Development of a Wearable Computer Orientation System

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Abstract: People with severe visual impairment need a means of remaining oriented to their environment as they move through it. A series of indoor and outdoor trials using a variety of technologies and interfaces led to the development and evaluation of three promising wearable orientation interfaces: a virtual sonic beacon, speech output, and a shoulder-tapping system. Street crossing was used as a critical test situation in which to evaluate these interfaces. The shoulder-tapping system was found most universally usable. Results indicated that, given the great variety of co-morbidities within this population, which is comprised of mostly older persons, optimal performance and flexibility may best be obtained in a design that combines the best elements of both the speech and shoulder-tapping interfaces.

Keywords: Blindness; Orientation aid; Street-crossing; Visual impairment; Wearable computer; Wearable interfaces

1. Statement of the Problem

There are approximately 11.4 million visually impaired persons in the United States, 10% of whom have no usable vision. The literature clearly shows that the prevalence of blindness rises steadily with age, and that nearly two-thirds of the visually impaired population is 65 years of age or older [1,2]. This rise in the average age of people with severe visual impairment is part of a major shift that has occurred over the last 25 years. It is the result of both the increase in average age of the general population, and the increased prevalence of diabetes and macular degeneration in this country. Because of these, the majority of people now experiencing the onset of a severe visual impairment are over the age of 60, and the number of people over 65 with a severe visual impairment will continue to rise dramatically [3].

The implication to rehabilitation strategies and the design of assistive technologies is that they must be adapted to suit the needs of this older population. While functional independence and good quality of life continue to be appropriate rehabilitation goals, the means of achieving these goals may be somewhat different for this older population. Many of these people are retired, or nearing retirement. At this age they may have a diminished interest in learning new skills, and may not want to learn Braille at all. They may also be experiencing the onset of various co-morbidities including hearing loss, loss of physical function, loss of cognitive function, loss of peripheral sensation (e.g. peripheral neuropathy), as well as smell and taste. The presence of these co-morbidities impacts the design of appropriate and useful assistive technology, and very directly impacts the design and usability of appropriate human interfaces.

Spatial orientation is a major problem for people with severe visual impairment of all ages, but is a particular problem for people who are older and may also be losing some cognitive, as well as proprioceptive and vestibular, function [4, 5]. Spatial orientation is distinctly different from mobility in that mobility depends on skillfully coordinating actions to avoid obstacles in the immediate path, whereas spatial orientation depends on coordinating ones actions relative to the farther-ranging surroundings and the desired destination [6]. Spatial orientation refers to the ability to establish and maintain an awareness of one's position in space relative to landmarks in the surrounding environment and relative to a particular destination [7]. Wayfinding is the means by which a person employs their spatial orientation to maintain a heading toward their destination regardless of the need to avoid or move around obstacles in their path. Successful coordination of actions within perceived

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surroundings in dynamic settings (such as traffic intersections) requires the guidance provided by *continuous* feedback from the environment [6].

Cues used to monitor environmental flow comprise the greater and most important part of such feedback. Environmental flow refers to the ordered changes in a pedestrian's distances and directions to things in the surroundings that occur while walking. Maintaining orientation is thus, to a great extent, a matter of keeping track of this environmental flow [6]. The environmental flow of walking can be perceived through a number of senses, though hearing is perhaps the most notable of these. When a person walks in the vicinity of soundmaking objects, changes in spatial relationships can be perceived with the shifting of sounds emitted by the objects. Listening to the echoes of object sounds, as well as sounds made by the person, can indicate distance to a wall, doorway, etc. [7].

The ability to detect heat and to smell is also important. Directionally specific sources of heat and odor can indicate location and facing direction. Temperature changes felt when walking into the shade of a familiar setting are useful, and the door of an air-conditioned bus can be detected by the cool air that flows out when the door is opened [6].

The sensation of walking is also an important source of perceptual input. Skillful travelers keep track of how their walking affects their distances and directions to objects in their surroundings, and use this information to guide them [6]. This type of sensate feedback has both proprioceptive and vestibular components. [8].

Orientation and Mobility (O&M) instructors train their students to make use of all the above, and more, in learning the skills needed for travelling independently. Even for young students with acute senses, acquiring the perceptual awareness and needed skills is not easy, and comes only with much practice, patience and experience [9]. For the older adult with some hearing loss, and perhaps other sensate losses as well, it may not be possible to acquire all the needed skills taught by O&M instructors. For example, with a hearing impairment it may not be possible to learn to judge object distances by becoming aware of the loudness of sound sources and how loudness varies with distance [6]. As a result, the instructor may warn some older students not to attempt independent travel in certain environments.

With regard to wayfinding, the tendency to veer from a straight path is a major problem. Even if the individual is initially oriented to the environment, starts out facing their destination, and encounters no obstacles; problems with veering can make it necessary to re-orient often. This is the case for people of all ages. A large body of research documents the inability of blind pedestrians to maintain a straight-line path (i.e. not veer) in the absence of external guidance [10–12]. Even the highly experienced blind pedestrian exhibits random variable error large enough to occasionally result in their veering into a parallel street when crossing at an intersection [6].

2. Existing Orientation Technologies

While there has been a great deal of research in the area of electronic travel aids for obstacle avoidance [13], there has been little comparable research for the development of general-purpose orientation devices. The few orientation devices that exist have many limitations, not the least of which is the fact that none offer a full complement of the types of orientation information most often needed. From the above discussions it should be clear that, a "full complement" of orientation information should include: (1) current location and heading relative to known landmarks and the desired destination; (2) distance and direction to surrounding landmarks and the desired destination; (3) overall layout of the greater surrounding environment; and (4) things of particular interest to the user in the greater surrounding environment.

