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Blind Navigation and the Role of Technology

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25.1 INTRODUCTION

The ability to navigate from place to place is an integral part of daily life. Most people would acknowledge that vision plays a critical role, but would have great difficulty in identifying the visual information they use, or when they use it. Although it is easy to imagine getting around without vision in well-known environments, such as walking from the bedroom to the bathroom in the middle of the night, few people have experienced navigating large-scale, unfamiliar environments nonvisually. Imagine, for example, being blindfolded and finding your train in New York's Grand Central Station. Yet, blind people travel independently on a daily basis. To facilitate safe and efficient navigation, blind individuals must acquire travel skills and use sources of nonvisual environmental information that are rarely considered by their sighted peers. How do you avoid running into the low-hanging branch over the sidewalk, or falling into the open manhole? When you are walking down the street, how do you know when you have reached the post office, the bakery, or your friend's house?

The purpose of this chapter is to highlight some of the navigational technologies available to blind individuals to support independent travel. Our focus here is on blind navigation in large-scale, unfamiliar environments, but the technology discussed can also be used in well-known spaces and may be useful to those with low vision.

In Section 25.2 we look at some perceptual and cognitive aspects of navigating with and without vision that help explain why most people cannot imagine getting around in its absence. Section 25.3 presents four often ignored factors, from engineering blunders to aesthetic bloopers, which should be considered when developing and assessing the functional utility of navigational technologies. In Section 25.4, we summarize several of these technologies, ranging from sonar glasses to talking lights, giving the strengths and limitations of each. Section 25.5 concludes, the chapter by reviewing key features of these products and highlighting the best trajectory for continued development of future technology.

25.2   FACTORS INFLUENCING BLIND NAVIGATION

Two of the biggest challenges to independence for blind individuals are difficulties in accessing printed material [1] and the stressors associated with safe and efficient navigation [2]. Access to printed documents has been greatly improved by the development and proliferation of adaptive technologies such as screen-reading programs, optical character recognition software, text-to-speech engines, and electronic Braille displays. By contrast, difficulty accessing room numbers, street signs, store names, bus numbers, maps, and other printed information related to navigation remains a major challenge for blind travel. Imagine trying to find room n257 in a large university building without being able to read the room numbers or access the "you are here" map at the building's entrance. Braille signage certainly helps in identifying a room, but it is difficult for blind people to find Braille signs. In addition, only a modest fraction of the more than 3 million visually impaired people in the United States read Braille. Estimates put the number of Braille readers between 15,000 and 85,000 [3].

Braille signs indicating room numbers are installed by law in all newly constructed, or renovated, commercial buildings [4]. However, many older buildings do not have accessible signage, and even if they do, room numbers represent only a small portion of useful printed information in the environment. For instance, a blind navigator walking into a mall is unable to access the directory of stores or in an airport the electronic displays of departure and arrival times. When traveling without vision in an unfamiliar outdoor setting, accessing the names of the shops being passed, the name of the street being crossed, or the state of the traffic signal at a busy intersection can also be challenging. Although speech-enabled GPS-based systems can be used to obtain access to street names and nearby stores and audible traffic signals can provide cues about when it is safe to cross the street, these technologies are not widely available to blind navigators. Where an environment can be made accessible for somebody in a wheelchair by removing physical barriers, such as installing a ramp, there is no simple solution for providing access to environmental information for a blind traveler [5]. As our interest is in blind navigation and environmental access, most of the navigational technologies discussed in this chapter collect and display environmental information rather than require structural modifications. For a review of the benefits of some physical modifications that can aid blind navigation, such as the installation of accessible pedestrian signals, see the article by Barlow and Franck [6].

Compared to the advances in accessing printed material in documents, there has been far less development and penetration of technologies to access print-based information in the environment or to aid navigation. The reason for this limited adoption inevitably

stems from several factors. Most navigational technologies cost hundreds or thousands of dollars. This makes it prohibitively expensive for most blind people to buy these devices on their own budgets. Rehabilitation agencies for the blind will often assist in the purchase of adaptive technology for print access but rarely provide their clients with technologies for navigation. In addition to cost constraints, broad adoption of navigational technologies will likely not occur until greater emphasis is given to perceptual factors and end-user needs. In other words, there needs to be more research investigating whether these devices are providing a solution to something that is in fact a significant problem for blind navigators (see Sections 25.3 and 25.5 for more detail). Until then, safe and efficient travel will continue to be a stressful endeavor for many blind wayfinders.

Another factor to be addressed is the population of potential users of navigational technologies. The vast majority of impaired vision is aged-related with late onset [7], such as from macular degeneration, glaucoma, or diabetic retinopathy. Those with age-related vision loss may have more difficulty than younger people in learning to use high-tech devices. Compounding the problem, older people often have coexisting physical or cognitive deficits that could render the adoption of some technology impractical. Given these concerns, more research is needed to address how to best develop devices to aid navigation for people with late-onset vision loss.

While the goal of navigating with or without vision is the same, that is, safely locomoting from an origin to a destination, the environmental information available to sighted and blind people is quite different. Understanding the challenges to blind navigation requires appreciation of the amount of spatial information available from vision. Think of walking from your front door to the mailbox at the end of your driveway. If you are sighted, your movement is guided entirely by visual perception. You simultaneously observe the distant mailbox and intervening environment from your door, and navigate a route that gets you there as directly as possible while circumventing the bicycle on the front path and the car in the driveway. You likely pay little attention to what you hear from the environment as you avoid the obstacles along the way. With vision, it is trivial to see the spatial configuration of objects in the environment around you and how the relation between yourself and these objects changes as you move. This example represents what is called *position-based navigation* or *piloting*. Piloting involves use of external information to specify the navigator's position and orientation in the environment [8]. Although vision is typically used to estimate distance and direction to landmarks and guide one's trajectory, a navigator can also use tactile, auditory, or olfactory information, as well as signals from electronic aids, such as GPS-based devices for piloting [9]. Navigation can also be done without reference to fixed landmarks, such as through velocity-based techniques that use instantaneous speed and direction of travel, determined through optic or acoustic flow, to keep track of translational and rotational displacements. Inertial techniques may also be used that utilize internal acceleration cues from the vestibular system to update these displacements (see Refs. 8 and 10 for general discussions of these navigational techniques).

