimble Planning Software Venison 2.7) showing that the horizontal dilution of precision (HDOP) was less than 2.0.[1] While walking to the test site, subjects used and tested features of both output devices. They first used the HPI for a walk of approximately 428 m along straight and curved sidewalks. Next, the virtual sound display earphones with air tubes were used to cross a large parking lot and then travel on sidewalks to the starting point, a length of 320 m. Both of these practice routes had multiple waypoints and thus participants could learn how to find a waypoint, and, then, how to react correctly to the waypoint turn information using both displays.

Each of the two practice walks started with the participants holding down a button, which gave continuous beeps that indicated the direction of travel. Midway through each of the two walks, where there were curbs on a straight sidewalk, participants were asked to release the button triggering the spatial display, so that they received only the automatic distance update every 8 s. It was suggested to the users that they might not always need to hear the constant target direction information delivered by the spatial display. However, no mention was made that we would be recording how often they used the button for spatial information during the test. In addition, before starting the experiment, participants had a few practice trials using the Talking Signs RIAS receiver to find an off-route transmitter mounted on a bus stop pole. Before starting with the virtual sound display, they practiced with the regular RIAS receiver worn around the neck; when starting the test with the RIAS-based HPI, they used that hand-held unit to practice finding the bus stop.

3.6 Test Areas

Previous experiments using the UCSB PGS took place in open areas, with no tactile or environmental cues (sidewalks, curbs, traffic noise, and other people, etc.) for guidance. In those previous tests, subjects

[1]Various measures (dilution of precision) can be used to estimate GPS accuracy. They are based on the geometry (location and number) of satellites available at any point in time. The horizontal dilution of precision, used here, reflects the accuracy of 2D space on the ground and does not include altitude in its calculation. Smaller numbers indicate better accuracy.

Fig. 2. City sidewalk experiment site with four waypoints. Participants started at waypoint 0 and walked to street corners 1 and 2. Waypoint 3 was a bus stop pole, the location of which was stored in the database and identified by GPS. Waypoint 4 was another bus stop pole that was labeled with a RIAS transmitter and was identified using a RIAS receiver. Distances are shown in meters.

had to follow continuously presented guidance information delivered to the user. We call this type of space "unbounded." To enhance our understanding of what persons with visual impairments need or desire in a PGS to be used in the "real world," we conducted an experiment in two very different types of areas that can be described as "bounded" space [Gaunet in press; Gaunet and Briffault 2005] and also in a "semi-bounded" space—in this case, a city street and an urban park, respectively.

One site was on busy sidewalks next to streets, with a variety of street furniture, parked bicycles, and people. For this test, subjects followed the GPS information (direction of beeps and distance information) to four waypoints for a total of 244 m, as shown in Figure 2. The third waypoint was a bus stop pole coded in the database and announced by GPS. In both conditions, the spatial display announced this waypoint as being a bus stop.

The instructions to the user were to stay on the sidewalk and to locate the four waypoints; no other directional information was given. When participants were within 10 m of the final waypoint, an announcement through the HPI speaker or air tubes indicated that they were to use the appropriate RIAS receiver to locate a second bus stop pole (waypoint 4) that was equipped with a RIAS transmitter.

The other experimental site was a 187 m route in a park, shown in Figure 3. The paths included a stretch of concrete sidewalk along a street that bounded the park. Inside the park were paths of

Fig. 3. Park experiment site with seven waypoints. Participants started at waypoint 0 and walked progressively to 7, the final waypoint. Selected distances are shown in meters.

concrete, crushed gravel, and paver blocks. Participants were told to find seven waypoints. They were informed that some of the paths might have slight curves, and they should stay on the sidewalk or gravel path and not deviate into the grass.

Each participant followed both routes with both devices, in counterbalanced order across participants. The experiment lasted approximately two to three hours in one continuous session, including interviews, instructions, practice walks, the four test paths that were navigated, and the posttest interviews.

4. RESULTS

4.1 Overview of Performance

Time to complete each path, errors made, the percentage of the total time that users accessed the spatial directional information, and the distance traveled were recorded. With eight subjects, two displays, and two devices, there were 32 trials. Two trials were not run or aborted because of power supply failures. Of the remaining 30 observations, all participants were able to follow the routes and finish the experiment by finding the final waypoint, with no outside assistance.