Braille labels have been used to describe the layout of the immediate environment surrounding them. The problem, though, is that there is no means of knowing when Braille labels have been placed in a particular environment, and where they might be located. Technology has also been developed for the production of Braille and tactile maps to provide overview information about an area. However, these maps are bulky, not easily carried for *in situ* reference, and older people may have difficulty using them [13].

Talking Signs® were developed by, among others, the Smith-Kettlewell Eye Research Institute as a useful addition to Braille labels

[14,15]. These "signs" employ a coded beam of light to transmit a set message from the "sign" to a receiver held by the user. These signs provide information typically provided by printed signs. Further, the light beam from these "signs" can be used as a "beacon" to help the user orient to the setting. Special versions of these "signs" can be integrated into pedestrian crossing signals to provide "Walk," "Don't Walk," and "Don't Start" information, and orient the user to the direction of the opposite corner [14,15].

Existing talking sign systems have major limitations. To discover the existence of a "sign," a user must regularly scan each new setting with a hand-held receiver. However, for safety reasons, the manufacturers recommend the user not walk while using the receiver [15]. This limits utility to familiar settings. It also does nothing to prevent the user from veering while walking. Finally, the handheld receiver makes it difficult to carry a package as one hand is already occupied with a cane or dog harness.

Researchers at Arkenstone, Inc., have developed Atlas Speaks® and Strider®. Atlas Speaks® is a talking map for the PC that can be used to orient to a location prior to venturing out. Strider® is a more general purpose device that employs a laptop computer in a back-pack to integrate Atlas Speaks®, a Global Positioning System (GPS) receiver, and a digital compass into a single portable device the can provide *in situ* information about the user's location and heading, the direction of a particular destination, and information about the surrounding environment [16].

However, while Strider® represents a major step toward a general-purpose orientation device, there is much it does not do. Because it relies on GPS, it does not function indoors, and outdoors it does not provide sufficient resolution for the user to easily locate a doorway into a building. Even with the declassification of the GPS signal, 10-meter accuracy is all that can be claimed. This is not sufficient to direct a user across the street with an assurance that he/she will be able to find the opposite corner. Further, in large cities where buildings block line of site to four GPS satellites, obtaining accurate position information may be difficult.

Further, Strider® doesn't interact with devices in the environment to provide temporal information such as the state of a traffic light. Finally, Strider's® interface may not be usable by some older people, and may not be appropriate to every outdoor setting and situation.

Given the above situation, the authors have suggested that in order to make orientation technologies more generally beneficial and usable, (1) a complementary mix of location technologies should be integrated into a single device, and (2) portable user interfaces should be developed that are usable in all settings to the greatest extent possible by *all* people with severe visual impairments.

A widely usable mix of technologies might include GPS, a digital compass, cellular triangulation, inertial navigation, and wireless communications/data links to surrounding infrastructures and the Internet. Indoor infrastructures might include networks of ubiquitous computing devices. Such a network could be placed throughout buildings, malls, or transit plazas to provide location-specific information and directions [17]. Outdoors, links to pedestrian signals would be important for alerting a traffic light to the user's presence, obtaining intersection layout information, real-time traffic activities via the light's radar, and the state of the pedestrian signal. Finally, wireless links to the Internet could open up a wealth of orientation resources, including databases maintained by local area services for the blind.

However, such technology will provide only minimal benefit if the user interface is not suited to the user. Further, better interface design could considerably improve the utility of existing devices. For instance, if the talking sign receiver interface were designed for shirt pocket use, with its light sensor positioned to "peep" over the top of a pocket, hands-free operation could be achieved. A wideangle sensor might be used to help locate signs over a 180 ° forward preview area, while a narrow beam sensor could determine when the user was oriented toward a "sign."

Given this minor interface adjustment, the device could prevent veer while walking. When used for street crossing, this one interface improvement could keep the user from veering out into the parallel street and into oncoming traffic. Realization of the importance of optimal interface design for orientation aids was the impetus for the authors' herein described research.

3. Previous Work

3.1. Informational needs

In 1991, Blasch completed a study of "environmental information needs for orientation and wayfinding." The results of this study described the most usable form and content for orientation and wayfinding information, and showed the importance of presenting information to the subject *in situ*. It also showed the importance of presenting information on a timely, "as needed" basis in a concise and unobtrusive manner [18].

3.2. "Cyber Crumb" development

In 1996 and 1997, Ross and Blasch conducted two developmental projects, obtaining pilot data on potential orientation infrastructures and wearable interfaces. These projects were entitled, "Cyber Crumbs: Development of An Outdoor Orientation Infrastructure", and "Cyber Crumbs: Subject Testing Indoor Orientation Aids". The original "cyber crumb" concept was based on the potential of ubiquitous computing and the idea that one might leave a "trail" of tiny identifiers the size of a grain of sand along specific walking routes that could later be followed and used to maintain orientation.

As work progressed, the "cyber crumb" concept was shifted to encompass technologies that could provide location and heading information, but not necessarily specific information about the surrounding environment, as such information may be obtained via access to Geographic Information System (GIS) data, or other map databases. Further, given further development of an infrastructure, specific indoor data for buildings, malls, transit plazas, etc., might be obtainable via wireless links to information kiosks and/or business/public web sites containing such data. Toward this goal, investigators evaluated: (1) a system comprised of Global Positioning System (GPS) hardware and a digital compass; (2) outdoor IR beacons employed to orient to and cross traffic intersections; (3) passive and active Radio Frequency Identification (RFID) systems; and (4) the Locust IR system developed at the MIT Media Lab [19].