Since both position- and velocity-based navigation are best served by visual cues, navigation using other sensory modalities is typically less accurate. For instance, auditory, olfactory, or tactile input conveys much less information than vision about self-motion, layout geometry, and distance or direction cues about landmark locations [11,12]. Given that this information is important for efficient spatial learning and navigation, lack of access puts blind people at a disadvantage compared to their sighted peers. As we will see in Section 25.4, navigational technologies attempt to close this gap by providing blind

wayfinders access to the same critical environmental information available to sighted navigators.

Another major difference in navigating without vision is the added demand of learning to interpret nonvisual sensory signals. Blind navigators need to learn how to safely traverse their environment. They must learn how to detect obstructions to their path of travel, find curbs and stairs, interpret traffic patterns so as to know when the light is red or green, not veer when crossing the street, find the bus stop, and myriad other navigational tasks. They must also keep track of where they are in the environment and how their current position and orientation relates to where they want to go. These tasks are cognitively demanding and often require conscious moment-to-moment problem solving. By comparison, sighted people solve these problems visually in a more automatic, less cognitively demanding way. In other words, vision-based navigation is more of a perceptual process, whereas blind navigation is more of an effortful endeavor requiring the use of cognitive and attentional resources [13–15]. Vision also affords access to many orienting cues in the environment. For instance, use of local landmarks such as street signs or colorful murals and global landmarks such as tall buildings or mountain ranges can aid spatial updating and determination of location. Since access to this type of environmental information is difficult from nonvisual modalities, blind wayfinders must rely on other cues for orientation which are often ambiguous and unreliable (see Ref. 12 for a review). Most sighted people have never considered how they avoid obstacles, walk a straight line, or recognize landmarks. It is not something they consciously learned; it's just something they do. By contrast, the majority of blind people who are competent, independent travelers have had specific training to acquire these skills. This is called *orientation and mobility* (O&M) *training*.

The navigational components of orientation and mobility are sometimes ambiguously defined in the literature, but in general, *orientation* refers to the process of keeping track of position and heading in the environment when navigating from point *A* to point *B*, and *mobility* involves detecting and avoiding obstacles or drop-offs in the path of travel. Thus, good mobility relates to efficient locomotion and orientation to accurate wayfinding behavior. Effective navigation involves both mobility and orientation skills. As we will see, the aids that are available to augment blind navigation generally provide information that falls within one of these categories.

25.3 TECHNOLOGY TO AUGMENT BLIND NAVIGATION

Many navigational technologies have been developed throughout the years, but few are still in existence. Part of the reason may be due to a disconnect between engineering factors and a device's perceptual and functional utility; that is, a device may work well in theory but be too difficult or cumbersome in practice to be adopted by the intended user. Four important factors should be considered when discussing the design and implementation of technology for blind navigation.

25.3.1 Sensory Translation Rules

Most of the navigational technology discussed in this chapter conveys information about a visually rich world through auditory or tactile displays. These channels have a much lower bandwidth than does vision and are sensitive to different stimulus properties. For

instance, where cues about linear perspective are salient to vision, this information is not well specified through touch. By contrast, thermal cues are salient to touch but not vision. Thus, any mapping between the input and output modality, especially if it is cross-modal (e.g., visual input and auditory output), must be well specified. Rather than assuming that any arbitrary mapping will work, we need more insight from perception (auditory and tactile) and a clearer understanding of the cognitive demands associated with interpreting this information to guide the design principles of more effective mappings. The ideal device would employ a mapping that is intuitive and requires little or no training. How much training will be required, and the ultimate performance level that can be obtained, are empirical issues. As these prerequisite issues are often ignored, improved performance measures for evaluating such mappings are necessary.

It is tempting but probably misleading to assume that people can easily interpret arbitrary mappings of two-dimensional (2D) image data, such as video images, into auditory or tactile codes. The history of print-to-sound technology is instructive in this regard. The first efforts to build reading machines for the blind involved mapping the black-and-white patterns of print on a page to arbitrary auditory codes based on frequency and intensity. These efforts were largely unsuccessful; the resulting reading machines required too many hours of training, and reading speeds were very slow [16]. Print-to-sound succeeded only when two things happened: (1) optical character recognition algorithms became robust and (2) synthetic speech became available. In other words, arbitrary mappings from print to sound did not work, but the specific mapping from print to synthetic speech has been very effective. A related point is that the translation from print to synthetic speech requires more than analog transformation of optical input to acoustic output. There is an intervening stage of image interpretation in the form of optical character recognition. It is likely that the future of successful high-tech navigation devices will rely more and more on computer-based interpretation of image data prior to auditory or tactile display to the blind user.

25.3.2 Selection of Information

To be effective, the product must focus on conveying specific environmental information. To facilitate training with any navigational technology, it is important to understand exactly what information it provides. The complexity of the display is directly proportional to the amount of information that the developer wishes to present. It may be tempting to design a device that strives to convey as much information as possible, acting as a true visual substitute. However, more is not always better. For instance, the best tactile maps are simple, uncluttered displays that do not try to reproduce all that exists on a visual map [17]. An inventor should be cognizant of the basic research addressing such perceptual issues and carry out empirical studies to ensure that the display is interpretable and usable to the target population. Most of the technology discussed employs auditory or tactile output (see Ref. 18 for a review of echo location and auditory perception in the blind and Refs. 19 and 20 for excellent reviews of touch and haptic perception).

25.3.3 Device Operation

The optimal operating conditions depend largely on the characteristics of the sensor used by the device. For instance, sonar-based devices can operate in the dark, rain, and snow. This versatility provides a functional advantage of these devices for outdoor usage.