All users found the seven waypoints in the park, which were at the intersections of sidewalks and gravel paths having widths of 1.8 and 1.2 m, respectively. In the city sidewalk test, all participants found the first two sidewalk intersections and the third waypoint with the GPS-signaled bus stop. All subjects also successfully used both devices to find the last waypoint in the street environment. That waypoint—a bus stop pole—was announced through the PGS output display when users approached it within 10 m. They were then required to find it with the HPI RIAS directional beam, as shown in Figure 4, or, when using the virtual sound display, they used the RIAS receiver that was worn around the neck. The RIAS-equipped bus stop pole required, in both conditions, the transition from use of the PGS output to the RIAS output. All participants found all the waypoints and finished the test paths with both spatial displays.

Fig. 4. First author using the HPI RIAS interface to locate an infrared transmitter at a bus stop, street waypoint 4.

4.2 Distance Measures

A log file was created showing the position of the receiver every second. In addition, it shows when the request for directional information was turned on and when it was turned off. Examination of these plotted log files show that although the fidelity of the trajectory relative to the desired path varied, there is no doubt that subjects were successful at using both versions of the PGS in both environments. Actual traveled distance was compared to direct "scheduled" distance to determine the accuracy of participants' path following performance. Of path trials 27% were completed, with less than 10% additional distance, the mean extra distance for all trials was 18%.

In the park test, one person did not pay full attention and walked past a waypoint, before being aware that the auditory announcement of distance to the next waypoint was increasing, and turned back to complete the task. On the street sidewalk trial, one person could not always maintain a straight course of travel, and, in one place, veered off path and got trapped in a collection of bicycles parked in a large bike rack; these problems added about 94 m to the distance traveled.

Before discussing users' travel times, we briefly mention an important issue in the design of navigation systems for blind people. Research on the waypoint capture radius [Walker and Lindsey 2004, in press] shows that the size of the waypoint activation radius can influence the speed–accuracy tradeoff. They conducted a virtual reality guidance test with a small, medium, and large capture radius, 0.5, 1.5, and 15 m, respectively. If the radius is too small, a person can overshoot the waypoint and spend time searching for it. When the radius is too large, it is easy to find and trigger the waypoint, but this leads to making turns well before the true waypoint is found, leading to shorter walking distances, but negatively impacting the accuracy and safety of the navigation task. In their experiment, the medium capture radius, 1.5 m, was the best speed-accuracy tradeoff.

Table I. Mean Times (Seconds) Using Two Displays at Two Sites

	Street		Park	
	Virtual Sound	HPI	Virtual Sound	HPI
Mean	406.7	438.5	344.3	427.5
SD	95.5	108.6	97.5	138.4

The UCSB group has been using a similar waypoint radius, 2.1 m. The correlations over subjects (where data were available) between distance and time were positive for all four conditions (0.81, 0.27, 0.62, and 0.76 for street earphones, street HPI, park earphones, and park HPI, respectively), suggesting that subjects did not truncate distance at the expense of time, which would be expected from too large a radius. This waypoint radius has continued to show good results, and, as our participants always use their cane to avoid obstacles, has proved very safe.

4.3 Time to Complete Routes

The mean times and SDs are shown in Table I. One outlier was removed from the virtual sound/street condition, where the subject became trapped for some time between parked bicycles, yielding a time more than 2 SDs from the mean for that condition. When data from the two sites were averaged, observations at one or both sites were available for all eight subjects. A t-test of the hypothesis that times would be shorter for the virtual sound display approached significance, $t(7) = 1.80$, $p = .058$.

4.4 Standardized Completion Times

The distance and difficulty of the two paths were different and we standardized the data compared to the walking time of sighted people using the PGS. Mean times were calculated for three sighted people (i.e., without blindfolds) who walked the paths with the equipment, using a cane as they walked and listening to the distance, waypoint announcements, and turn information (this was done because there is a small amount of lag time when using a GPS). This allowed us to understand the minimum time it would take to use the system when no visual impairment was present. A relative access measure (RAM) has been used to show the extra effort that people with disabilities face. By comparing the travel time (TT) or distance of a trip to that of a fully mobile person, we can standardize these measures and produce a ratio ($TT_{participant}$ / $TT_{sighted}$), which reflects this extra "penalty" of travel with various limitations [Church and Marston 2003; Marston and Church 2005]. A RAM of 1.0 indicates that the person with the disability is able to complete the task with the same time as a typical sighted person, while higher numbers reflect added difficulty of the task for those with a disability.