Results of the GPS/digital compass evaluation made it clear that while such a system could be used to obtain a general overview of the surround, this system lacked the requisite accuracy to direct a person across the street to the opposite corner, or to direct them to the entrance of a mall or transit station. Position accuracy varied by as much as 25 meters at times, and there were times when no position information was available. Since this work, the GPS signal has been declassified, thus a further evaluation of this system is warranted. However, the degradation (and/or total loss) of location data that occurs when one or more of four visible GPS satellites is eclipsed by tall buildings, will continue to be a problem. Further, accuracy of the digital magnetic compass was found to be severely affected by structures in the immediate environment, which caused plus and minus swings in the compass reading as great as 30 degrees.

3.3. Infra-red beacon evaluation

Evaluation results of a constructed digital IR beacon and receiver were more promising. This system was constructed using off-the-shelf components employed in television IR remote control systems. These systems employ a 40 kHz digital carrier that investigators found could be detected and decoded very accurately in very "noisy" outdoor environments. A typical remote/VCR combination was evaluated in this regard by investigators on the rooftop of the Atlanta VA Hospital under very bright and hot sunlight conditions in mid-June, and the effective range was found to be 20 feet. Given this result, and the fact that the tested remote employed dual IR LEDs, the investigators constructed an IR beacon employing 10 IR LEDs, with the intention of obtaining a range of about 100 feet, or approximately the distance across a four-lane street with added middle and right turn lanes. Once constructed, the actual effective range was found to be about 85 feet. A receiver was constructed consisting of a sensor and a decoder box that converted the detected signal into an audio tone. The sensor was a small one-centimeter cube. Two versions of this sensor were constructed: one that hung around the neck and lay flat against the chest so that it would point forward from the torso, and one that clipped to a pair of glasses and pointed forward in a line-of-site direction. Blinders were placed on either side of the sensor to make it directionally sensitive. When facing the signal source, turning the torso (or head) by more than $\pm 5°$ caused signal loss, and consequent loss of the audio tone.

Twenty severely visually impaired subjects tested this IR beacon system. They were asked to walk to the beacon location from a distance of 80 feet. They performed this task three times with the detector resting on their chest, and three times with the detector worn on a pair of glasses. Trial order was randomized across subjects. Also, three pre and three post baseline measures were recorded in which the subject was oriented to the direction of the beacon by listening and orienting to the direction of the investigator's voice. The subject was then asked to walk to the investigator, but was given no further sound cues. Recorded information included travel time, and accuracy in arriving at the destination.

Analysis of results showed no significant differences in travel time, but differences in accuracy were quite significant. Average error (left or right of the destination point) over the best three trials out of six using the device was 2.5 feet. Average baseline error for the best three trials out of six was 8 feet. There was also a significant difference in performance based on which sensor location was used. Seven of the subjects performed best with the sensor resting on the chest, while 13 performed best with the sensor mounted on their glasses. All seven of the subjects who performed better with the sensor on their chest were blind at birth, while only one of the 13 subjects who performed better when wearing the sensor on their head was blind at birth. Investigators noted that these congenitally blind subjects habitually walked with their head cocked to one side or the other, and that keeping their head trained forward to track the beacon sound was difficult for them. Finally, subjects overwhelmingly commented that they liked the system concept, but felt it could be improved (1) by inverting its operation such that a tone would only be heard when they get off course, (2) by indicating which direction they had gotten off course, and (3) by not covering up their ears with headphones.

3.4. RFID and Locust evaluations

Evaluations of the RFID and Locust systems were performed indoors in the hallways of the Atlanta VA Hospital. The purpose was to investigate how an indoor infrastructure might be established by using these systems to provide location specific data to the user at specific points along their path of travel through a building to a particular destination. Given such an infrastructure, the investigators conceptualised a scenario whereby a person with a wearable computer could enter a building, download a building map from the information desk (or info kiosk), select a destination, and be guided there by the wearable.

Given the weight and unwieldy nature of existing passive RFID tag readers, a simulation of a lightweight reader was constructed. This was accomplished by pairing an active RFID tag with a receiver that simulated passive tag reception via the use of an analog inverse r^4 RF amplifier stage. The receiver was built into a typical "white cane" used by the blind, with the antenna placed at the tip of the cane. The active RFID "tag" was constructed in a small, battery-powered box that was placed in building hallways on the floor next to the wall to mark specific locations.

Evaluating the operational range of these "passive" tags, the investigators were able to detect an RF carrier signal from a distance of 6 feet ± 1 foot, where the variance seemed to depend on how much metal was in the hallway walls and floors where the tag was placed. However, data from the tag could not be accurately "read" until the tip of the cane was brought to within a distance of 10 inches ± 6 inches of the tag. Given this very short data reception range, the investigators designed the receiver's human interface to generate an audio tone that varied in amplitude with the received RF signal strength. Using this audio feedback, subjects were able to walk down a hallway, detect the presence of a tag, and easily locate the tag with the tip of the cane. Then, when the tip of the cane was moved close to the "tag", the tone was replaced with a digitised message. For this study, the data transmitted was a number that referenced one of three specific digitised phrases: "turn right," "turn left," or "continue straight."

Given this successful strategy for obtaining data from "passive" RFID tags, the investigators attempted to implement this same operational procedure using active RFID tags, but with little success. When the active tag signal strength was adjusted so it could first be detected from a distance of between 6 and 8 feet, a phenomenon occurred whereby the metal studs in the wall picked up the signal and relayed it down the hallway from one stud to the next. Each stud became a phantom signal source that would fool the user into searching around the stud for a non-existent tag. Thus, it was that active tags were not implemented for testing, as the most obvious solution to this phantom signal problem was to use the inverse r^4 receiver that was already being evaluated as described above.