However, they are not ideal for use in crowded or confined places as the sonar echoes become distorted, rendering the information received by the user unreliable. By contrast, camera-based technology can work well under a wide range of operating conditions both inside and outside, but these systems may have difficulty with image stabilization when used by moving pedestrians, and wide variations in ambient luminance within and between scenes. GPS-based devices are fairly accurate across a range of atmospheric conditions, but the signal is line of sight and can thus be disrupted or completely occluded when under dense foliage or traveling among tall buildings. Also, GPS does not work indoors. The bottom line is that each technology has its own strengths and weaknesses, and successful navigation over a wide range of environmental conditions will probably require the integration of multiple technologies.

25.3.4   Form and Function

Another often neglected consideration is the aesthetic impact on the user; that is, a device should be minimally intrusive. A survey carried out by Golledge and colleagues found wide variability in the "cosmetic acceptability" of navigational technology [21]. The finding that some people felt strongly enough to rate this issue as more important than having a device that improved navigation shows that aesthetic impact cannot be ignored.

25.4   REVIEW OF SELECTED NAVIGATIONAL TECHNOLOGIES

Tools used in blind navigation are often called *mobility aids* or *electronic travel aids* (ETAs). While they generally provide information useful for mobility or orientation, they can be further divided into two categories depending on the information displayed. The most common devices are used as a mobility aid and serve as obstacle detectors. Such aids are generally limited to providing low-resolution information about the nearby environment (see Ref. 22 for a review). Another class of devices attempts to convey more detailed environmental information over a wider range of distances. These ETAs are called *environmental imagers* as they serve as vision substitution devices (see Ref. 23 for a review of vision substitution). The following discussion highlights some key technologies from these categories and provides some strengths and weaknesses of each. This review is not meant as an exhaustive list, but focuses instead on providing a brief historical context of each technology while emphasizing those devices that are commercially available or part of an active research program. For a more thorough discussion of blind navigation and some of the technologies discussed below, see the classic book on orientation and mobility by Blasch and Welsh [24].

The long cane and guide dog are the most common tools for mobility. The cane is a simple mechanical device that is traditionally used for detecting and identifying obstacles, finding steps or drop-offs in the path of travel, or as a symbolic indicator to others that a person is blind. Although direct contact with the cane is limited to proximal space, its effective range for detecting large obstacles is increased with the use of echo location cues created as a result of tapping [25].

The guide dog performs many of the same functions as the cane, although navigation is often more efficient because the dog can help take direct routes between objects, instead of following edges, or shorelining, which is a standard technique with a cane.

The dog also helps reduce veering, which is often a challenge when crossing streets or traversing large open places. The cane and guide dog have similar limitations. They are most effective for detection of proximal cues, are limited in detecting overhanging or non-ground-level obstructions and do not provide much in the way of orientation information about the user's position and heading in the environment.

It is important to note that most of the electronic travel aids discussed here are meant to complement, not replace, use of the long cane or guide dog.

An ETA can be regarded in terms of its sensor, the component receiving information about the environment and the display, where the information is conveyed to the user. Some devices, such as GPS-based navigation systems, also incorporate a user interface where specific information can be entered or queried from the system. In the following discussion, the navigational technologies are classified according to their sensor characteristics: sonar-based (using sonic sensors), vision-based (using cameras or lasers), infrared (IR), or GPS devices. All of these technologies provide auditory and/or tactile output to the user (devices based on visual enhancement or magnification are not included in the following discussion).

25.4.1 Sonar-Based Devices

The first sonar-based mobility aid was the handheld sonic torch, using a special ultrasonic sensor developed by Leslie Kay in the early 1960s. Kay's company, Bay Advanced Technologies (BAT), has developed many sonar-based devices since then; the latest is the BAT 'K' Sonar-Cane. This cell-phone-sized device costs around $700 and can be affixed to the handle of a long cane, increasing its effective range to detection of a 40 mm diameter object out to 5 m [26]. With the BAT 'K' Sonar-Cane, a user is able to hear echoes from multiple sources, facilitating simultaneous tracking of more than one object in the environment. The auditory output, delivered threw earphones, modulates pitch proportionally to distance. Low-pitched sounds are heard for close objects, and high-pitched sounds relate to far objects. This is Kay's latest product, and no empirical studies have yet been carried out with the device. It employs a simpler display than do several other of his devices (see text below) indicating that the complexity of the earlier ETAs may have limited their acceptance by blind users.

Kay's sonic glasses (or Sonicguide) and Trisensor (also called KASPA) were designed to provide a sonic image, albeit coarse, of the environment. The Sonicguide was a head-mounted binaural device, commercially available through the mid-1990s, utilizing ultrasonic echo location. KASPA, which became commercially available in 1994, costing around $2500, used a triad of high-resolution ultrasonic spatial sensors on a head-mounted device. The three sensors covered a $50°$ forward field of view, and the auditory "image" was heard through stereo headphones. The auditory information provided by the three sensors, one centrally mounted and two peripherally, was meant to model the visual information that would be available from the central and peripheral visual field of view. KASPA afforded access to detection and location of multiple objects in 3D stereo space up to 5 m ahead of the user. The frequency of the tones provided information about distance, direction was indicated through delivery of the sounds in the binaural headphones, and the timbre from the multiple reflections provided information about the object's unique surface properties. By learning the invariant sound signatures reflected from different objects, navigators could, in theory, learn to recognize specific objects and build up a 3D representation of the space they are navigating. Much work has gone into merging the

technology with our understanding of the perceptual aspects of visual and auditory processing and the associated neural correlates of 3D auditory perception [27,28]. The results from behavioral studies carried out using these more complex ETAs are mixed (see Ref. 29 and Kay's Website [26] for several theses and technical reports).