Figure 5 shows the RAM for the eight participants, for each of the sites, and spatial displays. Considering the difficulty of the area and the fact that this was the first time that these people had ever attempted these paths, all performances were quite successful. Although all RAMs were greater than 1, some subjects were close to the time of the sighted travelers, and four of eight were well within a factor of double the time of the sighted users. From best to worse, the RAMs for the four conditions, park earphones, street HPI, street earphones, and park HPI, were 1.93, 2.08, 2.14, and 2.36, respectively. The mean for all subjects was slightly over twice as slow as the sighted users (a factor of 2.1).

As measured by RAM, differences in performance between the two devices were observed in the park site. Considering the six participants for whom data were available, they all performed better with the virtual sound display than with the HPI in the park.

4.5 Performance Relative to Blindfolded Sighted Users

To evaluate the value and use of visual memory, we measured the tasks' walking times for the two sighted field researchers while they were blindfolded and using the PGS. One of the researchers had used a blindfold and cane before, but had never had formal O & M training (some experience), while the

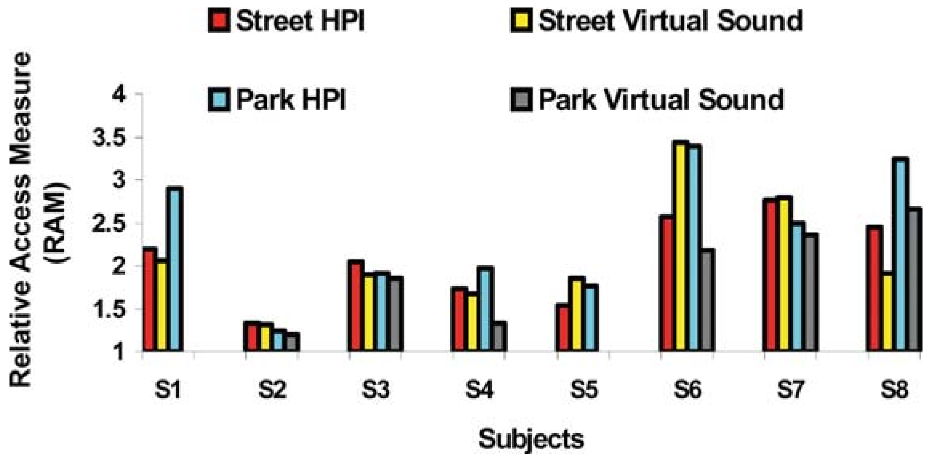

Fig. 5. Relative access measure (RAM): Travel time compared to a sighted user.

Table II. Mean Time (Percentage) that Spatial Display was Queried

	Street		Park	
	Virtual Sound	HPI	Virtual Sound	HPI
Mean	76.8	76.9	91.8	85.7
SD	16.9	18.3	9.0	18.7

other researcher had never attempted blindfolded cane travel (novice). This test was conducted after the two field researchers had walked the paths many times before and during the experiment. The novice cane user, when blindfolded, had times that were slower than all of the blind participant's results at the street site, while the other experimenter (some experience) was slower than 69% of those trials. Although the two sighted researchers reported having a vivid mental image of the path, the varying amount of street furniture, such as bicycles, signs, planters, and other obstacles) caused many problems for these two untrained travelers. The park site had no obstacles on the paths and was much easier for them. Visual memory appeared to help much more in that situation, as all that was needed was to turn at each intersection and follow the path with the cane. However, the repeated visual exposure to the test site was still not enough to overcome the travel and cane skills of some of the blind people on their first exposure to this site. The "novice" was slower than 50% of the timed performances and the "some experience" person was slower than 21% of the time trials in the park.

4.6 Use of Directional Information

In our previous experiments, participants were required to use the spatial directional cues at all times to follow computer-defined paths in an open area. At our current two test sites, participants were allowed to choose when to use the directional information. Table II shows the percentage of the total travel time that the direction cues were accessed. Participants tended to query this type of information more often while in the semibounded area of the park than in the bounded city sidewalk task. In all cases where data are available for the same display in both sites, users accessed the spatial directional information more often in the park than on the city sidewalk. When data from the two devices were averaged, observations from both sites were available for all eight subjects. A t-test comparing the street and park confirmed significantly greater use in the park, $t(7) = 4.83$, $p < 0.001$.