The locust system (see the MIT Media Lab website: http://lcs.www.media.mit.edu/projects/wearables/locust/) employs IR data transmitters that are hung from the ceiling with their IR light beam pointed at the floor. The user walks around with a receiver that has its sensor pointed at the ceiling. The investigators built this receiver into the headphones worn by the user. The focused transmitter IR LEDs formed a beam that covered about a 6-foot wide circle on the floor. A person standing within this circle automatically received data from the transmitter, which was immediately converted by the wearable into one of three digitised phrases: "turn left," "turn right," or "continue straight."

Twenty aging subjects with severe vision loss evaluated both the "passive" RFID tag system and the Locust system infrastructures. Both RFID tags and Locust transmitters were placed at the same hallway intersections. The transmitted codes from these devices were set to guide subjects along specific paths through the VA Hospital. Three different, but equivalent, paths were established, each the same length, with the same number of left and right turns, passing through sections of the hospital where the amount of traffic encountered was moderate. Testing consisted of three trials using each system, and three pre and three post baseline trials. The route followed and the device used for each trial were randomised across subjects. In the pre and post baseline trials subjects were given verbal directions at the start of each route and asked to walk the route. Measures taken included time to walk the route, recoverable errors and "fatal" errors. A "fatal" error was one that left the subject hopelessly lost.

Results were mixed. No "fatal" errors occurred when the RFID tags were used; however, a total of three "fatal" errors occurred during Locust system trials, and a total of six "fatal" errors occurred during baseline trials. A total of six recoverable errors occurred during the RFID trials, while a total of five recoverable errors occurred during the Locust trials, and five recoverable errors occurred during baseline trials. Finally, route-walking times for people using the Locust system averaged 30% less than for people using the RFID system, but was not significantly different from baseline trials. Participants commented that they had to go slower when using to RFID system to make sure they didn't miss a tag, and that it took time to "home in" on the tag to get the information, while with the Locust system they got the information without breaking stride. Research assistants observing these trials noted that the Locust system occasionally failed to provide information to a subject when the subject wandered onto the wrong side of the hallway when passing a Locust transmitter.

Almost all the subjects for whom use of a cane was an absolute necessity, preferred the RFID system, explaining that because it was built into the cane they didn't have to carry a separate device around. Subjects who did not always use a cane preferred the Locust system because it didn't require any extra effort on their part to get the information. They also commented that "even sighted folks" would probably find the Locust system helpful in getting around, and that having a larger market would make the system less expensive. Finally, almost all the subjects mentioned that they did not like wearing headphones.

What was most interesting about the subjects' comments was that the majority of comments were directed more at the user interface than the type of technology employed. It was these interface related comments, both from the previous outdoor trials and these indoor trials, that led to the research that is the topic of this article: namely, the development and evaluation of three wearable orientation and wayfinding interfaces.

4. Selection of Test Setting

To thoroughly test the three suggested interface designs (virtual beacon, speech output and tapping output), a testing situation had to be established that would provide information about how the interfaces would perform in critical situations, as well as how they would perform in a variety of outdoor and indoor settings. Of all the tasks taught by O&M instructors, street crossing was found to be the most critical [20]. Street crossing also encompasses most of the orientation tasks performed when moving through indoor and outdoor environments, including: establishing and maintaining an awareness of position in space relative to the surrounding environment and relative to a particular destination, and keeping track of environmental flow. Adding difficulty to the streetcrossing task is the fact that it may need to be performed in a very noisy environment and under a wide variety of weather conditions ranging from ice and snow to heat and rain.

To cross a street, one actually performs four critical tasks: (1) detecting the street or curb, (2) aligning the body with the edge of the curb facing the opposite corner, (3) initiating crossing at the proper time, and (4) walking a straight path across the street to the opposite corner [6]. All four of these tasks have become more problematic in recent years. The advent of curb ramps has made it easy to unknowingly walk out into the street. They also make it difficult to orient properly to the intersection [5,15].

Traffic sounds can provide orientation cues. However, when Chew [21], and Guth, Hill and Rieser [22], assessed the skill with which experienced blind pedestrians aligned themselves parallel to and perpendicular to traffic, they found trial-to-trial variability large enough that over time every subject would eventually walk out into the centre of an intersection [22].

Knowing when to cross has also become increasingly difficult. The cue to cross is normally the start up of cars on the parallel street [6]. However, if there is a left turn arrow, this initial surge places vehicles in the path of the pedestrian. Knowing when to cross is particularly difficult when the person has some hearing loss [22].

Finally, walking a straight line across the street is very difficult, especially if there is no parallel traffic and/or the person has a hearing impairment [22]. Compounding the difficulty are quiet motor vehicles, right (and left) turn on red laws, and traffic signals, which change their timing and sequence according to the flow and location of traffic [21].

Thus, of all the tasks one might select for testing an orientation aid, street crossing is one of the most difficult, hazardous, critical and crucial. If a subject feels confident and safe in the use of an orientation aid for street crossing, then this aid would most likely suit their needs in many other less crucial settings as well.

5. Prototype Design

5.1. Development of design philosophy

Along with development of a wearable prototype, the authors began developing a design philosophy with the idea that it be employed in a planned follow-up project. For this follow-up project the authors plan to develop a fully integrated wearable orientation aid capable of obtaining information from a variety of sources to provide seamless orientation information to the user. Such a device will require the development of new modes of user control, user data input, and user interactions. Towards this purpose the authors consulted with Gary W. Kelly, who has been working on just such a philosophy. Mr. Kelly, who is both a consumer with severe vision loss and a designer of assistive technology with a 25-year history of research and development, has been developing a philosophical construct called Values Oriented Design (VOD).