In contrast to Kay's high-resolution sensors, several sonar-based mobility aids have been developed that use a relatively simple display. These ETAs provide extended information about object detection but do not attempt to convey complex sound signatures about multiple objects in the environment. The Sonic PathFinder, developed by Tony Heyes and his company Perceptual Alternatives, is an outdoor device meant to complement other obstacle avoidance techniques, such as the long cane or guide dog [30]. The Sonic PathFinder costs around $1600 and is a head-mounted system employing five ultrasonic transducers that are controlled by a microcomputer. The system uses the notes of a musical scale to give a navigator advanced warning of obstructions to their path of travel. As the person approaches an object, the musical scale descends with each note representing a distance of ~0.3 m. Objects picked up from the left or right of the user are heard in the left and right ears respectively. Those straight ahead are heard in both ears simultaneously. Rather than adopting a fixed distance, the range of the device is determined by the walking speed of the user. Thus information is provided about objects that would be encountered during the next 2 s of travel. Behavioral studies with the device yielded mixed results, demonstrating that it did not improve travel time but did reduce contact of the cane with obstacles in the environment [31,32].

Two other devices using ultrasonic echo location are the Miniguide and UltraCane. The Miniguide is a handheld device, produced by GDP Research and costing approximately $600 [33]. In addition to auditory output, the Miniguide uses vibration to indicate object distance. The faster the rate of vibration, the closer the object. It is used to detect single objects at a range of 0.5–8 m (with the optimal size, accuracy tradeoff for object detection at 4 ms). Since this device cannot detect drop-offs, it must be used in conjunction with a cane or guide dog.

The UltraCane, developed by Sound Foresight and costing approximately $800, works in a similar fashion out to 4 m but has front- and upward-facing ultrasonic sensors that are part of the long cane's handle. This design makes it possible to easily detect drop-offs, via the cane and overhangs, via the sensors. Detection of overhangs by this and other devices is particularly useful, as canes and guide dogs provide poor access to this information. In addition to indicating distance through vibration, the arrangement of the UltraCane's vibrators provide coarse spatial information about where the object is located; for instance, a head-level obstruction is felt on the forward vibrator, and ground-to-chest-level obstacles are indicated by the rear vibrator [34].

The final sonar-based device discussed here is the GuideCane, developed in the Advanced Technologies Lab at the University of Michigan. Although research and development of this product have been discontinued, it is included here because of its interesting approach to information presentation.

The focus of the GuideCane was to apply mobile robotic technology to create a product that reduced conscious effort from the person by acting autonomously in obstacle avoidance decisions. As accurate mobility can be cognitively taxing, the philosophy of the GuideCane was to reduce the effort associated with determining a safe path of travel. The device resembled an upright vacuum cleaner on wheels and employed 10 ultrasonic sensors to detect obstacles in a 120° forward field of view. To operate, the user pushed the GuideCane and when the ultrasonic sensors detected an obstacle, an embedded computer

determined a suitable direction of motion to avoid the obstruction. The GuideCane then steered the user, via force feedback in the handle, around the obstacle and returned to the original path of travel. The system determined and maintained position information by combining odometry, compass, and gyroscope data as it moved. (For technical details on the system and how it dealt with accumulated error from the sensors and determination of the best path of travel, see Ref. 35.)

In an attempt to reduce complexity, the GuideCane analyzes the environment, computes the optimal direction of travel, and initiates the action automatically. This transparent automaticity, while lauded as a benefit by the developers, is also a limitation as the user is simply FOLLOWING the device. The reduction of information to this single FOLLOW action by a fully autonomous device during navigation is potentially dangerous as it removes all navigational decisions from the operator's control. Although the problems of detection and avoidance of obstacles are often tedious to a blind person, being actively engaged in this process is important for spatial learning. For instance, contacting an object with the long cane allows the user to know that it is there and encode this location in memory. Simply being led around the object does not allow one to know what is in one's surrounds. Even with the guide dog, the first tenant of the handler is that they are always supposed to be in control. While you let the dog alert you to obstructions or suggest a path of travel, you must always be the one to make the final decision and give the commands.

Several clear benefits to the various sonar devices are discussed in this section. Both the mobility aids and more complex vision substitution systems extend the perceptual reach of a blind navigator from single to multiple meters. Not only do they alert user's to obstacles in the immediate path of travel; most devices also provide access to off-course objects or head-height obstructions, elements that are difficult to find using the long cane or guide dog. The availability of this information may benefit safe and efficient travel as well as the opportunity for blind individuals to learn about their surroundings. Finally, regarding expense, since all necessary hardware is carried by the user, no installation or maintenance costs are incurred by third parties. This provides an up-front benefit to mass penetration of sonar devices, as there is no need for retrofitting of the environment in order for the device to work.

Sonar-based devices have limitations. They are not very effective in crowded environments because the signal is prone to reflection errors. The technology is also expensive, as the ultrasonic sensors are not built on off-the-shelf hardware and software, such as commercially available sonar range-finding devices. With the exception of the vibrating interfaces, these devices provide a continuous stream of audio information. Since blind people rely heavily on listening to their environment, the presence of auditory output could be distracting, or could interfere with other ambient cues from the environment. Given the importance of acoustic cues, such as hearing traffic, the reflected echoes from cane tapping, or distinctive auditory landmarks, masking this information could have deleterious effects on safe and efficient navigation.

Another major limitation is the time and effort needed to become proficient using these devices. The learning curve will be especially steep for ETAs like KASPA or the Sonicguide, which afford access to a much higher-resolution display than the basic obstacle detection devices. In addition, while the cane-mounted devices are integrated into the aid that they are designed to augment, the head-mounted systems are less aesthetically discreet, which may be undesirable to some people.

25.4.2   Optical Technologies (Camera or Laser-Based Devices)

The first incarnation of a laser-based navigational technology was the Nurion laser cane, developed in the late 1970s and now updated and commercially available for around $3000. This device is similar to the cane-mounted sonar ETAs but uses diode lasers rather than ultrasonic sensors. Three laser transmitters and receivers, directed up, ahead, and down, provide the user with three levels of extended obstacle detection, including drop-offs and overhead obstructions, out to 4 m [36]. The output is signaled by the rate of auditory tones or vibration felt in the cane's handle.