Table III. Ratings of Air-Tube Earphones in "Real-Life" Situations

Statement	Mean	SD
The headphones [earphones] do not block out traffic and other sounds that I need to hear for safe travel	4.5	0.53
These headphones [earphones] would interfere with my normal travel	1.6	0.52
I would not like to use this type of headphone [earphones] while exploring areas.	2.0	0.76
A commercial GPS system for the blind should offer this type of headphone [earphones] with spatialized sounds as an option.	4.6	0.52

Table IV. Ratings of Two Types of Acoustic Displays

	Air-Tube Earphones	Regular Headphones
Mean	1.3	2.9
SD	0.46	1.13

To determine whether use of the directional display was related to travel skill, we measured the correlation, across subjects, between average percentage use of the display and average time on the routes. The correlation was significant, $r(6) = 0.73$, $p < 0.05$, indicating that users who took less time to travel the route also used a lesser percentage of that time to query the system.

4.7 Evaluation of Air-Tube Earphone Display

After the field test was concluded, participants were asked to evaluate the equipment and to judge if certain features should be offered in commercial GPS products. Given previous reservations about headphones blocking environmental sounds, we included questions intended to determine their attitude toward using the air-tube earphones. These questions were asked after the field test and after they were given some additional comparison with no sound, in which they walked an additional 130 m along the busiest street without auditory input. The ratings were on a five-point scale from 1 = strongly disagree to 5 = strongly agree. Table III shows these results.

With little variation, participants rated the earphones as safe and valuable. To compare the new earphones to the headphones used earlier, we had participants stand on the busiest street corner for 2 minutes while wearing normal headphones and again while wearing the air-tube earphones. No audio was present at this time. They were asked to make a judgment, "With these headphones the important sounds I need to hear are blocked." The scale was 1 = none to 4 = a lot. Table IV shows that the air-tube earphones were judged to have almost no blockage, and the regular headphones were perceived to block important sounds a small amount. Thus it appears both head-mounted sound displays could be used, but there is some advantage for the air tubes with respect to access to environmental sounds.

4.8 Usage of Directional Information

Recall that users had the option of getting a directional beep when they wanted guidance on a pathway. If the option was not activated, they received only the distance information, at an interval of 8 s. We asked posttest questions to elicit their opinions about this option. The rating scale was 1 = strongly disagree to 5 = strongly agree. Table V shows users liked the positive confirmation of the correct direction and the option to turn it on and off. They said they would use this kind of directional information and that this type of spatial display should be available as an option for a commercial GPS product. The low SD indicates considerably uniformity on these opinions.

4.9 Use of High-Accuracy GPS Receiver to Find Specific Locations

This experiment used a very accurate GPS receiver that allowed participants to get very close in order to find specific locations. They were also able to switch from the GPS signal to receive information from

Table V. Ratings of the User-Controlled Spatial Display Output Devices

Statement	Mean	SD
I like the positive confirmation when correctly pointing toward the direction of travel	4.4	0.52
I like to be able to turn off the directional cues when I don't need them	4.4	0.52
I like being able to turn on a directional cue if I need it	4.5	0.53
I would never need to use the pointing information while traveling	1.6	0.52
A commercial GPS system for the blind should have the option to get path direction cues when needed	4.4	0.52

Table VI. Ratings of High-Accuracy GPS and Interface with Other Location-Information Devices

Statement	Mean	SD
Finding a specific location like a bus stop pole is important for successful independent travel when using a GPS system	4.5	0.53
Being able to switch from GPS to another system, like Talking Signs is helpful, especially when the GPS cannot receive signals (like indoors)	4.1	0.64
A commercial GPS system for the blind should allow users to access other types of technology that provide spatial information	4.6	0.52

Table VII. Comparisons of the Two Spatial Displays

Statement	HPI	SD		Virtual Sound	SD
Precision of the directional information	4.0	0		4.1	0.83
Personal safety while using the device	4.1	.35		4.0	0.76
Ease of use	3.5	.53		4.6	0.52

RIAS. Participants rated their agreement with the following question on a five-point scale from 1 = strongly disagree to 5 = strongly agree. Table VI shows that they strongly agreed that finding specific locations, such as a bus stop, is important in a commercial GPS product, and that a commercial GPS should allow users to access other types of location-based information.

4.10 Comparison of the Two Spatial Displays

Table VII shows the results of three questions that asked participants to rate the perceived precision of the spatial information, their perceived safety when using the equipment, and the ease of use. The ratings were on a scale of 1–5, from 1 = very unacceptable to 5 = very acceptable. Equal ratings were accepted for both configurations. Ratings for perception of precision and safety were about equal, but the HPI was judged less easy to use. As explained in the user comments in this experiment and a previous one [Loomis et al. 2005], the HPI needs to be held level and occupies one hand, while the earphone requires only that users keep the head level.