Given the diverse needs of the population being addressed in this design, the authors were dissatisfied with the limitations of existing research design protocols – protocols that have grown out of historical human factors principles originally developed for military and NASA projects in which humans are treated as the biomechanical components of a system. The intent of these original protocols was to improve system performance by (1) making the interface between the human and the machine as mechanically efficient as possible, and (2) minimizing human error by simplifying visual and auditory identification of controls and feedback displays. The goal was to minimise the amount of time the human "component" spent accomplishing specific tasks.

Ergonomics extended this concept to (1) include the energy expended by the person, and (2) include the entire human body, not just the hands manipulating the machine. This extension of the original human factors principles brought about the design of workstations that minimized physical effort and strain in the performance of tasks. However, while ergonomic analyses can be effectively used to minimise the amount of physical effort and strain associated with using devices, the human is still treated as a "component" of a system whose needs are analysed in only one dimension.

In contrast, many designers of assistive technology have become dissatisfied with this one-dimensional approach and have begun suggesting other dimensions of human user needs. These are summarised in the seven principles Universal Design (UD) developed by Ron Mace: (1) Simple and Intuitive Use, (2) Equitable Use, (3) Perceptible Information, (4) Tolerance for Error, (5) Accommodation of Preferences and Abilities, (6), Low Physical Effort, and (7) Space for Approach and Use. These seven principles provide a focus for evaluating designs with the idea that designers should be optimising their designs in each of these seven dimensions. Unfortunately, UD does not provide the designer with a structured means of determining how to satisfy each dimensional aspect within a design. Even worse, the UD principles provide no means of rating the overall "usability" of competing designs. Such listing of principles simply stress the fact that at least seven design dimensions should be considered when designing and evaluating the usability of a device.

What is missing from all the above is a design philosophy from which each dimension and design consideration can be generated, and by which the overall usability of a design can be evaluated. It was for this purpose that the authors asked Gary W. Kelly to assist in the planning of the now funded project to develop a fully integrated wearable orientation system. As Mr. Kelly's full VOD manuscript will not be published until at least the spring of 2002, a brief summary is included below so as to provide the reader with a context for the results, conclusions, and future design considerations described herein.

VOD is based on the values-oriented business model successfully used by IBM for over 60 years beginning in 1915. This business model was based on three values: (1) mutual respect; (2) open communications, and (3) excellence in customer service. Up until the 1970s IBM was in the business of leasing machines to their customers. In this capacity, IBM's values-oriented business model sustained an environment for employees and their customers that encouraged continuous customer interactions. IBM engineers and programmers knew their customers and their customers' needs very well, and the values-oriented climate encouraged them to work together openly with full and mutual respect for each customer's problems. Each employee took personal responsibility to insure that problems were solved to their customer's satisfaction. It was this values-based relationship with customers, fostering the ability to meet the needs of customers to their total satisfaction, which enabled IBM to dominate the computing world up through the late 1970s.

However, with the advent of the minicomputer and the desktop computer, customers could afford to buy machines of their own and hire their own technical support personnel. This effectively severed the close link between the provider of computers and end users, and ended IBM's dominance in the field. Gary W. Kelly points out that what was also lost at this time were the values that had originally driven IBM to its great success; the values that had made the computer revolution possible. With the close link between IBM personnel and the customer in effect severed, the customer began interacting with the machine and software more directly, and less with supportive people. The IBM business model failed to adapt to the changing times, and extend the values through the new media with which the customers were now interacting.

With the advent of the desktop computer the needs of customers began to drastically change, but the changing corporate value system now began discouraging interactions with customers. As a result, customer needs became more difficult to understand and design toward. The original IBM values were no longer being expressed by the myriad of new software/hardware options being developed and offered by the hundreds of new competitors in the software/hardware market. The market climate changed. Competitive advantage became the key to survival, and the products developed over the next 20 years increasingly reflected the values of profitability to the producer and efficiency of delivery, with little attention given to the degree to which products satisfied the end users.

The philosophy of VOD states that the responsibility for successful interactions of people with computer hardware and software be shared between the designer and the users, and that shared values necessary to support such an interactive climate must include mutual respect, open communication, and a shared sense of excellence in the cooperative effort of a successful interaction – much like IBM fostered through human interactions for so many decades. VOD attempts to reorient the design of software/hardware so that the person interacting with the system experiences a sense of respect from the designers; a knowledge that effective communications have been employed through the system, and that the designers desire the person and the system to mutually experience a successful interaction in accomplishing the tasks for which the system was designed.

In collaboration with Mr. Kelly, the author asserts that such a values-oriented approach to design can be generalized to most devices and systems in use today. A striking example of a device that could benefit from VOD is the VCR. Studies show that more than 80% of VCRs are sitting in homes with their displays blinking because most users never manage to set the time, let alone figure out how to program the VCR to record television shows. This is a surprising finding after nearly 20 years of commercialisation.

Implementing VOD philosophy is not difficult, as the designer need only incorporate the three VOD values into the design process. As an example and exercise, the reader can gather a few friends and carry out an interaction, or series of interactions, that illustrate the values of mutual respect and open communication. If one takes the VCR example, it is possible to have one person pretend to be a VCR and another person be the operator. Try using verbal English commands to provide menus and responses to program the VCR for various functions.

Performing this exercise, the reader will quickly see that the "normal" interaction of a VCR with an operator is cryptic, abrupt, and demonstrates a lack of respect in terms of courtesy and facility of use. Performing the exercise a few more times, it is possible to imagine engineering a sequence of interactions that are courteous, clear and concise, and that do provide easy facility of use.

In carrying out this activity, readers with a background in human factors may see how a human factors analysis could help implement a better design. A reader with a background in ergonomics may discover ways to improve the ergonomics of the device, etc. The purpose of VOD is not to preclude the designer from using their formally-trained design methods. Rather, it is to focus the designer on the real issues and problems as they become evident through interactions with the user. It is then the designer's responsibility to apply their expertise to resolve these issues and problems in a professional manner.