The talking laser cane is another cane-mounted ETA using a laser sensor. This device, developed by Sten Lofving of Sweden, is no longer being produced because of to funding limitations but is discussed here because of its novel design. In addition to providing auditory feedback about the presence of objects in the forward path of travel with a $20°$ spread angle, the receiver could also be used to pick up reflections from special retroReflective signs out to 10 m. Each sign consisted of a different barcode (thick or thin strips of retroreflective tape). When the laser detected a sign, a distinctive beep was sounded and a microprocessor in the unit tried to identify the bar codes. If recognized, the navigator heard a spoken message from a small built-in loudspeaker. Personal communication with the developer clarified that sign recognition occurred significantly closer (≤ 3 m) than its original detection, but empirical tests have not been conducted. Each sign conveyed 4 bits of information, allowing 16 specific labels to be predefined with a verbal message. The 16 spoken messages consisted of the numerals 0–9 and words like door, elevator, or bathroom. The device worked both indoors and outside, and the signs could be attached to any landmark that might help facilitate navigation. Thus, this device served as both a mobility aid and an orientation tool, as it could be used to detect obstructions and also provide position and direction information about specific landmarks in the environment. For ongoing research using recognition of passive signs to provide orientation information, see the DSS project discussed in Section 25.4.5.

As with the sonar devices, laser-based ETAs require a line-of-sight (LOS) measurement and the reflections can be easily blocked or distorted, such as by a person walking in the hall or from a door being opened.

Another approach to optical sensing uses cameras to capture environmental information. The vOICe Learning Edition video sonification software, developed by Dutch physicist Peter Meijer, is designed to render video images into auditory soundscapes. This is called "seeing with sound." It is the most advanced image to sound product available and according to the developer's listserv, is actively being used by blind people on a daily basis. For a detailed explanation of the software and demos, hints on training, user experiences, and preliminary neuroscientific research using vOICe, see the developer's expansive Website [37]. The vOICe software works by converting images captured by a PC or cell phone camera, through a computer, into corresponding sounds heard from a 3D auditory display. The output, called a soundscape, is heard via stereo headphones. This is a vision substitution device that uses a basic set of image-to-sound translation rules for mapping visual input to auditory output. For instance, the horizontal axis of an image is represented by time; for example, the user hears the image scan from left to right at a default rate of one image snapshot per second. The vertical axis is represented by pitch, with higher pitch indicating higher elevation in the visual image. Finally, brightness is represented by loudness. Something heard to be louder is brighter; black is silent and white is heard as loudest. For instance, a straight white line, running from the top left to

the bottom right, on a black background, would be heard as a tone steadily decreasing in pitch over time. The complexity of each soundscape is dependent on the amount of information conveyed in the image being sonified (for details, see Ref. 38).

The vOICe software also allows the user to reverse the polarity of the image, slow down or speed up the scan, and manipulate many other parameters of how the image is heard. The power of this experimental software is that it can be used from a desktop computer to learn about graphs and pictures or used in a mobile context. In this latter capacity, the software is loaded on a laptop, wearable computer or PDA-based cell phone, coupled with a head-mounted camera, and used to sonify the environment during navigation. The continuous stream of soundscapes heard by the user represents the images picked up by the camera as they move in real time.

In theory, the system could enhance mobility, by detecting potential obstacles and orientation, as the information provided could be used to locate and recognize distal landmarks in the environment. As of yet, there is no performance data with the vOICe software demonstrating that it can support these spatial operations. In deed, beyond individual case studies [39], it is not clear whether people can easily learn the mapping of visual images to soundscapes. If the information can be used in a meaningful way, it will require a steep learning curve. In addition, processing of the continuous, complex signals inevitably imposes stiff cognitive demands, something that could negatively impact safe navigation by blind wayfinders, which also requires significant cognitive effort.

An advantage of the vOICe experimental software over other devices that we have discussed is that it is free of charge and runs on all modern Windows-based computers, works with off-the-shelf cameras and headphones and requires no installation of specialized equipment in the environment. These factors make the vOICe accessible to a broad base of people. However, to be adopted, more behavioral research is needed demonstrating that the vision-to-sound mappings are interpretable and that the utility of the information provided is commensurate with the learning curve required to achieve competence.

Finally, another camera-based device that may be used for object detection and navigation is the tactile tongue display. This technology converts images from a camera into patterns of vibrations delivered through an array of vibrotactile stimulators on the tongue. Stemming from the pioneering work in the early 1970s by Paul Bach-y-Rita, the original research demonstrated that vibrotactile displays on the back or abdomen can be used as a vision substitution device [40]. Although the empirical studies with the system focused on detecting or recognizing simple objects, it was hoped that it could also work as a navigational technology. The modern incarnation of the system uses vibrotactile stimulators on the tongue, which has a much higher receptor density than does the back or stomach. In theory, this could sufficiently improve resolution such that the camera images could convey information about the distance or direction of objects, which could then be represented as a 2D image via the tongue display. The efficacy of this system as a navigational technology has not been shown, but research with the device by Bach-y-Rita and his colleagues is ongoing [41].

25.4.3   Infrared Signage

The most notable remote infrared audible signage (RIAS) is a system called "Talking Signs." This technology, pioneered and developed at the Smith-Kettlewell Eye Research Institute in San Francisco, consists of infrared transmitters and a handheld IR receiver