4.11 Desired Distance Interval

When participants were asked how often they would like to hear distance information to the next waypoint, the responses were between 5 and 10 sec, with a mean of 8.3 and SD of 1.9. This is close to the original 8 s that was used in the current display. When asked if they would like this information to be variable, all eight subjects agreed, indicating that they would like the information more often as they approached the waypoint, as required, or on demand.

4.12 User Comments

After the experiment, participants were asked for any additional comments; both positive and negative opinions were encouraged. They were very impressed with both spatial displays and the PGS as a navigation tool. One participant mentioned how he could "see" while blindfolded, and another said he really liked to "look" toward the next waypoint. Many praised the distance confirmation and mentioned how this made it easy to find street corners. They also mentioned the ease of finding specific locations, such as finding a bus stop pole. Comments mentioned how easy it would be to travel to new locations and how they could even cross large parking lots with this type of system. One person said, "PGS is able to direct blind people to locations and bus stops."

As expected, the air-tube earphones received more positive comments. The intuitive nature of the spatial display from the earphones was mentioned. With them, one does not have to hold anything, and one can receive information just by turning the head. Although the HPI worked well, some people mentioned that they did not like to keep the device level, and that they had to keep it in their hand. (A small electronically gimbaled compass would enable a display that could be mounted on the finger, wrist, or on the cane itself and would free up the hand and eliminate the need to keep the device level.)

5. DISCUSSION

One of the major goals of this research was to see how the PGS performed in real-world environments and to determine if the system could be used to safely navigate common environments (a park and streetscape) and find specific goals. The other goals were to determine how often users would query the system for directional information while moving through the environment and to evaluate the differences and efficacy of using two interfaces: a HPI hand-held device and a head-mounted spatialized sound display. The fact that all participants were able to complete the tasks with both spatial displays shows the power of these two display options. The precise GPS receiver used in this experiment allowed people to find bus stop poles and sidewalk intersections, indicating how highly accurate GPS receivers, when coupled with accurate databases, hold great promise to increase travel and navigational opportunities for persons with visual impairments. This type of accuracy could be coupled to databases that are imbedded with transit stop and schedule information, making walking and transit trips in an unfamiliar area a seamless endeavor, with no need to painstakingly memorize schedules as well as find and use various transit stops. No longer would a blind person be dependent on others when learning to find and use transit access points along new or infrequently used routes. This type of accuracy would allow users to locate individual doorways to buildings and shops, find wastebaskets on the street, crosswalk locations, or even find a mailbox (as demonstrated on the UCSB campus).

In addition, the finding that participants found it easy to switch from a GPS signal to another location-based system, the RIAS system that labels specific locations, indicates that this kind of flexible interface is another desired requirement for a truly useful PGS. Users could move seamlessly from the outdoor environment into transit terminals, and other buildings equipped with RIAS or other forms of location identifying systems. The RIAS receiver can provide route identification information transmitted from an approaching vehicle. RIAS also provides real time information from dynamic displays, such as those manufactured by NextBus, inform waiting passengers of the arrival time of the next transit vehicle.

Participants did not use the spatial display all the time, but used it quite often. They used it less when other environmental cues were available. The better skilled travelers used it less than the others. We would assume that with more use, especially in the same area, their use would decrease further, but that this feature is a highly valued option for a PGS. When in doubt as to the correct direction to walk, or to gain the proper facing direction, one would have only to request that information from the system and orientation would be given in an intuitive and easy to understand manner.

The air-tube earphones were judged to be very acceptable for use in everyday situations. This allows people to access spatialized directional cues and instructions while still being able to hear needed environmental sounds.

6. CONCLUSION

Spatial displays, as developed and evaluated at UCSB, were shown here to be highly effective, even for first time users. The findings about the desire for a highly accurate system, which vastly increases navigation options, the desire to use a system that can interact with other location technologies, and the participants' acceptance of the air-tube earphone output device should add focus to future research on blind navigation aids. The high qualitative ratings given the spatial display and participants' strong desire to see these items in commercial systems might lead to a PGS that would allow persons who are visually impaired or blind to gain access to types of opportunities and travel options that have been either full of stress or required dependence on others. Systems, as reported here, have the potential to vastly increase the quality of life for this group and to increase opportunities for access to work, education, shopping, recreation, and social events located in unfamiliar areas, or even the ability to travel to a different city with little loss of independence.

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