The purpose of VOD is to provide a climate conducive to designer-customer interactions that will lead to designs that fully satisfy the needs of customers and consequently the needs of the designer as well. It orients the designer to the real problems that are to be solved in the development of their design. Finally, VOD highlights the fact that users must fully participate in all aspects of the design process, from inception to completion, and ongoing interactions with customers must drive the continued refinement of designs if existing devices are to continue to meet customer needs.

Working in collaboration with Mr. Kelly, the authors are developing a means of evaluating designs based on a values-oriented user evaluation scale. This rating scale will be developed through interactions with potential buyers of the proposed wearable orientation system. This rating scale will then be formalised, tested and published in a future article.

5.2. Prototype development

Using subject comments from the prior research, an orientation prototype was designed and constructed that integrated into a single device three interfaces (virtual beacon, speech output and tapping output) and the two orientation modes (head vs. body reference) to be tested. A wearable computer was used as a base for controlling the interfaces, and for interpreting directional information from a digital compass. As the purpose of this study was solely to test the proposed interfaces, new location technologies were not incorporated into this prototype. A digital compass was used to determine the user's orientation within the test site intersections. This compass was designed and constructed to be mounted on either the user's cap or shoulder, and to be easily moved between these two locations. The intent was to switch between a head-oriented and a body-oriented reference system in this way. Once in position, the compass was initialised for each intersection with the subject standing on the curb facing the opposite corner.

The interfaces were built using a wearable computer base. This wearable was built from boards manufactured by Adaptive Systems, Inc. It contained a 66 MHz 486 with 16 Meg of

RAM, a 200 Meg Hard drive, an I/O card with two serial ports, and a SoundBlaster® card for stereo sound presentations. The Windows 95 operating system was used to take advantage of its 3D sound modules. Software was written to interpret compass data, drive the three interfaces, and implement testing procedures.

Virtual beacon presentation was performed via use of the Windows sound modules and the SoundBlaster® card. The sound produced was a recorded bell-like tone. The location of this "bell" relative to the user's head (or body) was calculated by a routine that employed data from the digital compass, as well as known data about the widths of the test site intersections. "Bell" location values were updated approximately 30 times per second, so that perceptual latency was minimal. The "bell" sounded once every 700 milliseconds. Presentation of the stereo output to the user was accomplished via a pair of ear-buds mounted on cap worn by the user. These were adjustable so they could be positioned just in front of the ear canal at a distance of about half an inch away from the ear. This was done so as not to interfere with the user's ability to easily, and naturally hear subtle environmental sounds.

Speech presentation was accomplished via digitized speech played at appropriate times by the SoundBlaster® card. Developed software converted digital compass data into both clock face positions and degrees. The user was given the option of using whichever system they preferred. The relative position of the destination was announced once every 1.3 seconds (e.g. one o' clock, one o' clock, ...). As with the virtual beacon, speech was presented to the user via the cap-mounted ear buds.

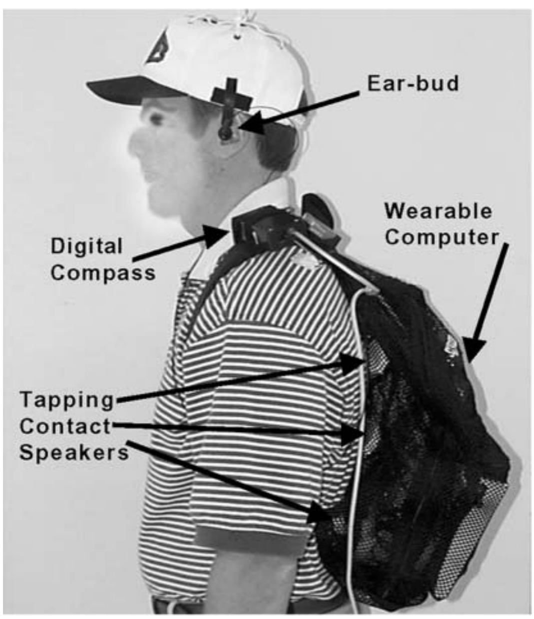

Fig. 1. Picture of person wearing the prototype interfaces.

The tapping interface was a sensory saltation device developed by MIT investigators as a means of helping drivers follow a map without distracting their visual attention. As designed by the MIT investigators [23], this device was comprised of a three by three array of small "contact" speakers that lightly thumped the person's back in sequences of three "taps" up the back. This was experienced by the user as something moving up their back in a specific direction. Movement straight up the back indicated the person should move straight forward. Movement from lower left to upper right indicated the user should angle to the right; and movement from the left to right side of the back indicated a right turn.

After building and testing this device themselves, the authors modified the design to use only three contact speakers: one that tapped on the right shoulder, one that tapped on the left shoulder, and one that tapped in the middle. The modified device tapped in the centre to signal straight ahead movement, or on a shoulder to indicate the need to move to right or left. A tap to the appropriate location was performed once every 700 milliseconds.

6. Methodology

6.1. Subject testing protocols

A total of 15 subjects were recruited and tested. When the subjects presented themselves their visual pathology, along with any age-related co-morbid pathologies, were recorded. Testing took place at three intersections (A, B, and C) near the Atlanta VA Medical Center (Fig. 2). Pre and post baseline (device not used) measures were taken of subject performance crossing over all three intersections (A, B, C) and then back (-C, -B, -A). During these tests, subjects were allowed to use their cane, but not a dog guide.