[42]. The cost of the receiver is approximately $250, and the transmitter and its installation total $2000. The Talking Signs system works by installing the transmitters in strategic locations in the environment. Each sign sends short audio messages, via a constantly emitted IR beam, which can be decoded and spoken when picked up by the receiver. A person carrying the Talking Signs receiver uses hand scanning to search the environment for a signal. The signal can be picked up from up to 20 m away, and when detected, the navigator hears a message from the onboard speaker (or attached headphone) indicating that he/she is in the proximity of a particular location. For example, when scanning, one might hear "information desk," "entrance to main lobby," or "stairs to the second floor." Users can navigate to the landmark by following the IR beam, such as walking in the direction of the message they are receiving. If they go off course, they will lose the signal and will need to rescan until they once again hear the message. The signals sent out by the transmitter are directional, and for maximum flexibility, parameters such as beamwidth and throw distance are adjustable. Talking Signs work effectively in both interior and exterior environments and can be used anywhere landmark identification and wayfinding assistance are needed. In contrast to most of the technology previously discussed, Talking signs are an orientation device as they convey positional and directional information. If more than one transmitter is installed (e.g., multiple signs to indicate the location of several doors in a transit station), a person may detect several messages from a single location. This can aid in learning the spatial relations between multiple landmarks [43]. As transmission of the infrared messages are frequency-modulated, there is no cross-interference between nearby transmitters; only information from the strongest signal detected is spoken at a time [44]. Several studies have shown that Talking Signs can be used to identify bus stops and information about approaching buses [45], to describe orientation information as a navigator reaches an intersection [42], and to improve efficient route navigation of large environments, such as San Francisco transit stations (see Refs. 44 and 46 for discussions). These studies also demonstrated that access to Talking Signs increased user confidence and reduced navigation-related anxiety.

The main limitation of Talking Signs is that they require access to a permanent source of electrical power, which can require expensive retrofitting of a building or city. At $2000 per sign, an installation base of sufficient density to cover the major landmarks or decision points in a city or every room number in a building would cost many millions of dollars. Thus, the more practical solution is to have Talking Signs provide information about only key landmarks in the environment, but this means that many potentially important features remain inaccessible to the blind navigator. It should be noted that while the up-front cost of installing the signs is significant, they have little subsequent costs. By contrast, other orientation technologies, such as GPS-based devices, may have a minimal initial cost but incur significant back-end expense in order to stay up to date with changing maps and other databases of location-based information.

In contrast to IR technology, radiofrequency (RF)-based signage systems are omnidirectional. Thus, messages are accessible from all directions and can be received without the need for environmental scanning. In addition, RF signals are not LOS and so are not blocked by transient obstructions. However, because of their omnidirectionality, RF signals generally have a smaller range and provide no information about the direction of a landmark with respect to the user. A study comparing navigational performance using Talking Signs Versus Verbal Landmarks, a RF-based audible signage system, found that access to Talking Signs resulted in significantly better performance than the RF alternative

[47]. This result demonstrates the importance of providing directional information to aid orientation in navigational technology.

25.4.4 GPS-Based Devices

The global positioning system (GPS) is a network of 24 satellites, maintained by the US military forces, that provides information about a person's location almost anywhere in the world when navigating outdoors. GPS-based navigation systems are a true orientation aid, as the satellites provide constantly updated position information whether or not the pedestrian is moving. When in motion, the software uses the sequence of GPS signals to also provide heading information. Because of the relatively low precision of the GPS signal, providing positional information on the order of one to 10 m accuracy, these devices are meant to be used in conjunction with a mobility aid such as a white cane or a guide dog.

The first accessible GPS-based navigation system developed by Jack Loomis and his colleagues at the University of California, Santa Barbara, was initially envisaged in 1985 and became operational by 1993 [48]. This personal guidance system (PGS) employs GPS tracking and a GIS database and has been investigated using several output modalities, including a haptic interface using a handheld vibratory device, synthetic speech descriptions using spatial language, and a virtual acoustic display using spatialized sound (see the PGS Website for more information [49]). The use of spatialized sound is especially novel, as it allows a user to hear the distance and direction of object locations in 3D space. Thus, the names of objects are heard as if coming from their physical location in the environment. Use of this system has proved effective in guiding people along routes and finding landmarks in campus and neighborhood environments [50–52].

Although there are many commercially available GPS-based devices employing visual displays (and some that even provide coarse speech output for in-car route navigation), these are not fully accessible to blind navigators. The first commercially available accessible GPS-based system was GPS-Talk, developed by Mike May and Sendero Group in 2000. This system ran on a laptop computer and incorporated a GPS receiver and a GIS database that included maps of most US addresses and street names. It was designed with a talking user interface that constantly updated the wayfinder's position and gave real-time verbal descriptions of the streets, landmarks, or route information at their current location. A strength of this system was that it was highly customizable; for instance, verbal directions could be presented in terms of right left, front back, clock face, compass, or 360° headings. A person could get information about the length of each block, the heading and distance to a defined waypoint or destination, predefined and programmable points of interest, or a description of each intersection. There was also a route-planning facility that allowed creation of routes from a current position to any other known position on the map. Another advantage of this system was that it could be used in virtual mode, such as using the keyboard to simulate navigation of the digital map. This allowed a person to learn and explore an environment prior to physically going there. Research on a similar European GPS initiative, MoBIC, demonstrated the benefits of this pre-journey planning for blind wayfinders [53].

Sendero's most current version, the BrailleNote GPS, works on the popular BrailleNote accessible PDA and is now one of three commercially available GPS-based navigation systems for the blind (see Ref. 54 for a review). Many of the core features between the three systems are similar but while Sendero's BrailleNote GPS and Freedom Scientific's

PAC Mate GPS work on specialized hardware, Trekker, distributed by Humanware, runs on a modified mass-market PDA. Trekker is a Braille input and speech output device, where the other two systems have configurations for Braille or QWERTY keyboard input and speech or Braille output.

Whether this GPS technology is used as a pre-journey tool to explore a route or during physical navigation, the information provided is expected to greatly improve blind orientation performance and increase user confidence in promoting safe and independent travel. No other technology can provide the range of orientation information that GPS-based systems make available. As we discussed in Section 25.2, effective orientation can be particularly difficult for blind navigators. Thus, these devices have great potential to resolve the orientation problem that has been largely unmet by other navigational technologies.

There are several notable limitations to GPS-based navigation systems. First, although the accessible software may not be very expensive, the underlying adaptive hardware on which it runs can be quite costly (e.g., up to $6000). The user must also periodically buy new maps and databases of commercial points of interest, as these change with some regularity.