After the pre-test baseline measures, each subject was fitted with the wearable device and trained in its use. In an outdoor courtyard, some distance from intersections and noisy traffic, investigators explained how each of the three interfaces functioned, and subjects practiced two

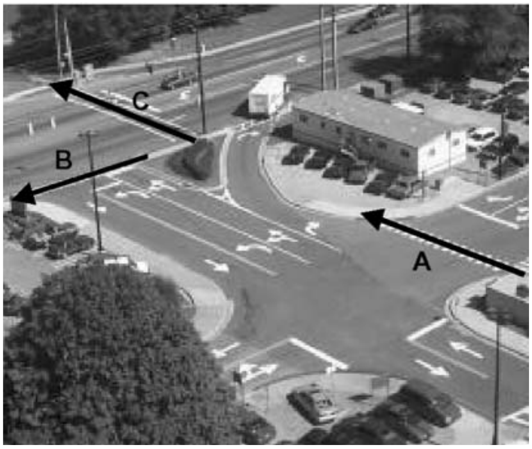

Fig. 2. Picture of the test-site intersections (A, B, C).

trial runs across the courtyard using each interface. The order in which they learned to use each of the three interfaces was randomised across subjects.

The subjects then used each of the interfaces in two different modes (head-referenced and body-referenced feedback) to cross the three intersections in either the forward or backward directions. The order of testing the three interfaces, as well as the mode of operation, was randomized for each subject. In this way subjects crossed over each intersection in order (A, B, C) three times, testing a different interface/mode of operation each time; and then back (-C, -B, -A) three times testing an additional three interface/modes of operation, so that all six interface/mode combinations were tested. Following the device tests, the subjects removed the prototype and crossed each of the three intersections both forward and back in post baseline tests. Measures recorded were crossing time, off target error, out of crosswalk errors, hesitations, and any apparent subject confusion.

Following these tests subjects were asked to rank order the interfaces and modes of operation from the most useful to the least useful. Then they were asked if any of the interfaces/modes helped them find their way across the street better than using their cane or dog; and if so, how it was better; and if not so, what it was about each interface that made it difficult to use. Finally, they were each asked for ideas on how each interface/mode might be improved to become more useful; and, given this improvement, what interface or interface combinations they would then prefer.

6.2. Data analysis

Street crossing times were converted to walking pace in feet per second. Target errors were converted to inches of veer per foot forward. Average "normal" pace and veer for each subject were calculated from pre- and post-baseline measures. The ratio of prototype performance (pace and veer) to baseline performance was calculated for each subject for each interface and mode of operation. These ratios were used as relative indicators of performance improvement for each subject. Standard t-tests were performed to determine significance of performance improvements for each interface and mode of operation. Subject rankings were used to produce weighted "votes" for each interface/mode. T-tests were used to identify significant differences in the "vote" tallies. Finally, subject critiques and comments were grouped by type of comment/criticism/improvement idea and tallied.

7. Results

7.1. Demographics

Subjects ranged in age from 62 to 80, with the average age being 68. Their condition ranged from totally blind for over 40 years to partially sighted with the best acuity being 20/300. Over half the subjects were totally blind. Subject outdoor activity in street crossings ranged from a few street crossings a week to several street crossings a day. Type of streets crossed ranged from local low volume streets close to home to high-traffic streets some distance from home. Independence ranged from almost always crossing with someone else, to almost always crossing streets on their own. Two of the subjects had dog guides; the others consistently used a cane.

7.2. Objective data

Performance using the various modes of operation for each subject varied widely and some quite significantly. Most subjects, however, clearly performed their best when using one particular interface and mode of operation. "Best" was determined by totaling the performance to baseline percentage change scores for crossing time, veering, hesitations, confusing episodes and "out of crosswalk." A minimum determined the winner. In most cases, the change score for veering alone was indicative of "best" performance. The mode of operation that resulted in the best performance varied from person to person. However, using the mode of operation where the subject showed the most improvement in performance, a comparison of performance with and without the prototype (obtained by dividing the prototype performance score by the baseline performance score), gave the following:

Measure	Change	Significance
Walking pace	1.04	No Sig.
Veering	0.31	0.001

The above indicates that there was no significant improvement in walking pace when each person used the interface/mode that helped them perform their best. However, a very significant improvement in veering performance was achieved when subjects used the best interface/mode. On average veer was reduced to 31% of baseline veer. This was not only statistically significant, it was quite meaningful, considering that average baseline veer was around 10 feet when crossing the street. This was often enough veering to cause the person to completely miss detection of the opposite curb and walk into the parallel street. However, when veer was reduced to three feet, each person was able to detect the opposite curb and step up onto it.

Further, when each subject used their "best" interface/mode, the number of subject "hesitations," "confusions," and movement out of the crosswalk as compared with baseline measures was:

Measure	Change	Significance
Hesitations	0.33	0.001
Confusion Episodes	1.00	No Sig.
"Out of Crosswalk"	0.24	0.01

Thus, using their "best" interface/mode, subjects hesitated only one-third of the time and tended to wander out of the crosswalk only one-fourth the time. There were not enough confusing events noted to make any conclusions about improvements in this regard. There were also interfaces/modes that seriously degraded subject performance. The following lists degraded subject performance for the interface/mode where each subject performed their worst:

Measure	Change	Significance
Walking Pace	0.71	0.03
Veering	21.4	0.000
Hesitations	10.0	0.005
Confusion Episodes	9.0	0.001
"Out of Crosswalk"	1.18	No Sig.

To indicate which interfaces/modes were best, two types of ranking were done: one for actual performance, and one for expressed subject preferences. In these rankings, 2 points were assigned for best performance (or first choice preference) and 1 point for second best performance (or second choice preference). In the table below the interface is listed first and then the orientation mode. The abbreviation "3D" stands for 3D virtual sound beacon, "Sp" stands for speech interface, "Tap" stands for the tapping interface, "/h" stands for head oriented feedback, and "/b" stands for body oriented feedback.