In addition, GPS accuracy is not currently sufficient for precise localization unless the user has additional differential correction hardware, which is expensive and bulky. GPS technology is also unable to tell a user about the presence of drop-offs, obstacles, or moving objects in the environment, such as cars or other pedestrians. Thus, these systems are not a substitute for good mobility training. The base maps are also often incorrect, such that a street name may be wrong or the system may try to route the navigator down a nonexistent road or even worse, along a freeway or thoroughfare that is dangerous to pedestrian travel. As GPS signals are LOS, the signals are often disrupted when the user is navigating under dense foliage or between tall buildings and indoor usage is not possible. As orientation information is as important inside as it is out, this lack of coverage can be a significant challenge to blind wayfinders (see text below).

25.4.5   Technology for Indoor Navigation

While the advent of GPS technology has driven tremendous innovation in the development of accessible navigation systems for use in outdoor environments, much less is known about methods for tracking position and orientation indoors. Besides Talking Signs, which have a small installation base and provide information about specific landmarks only, there are no commercially available products to aid indoor wayfinding. This can pose a problem as it is often challenging for blind or visually impaired people to find their way in unfamiliar, complex indoor spaces such as schools or office buildings.

While several technologies may share in solving the problem of indoor wayfinding without vision, they all have a major limitation, namely, they are restricted to providing fixed messages about the immediate local environment. Braille, infrared or RF-based signage, "Talking Lights," fluorescent lights that are temporally modulated to encode a message [55] and use of wi-fi (wireless-fidelity) signals from known 802.11 wireless access points to locate a pedestrian within a building [56] are all based on static information. A more flexible system would couple an inexpensive method for determining a pedestrian's location and heading indoors with readily accessible information about the building environment. This system should be capable of guiding pedestrians along routes, supporting free exploration, and describing points of interest to the pedestrian.

The authors of this chapter are currently part of a team addressing the indoor navigation problem through research on a digital sign system (DSS) (see Ref. 57 for a preliminary report). The DSS consists of a handheld device that emits an infrared beam. The user pans the beam until a reflection is returned from a retroreflective barcoded sign. The image of the sign is "read" by computer software, and its identification code is fed to a building database. This database is part of a software application called "Building Navigator" that provides information to users, via synthetic speech about the content of the sign, the layout of nearby points of interest, and routing information to goal locations in the building. The codevelopment of indoor positioning technology and relevant indoor navigation software sets this project apart from most other methods of location determination, which are unable to provide context-sensitive and user-queriable information about the surrounding environment.

Critical to the success of this project is a clear method of describing the environment being navigated. To this end, several studies were conducted that investigated the efficacy of a verbal interface to support accurate spatial learning and wayfinding. These studies employed dynamically updated verbal descriptions, messages that are contingent on the user's position and orientation in the environment, as the basis of accessing layout information during navigation. The results from these studies demonstrated that both blind and sighted people could effectively use context-sensitive verbal information to freely explore real and virtual environments and find hidden target locations [58,59]. These findings provide strong initial support for the success of an integrated indoor navigation system incorporating the Building Navigator and DSS.

25.5 CONCLUSIONS

Many factors are involved in developing an electronic travel aid, but there is little consensus about the information that should be provided. On the one hand, we have vision substitution devices that attempt to convey a rich image of the environment, such as Leslie Kay's KASPA or Peter Meijer's vOICe. Although the resolution of these devices varies, they represent a school of thought predicated on the view that navigational technologies should provide blind people with as much information about the world as is possible. On the other hand, there is the notion that the most useful technology is based on a simple display, such as Tony Heyes's Sonic PathFinder or GDP Research's Miniguide. From this perspective, conveying detailed surface property information about multiple objects in the environment leads to undue complexity. Rather, a device should focus on providing only the most critical information for safe and efficient navigation, such as detection of objects in the immediate path of travel. These divergent perspectives bring up two important issues.

1. More impartial behavioral studies are needed to demonstrate the efficacy of ETA's. Most of the limited research in this area has been based on extremely small sample sizes or was carried out by the developer of the device. Given the extant literature, it is not possible to determine whether high-resolution displays are, indeed, providing useful information or if they are overloading the user with an uninterpretable barrage of tones, buzzes, and vibrations. In addition to perceptual issues, the functional utility of the device must also be considered. Ideas on the "problem to be solved" and best feature set of a device may differ between an O&M (orientation–mobility) instructor and the

engineer developing the product. The disconnect between what a product does and what the user wishes it would do is compounded as there is often inadequate communication between engineers and rehabilitation professionals or potential blind users. This lack of communication about user needs, coupled with the dearth of empirical research and limited funding opportunities for purchasing ETAs, are major reasons why navigational technologies have not gained broader acceptance in the blind community.

2. In addition, where the long cane and guide dog are tried and true mobility aids, it is not clear whether blind navigators want (or require) additional electronic devices that provide extended access to mobility information in the environment. This is not to say that such ETAs can't serve as effective mobility aids; it simply raises the question whether people find the cost–benefit tradeoff of learning and using the device worth the information provided. It is possible that the success of accessible GPS-based devices, demonstrated by the more recent emergence of three commercially available systems and the results of rigorous scientific studies, stems from the fact that this technology provides information that does not overlap with what is provided by the cane or guide dog. Since GPS-based navigation systems convey updated orientation information, incorporate huge commercial databases about the locations of streets and addresses, and often allow for route planning and virtual exploration of an environment, they provide access to a wide range of information that is otherwise difficult for a blind navigator to acquire. Given that no other technology directly supports wayfinding behavior, the growing success of GPS-based devices makes sense from the standpoint of addressing an unmet need for blind navigators.

Table 25.1 provides an overview of some of the navigational technologies discussed in Section 25.4.