	3D/h	3D/b	Sp/h	Sp/b	Tap/h	Tap/b
Performance	13	9	0	1	2	20
Preference	5	15	2	5	2	16

Although there is some individuality shown here in terms of performance and preferences, it is clear that both in terms of actual performance and subject preferences, that the tapping interface, when used in a body-oriented mode, comprised the best overall interface. However, the virtual sound beacon was a very close second, especially in terms of subject preferences. In fact, there was no significant difference between these two when evaluated by subject preference alone. Whether the virtual sound beacon is best used in the head or body-oriented mode is still unanswered. In terms of actual performance, it appears that it's best used in the head-oriented mode. It may be that when asked about this at the end of all the tests that the subject didn't really remember clearly which worked best for them. Most subjects said out of hand that they preferred body-oriented directions. However, the investigators suspect that this was true for all interfaces *except* the virtual sound beacon. That the beacon was an exception should not be a surprise, as it is more intuitive and natural to locate sound sources by moving the head than by moving the entire body.

7.3. Subjective data

Subjective data was comprised of the responses to the questions asked and comments offered. Thirteen of the 15 subjects said that at least one interface helped them cross the street more easily and with more confidence than with their cane alone. The reasons subjects preferred each particular interface is summarised as follows:

- *Speech Interface*: "Very easy and simple to respond to the voice".
- *Virtual Beacon Interface*: "It didn't cause me to overcorrect like the others"; "I didn't have to concentrate to use it ... I could hear where the tone was and follow it".
- *Tapping interface*: "It doesn't stand out like having on a headset, and doesn't cover ears or make it hard to hear traffic sounds"; "I can feel it even when I can't hear anything else because of the traffic noise"; "Natural and easy to know which way to turn or move to go straight".

Ways to improve each interface are summarized as follows:

- *Virtual Beacon Interface*: "Make the bell-sound higher, louder and more distinctive"; "Make it adjustable so I can set the volume and turn it off", "Make it usable with a hearing aid".
- *Speech Interface*: "Make it repeat less often when going correct direction, and tell me more quickly when I get off track"; "Make it louder so I can hear it over traffic".
- *Tapping Interface*: "Make it tap slower in middle for OK, and faster on the side to get my attention right away when I start to veer"; "Make it tap harder and not buzz"; "Make it like a collar or neck band small enough to wear under a shirt and not show".

Comments for improving the overall device included:

"Make it wireless and put compass in a belt or lapel pin"; "Make it smaller, with not so many wires"; "Needs to be tied into traffic information and tell me where the cars are;" "Make more adaptable to each person, especially people with hearing aids".

When asked which interface they would prefer if their suggested improvements were made, six of the subjects chose the speech interface, five chose the tapping interface, and four chose the virtual sound beacon. In addition to answering this question, four people volunteered the suggestion that a combination of speech and tapping interfaces would be ideal; and two volunteered that a combination of the speech and virtual beacon interfaces would be ideal.

8. Discussion

Given the above subject comments, there is no clear interface "winner." While the objective results clearly show that of the three interface designs tested, the tapping interface resulted in the best performance and was preferred by the majority of subjects; the constructed interfaces were not necessarily the best possible realisation of each type of interface. This was obvious from the subject suggestions for improvements. Most of the subject suggestions were very reasonable and can be accomplished using existing technology. The timing of orientation feedback was perceived as very important for all the interfaces. Many subjects indicated that with improved timing, the speech interface might become preferable.

Perhaps the question should not be "which interface is ultimately the best," but rather, "how can these interfaces be optimised and modularised so that users can easily assemble an overall interface that best suits their own needs and preferences?" Given the heterogeneity of the target population, it certainly may be true that each person within the population may find some customised combination of these interfaces suitable. These results reflect the authors' initial concerns about designing for a heterogeneous population and re-emphasise the need for a design philosophy such as VOD to address such diversity.

It should also be noted that different subjects came to this research from different street crossing experiences and community environments. Some were from more rural communities and some from very urban communities, so it is likely that subject comments varied relative to these different settings. For instance, subjects living in communities where traffic is light may not be concerned with noise being a problem for the virtual beacon and speech interfaces; where those living in a very urban environment may consider this a great concern. Further, for those with some hearing impairment, there is certainly a concern that operability with hearing aids be addressed.

9. Conclusions

First, the investigators conclude that each of the developed interfaces can clearly play a role in assisting people with severe visual disabilities in walking a much straighter path across the street. The most statistically significant result showed that on average the amount of veer to left or right was reduced to 30% of what it had been. In the majority of cases, this made the difference between finding the opposite curb and walking out into the parallel street.

Secondly, the investigators conclude that of the interfaces tested, the one that gave the best results in terms of subject performance and subject preferences was the tapping interface. Thirdly, the investigators conclude, based upon subject comments, that the speech interface can be considerably improved by optimising the timing of feedback. Given such improvement, speech could become as usable as the tapping interface.

Fourth, the authors note that if VOD had been employed in the methodological design of this project so that users were involved from the start in the design of the speech interface, then the above timing problems would have been resolved prior to final subject testing of the device and the results would have been more conclusive.

Finally, the investigators suspect that a tapping interface combined with an improved speech interface may become the most usable and flexible interface combination for orientation aids that suit the needs of the *majority* of the target population. It may also be the case that a virtual sound beacon combined with speech output may be the best for a *minority* of people in the target population.

The authors therefore recommend the further optimisation of the speech and tapping interfaces and the implementation of a combination of these. They also suggest that the potential of the virtual sound beacon be further investigated for those who do not have a hearing impairment.

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