As can be seen in the table, there are multiple approaches for conveying environmental information to a blind navigator. We believe that the future of navigational technology depends on consolidating some of these approaches into an integrated, easy-to-use device. Since there is no single, universal technology that aids in providing both orientation and mobility information in all environments, an integrated system will necessarily incorporate several technologies. The goal of such a system is to complement the existing capabilities of the user by providing important information about her/his surroundings in the simplest, most direct manner possible. The notion of an integrated platform for supporting blind navigation is not new. Work by a European consortium on a project called MoBIC represented the first attempt at such a system [53]. Although now defunct, the MoBIC initiative incorporated talking and tactile maps for pre-journey route planning, audible signage and GPS tracking for outdoor navigation. Another system being developed in Japan uses GPS tracking, RFID (radiofrequency identification) tags, and transmission of camera images to a central server via cell phone for processing of unknown environmental features [60]. An integrated Talking Signs–GPS receiver has also been shown to facilitate route guidance and on-course information about landmarks [52]. Finally, a consortium of five US institutions and Sendero Group LLC have been working on a integrated hardware and software platform to provide a blind user with accessible wayfinding information during indoor and outdoor navigation. This project brings together several of the technologies discussed in this chapter but is still in the R&D stage (see Ref. 61 for more information about the Wayfinding Group).

TABLE 25.1 Overview of Navigational Technology

Device	Input Transducer	Output Display	Information Conveyed	Mode of Operation	Requires Special Infra-Structure	Operating Environment	Approximate Cost	Developer
BAT 'K' Sonar Cane	Sonar	Acoustic	Presence of multiple targets, out to 5 m distance, including drop-offs and over-hangs	Cane-mounted	No	Indoors or outdoors	$700	Bay Advanced Technologies, http://www.batforblind.co.nz
Kaspa	Sonar	Acoustic, stereo sound	Acoustic image of multiple objects in 3-D space (out to 5 m), including over-hangs	Head-mounted	No	Mainly outdoors	$2,500	Bay Advanced Technologies, http://www.batforblind.co.nz
Sonic Path-finder	Sonar	Acoustic, stereo sound	objects contacted by a pedestrian in the next 2 seconds (including over-hangs)	Head-mounted	No	Mainly outdoors	$1,600	Perceptual Alternatives, http://www.sonicpathfinder.org
Mini-guide	Sonar	Acoustic and vibro-tactile	Object distance (0.5 to 8 m) including over-hangs	Hand-held	No	Mainly outdoors	$600	GDP Research, http://www.gdp-research.com.au
UltraCane	Sonar	Acoustic and vibro-tactile	Object distance (1 to 4 m) including drop-offs and over-hangs	Cane-mounted	No	Indoors or outdoors	$800	Sound Foresight, http://www.soundforesight.co.uk

TABLE 25.1 (Continued)

Device	Input Transducer	Output Display	Information Conveyed	Mode of Operation	Requires Special Infra-Structure	Operating Environment	Approximate Cost	Developer
Nurion Laser cane	Laser	Acoustic and vibro-tactile	Object distance (out to 4 m) including drop-offs and over-hangs	Cane-mounted	No	Indoors or outdoors	$3,000	Nurion-Raycal, http://www.nurion.net/LC.html
vOICe Learning Edition	Camera	Auditory sound-scapes	Sonic image of multiple objects in 3-D space	Head-mounted or hand-held	No	Indoors or outdoors	Free	Peter Meijer, http://www.seeingwithsound.com/
Braille-Note GPS	Global Positioning System Receiver	Speech and Braille	Direction and distance to local points of interest, route planning, active and virtual navigation modes	GPS receiver and access-ible PDA worn over shoulder	Presence of GPS signal	Outdoors	$2,199 (including software, GPS receiver and all U.S. maps).	SenderoGroup, http://www.senderogroup.com/
Personal Guidance System (PGS)	Global Positioning System Receiver	Spatialized sound, haptic interface	Direction and distance to object locations in 3-D space, route navigation.	GPS receiver, compass, and laptop worn in backpack	Presence of GPS signal	Outdoors	Not comercially available	UCSB Personal Guidance System, http://www.geog.ucsb.edu/pgs/main.htm
Talking Signs	Infrared	Speech	Message about direction and location of landmarks in local environment	Hand-held	Talking sign transmitter (requires power)	Indoors or outdoors	$2000 per sign	Talking signs, http://www.talkingsigns.com/tksinfo.shtml
Digital Sign System (DSS)	Infrared	Acoustic, and speech	Indoor location and nearby points of interest	Hand-held	Passive bar-coded signs	Indoors	Not comercially available	Tjan et al. (2005) [57]

FIGURE 25.1 *A blind pedestrian is using a guide dog and five technologies for navigation. This figure illustrates the need for an integrated navigational system. The guide dog aids with mobility and obstacle avoidance. The compass provides the user with heading information when stationary. The GPS receiver integrates with a GIS database (digital map) to provide position and heading information during outdoor navigation. The talking signs receiver gives orientation cues by identifying the direction and location of important landmarks in the environment. The digital sign system (DSS) receiver picks up barcodes from signs and sends them to a database to facilitate indoor navigation. The BrailleNote accessible computer represents the ''brain'' of the system, allowing Braille input and speech and Braille output. In theory this device could serve as the hub to which all other technologies interface.*

As of yet, there is no commercial product that seamlessly integrates multiple technologies into a single system, but one can readily imagine such a product. Figure 25.1 shows components from several technologies, a Talking Signs receiver, a DSS receiver, a GPS receiver, a compass, an accessible PDA, and a guide dog.

Now imagine that the electronics for the compass, Talking Signs, DSS, and GPS receivers are merged into one housing. The maps needed for outdoor environments and indoor databases are consolidated onto one large compact flash storage card, and the accessible PDA serves as a common input/output device, providing speech and Braille access for all subsystems. With this configuration, a blind navigator receives traditional mobility information from the guide dog and uses the integrated PDA for all other orientation information in both indoor and outdoor environments. This system would be minimally intrusive, utilize a clear and customizable user interface, work under a wide range of environmental conditions, and guarantee compatibility and interoperability between the various technologies. Although training would inevitably be a critical factor in effective use of such a system, a major advantage is that all environmental sensors would utilize a common output modality. People would need to learn only one set of rules and could choose the information from the sensors that most benefited their needs.

If an ETA could be designed that could provide much of the information that many of the above mentioned devices did, in a package that seamlessly integrated mobility and orientation information, both indoors and out, it would probably experience a much higher level of acceptance than many of the existing technologies in isolation.

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