Audio-Based Navigation Using Virtual Environments: Combining Technology and Neuroscience

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Abstract

For individuals who are blind, navigation requires the construction of a cognitive spatial map of one's surrounding environment. Novel technological approaches are being developed to teach and enhance this cognitive skill. Here, we discuss user-centered, audio-based methods of virtual navigation implemented through computer gaming. The immersive, engaging, and heavily interactive nature of the software allows for the generation of mental spatial representations that can be transferred to real-world navigation tasks and, furthermore, promotes creativity and problem-solving skills. Navigation with virtual environments also represents a tractable testing platform to collect quantifiable metrics and monitor learning. Combining this technology with neuroscience research can be used to investigate brain mechanisms related to sensory processing in the absence of vision.

Keywords: blindness, orientation and mobility, navigation, neuroplasticity, gaming

Introduction

It is crucial for individuals who are blind to develop good navigation skills in order to remain functionally independent. Surprisingly, very little work has been done to elucidate how the brain itself carries out this task in the absence of sight. Orientation and mobility (O&M) training represents the formal instruction of these skills and is geared at developing strategies to assist with orientation, route planning, updating information regarding one's position, and reorienting to reestablish travel (Blasch, Wiener, & Welsh, 1997). To navigate effectively, a person needs to develop sensory awareness (i.e., acquire information about the world through remaining sensory modalities) and searching skills (so as to locate items or places efficiently) and to keep track of the spatial relationships between objects within the environment (Blasch et al., 1997; Loomis, Klatzky, & Golledge, 2001; Welsh & Blasch, 1980). The mental representation of an external space is referred to as a cognitive spatial map (Landau, Gleitman, & Spelke, 1981; Strelow, 1985; Tolman, 1948). In contrast to the sighted, individuals with profound visual impairment cannot rely on visual cues to gather this information and visually order and classify their physical environment. Instead, an individual who is blind has to rely on other sensory channels to obtain

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appropriate spatial information regarding their surroundings (Thinus-Blanc & Gaunet, 1997). Indeed, it is generally believed that an individual who is blind (both early and late onset) develop compensatory behavioral strategies through the use of their remaining senses (Carroll, 1961; Wagner-Lampl & Oliver, 1994).

The theoretical underpinnings related to navigation skills in the absence of sight have been the subject of intense debate. It has been classically assumed that because of this high reliance on visual cues, individuals who are blind (particularly, early blind children) must in turn have cognitive difficulties in representing spatial environments and, consequently, impaired navigation skills. However, a review of literature reveals contradictory results (particularly in relation to the role of prior visual experience), calling into question the conclusions of these earlier interpretations. In fact, some studies have reported that no differences exist in terms of how well individuals who are blind are able to mentally represent and interact with spatial environments (Landau et al., 1981; Morrongiello, Timney, Humphrey, Anderson, & Skory, 1995; Passini & Proulx, 1988), and in certain spatial navigation tasks, individuals with profound blindness have been shown to exhibit equal (Loomis et al., 2001) and, in some cases, even superior performance (Fortin et al., 2008) when compared to sighted control subjects.

Given these contradictory reports regarding behavioral performance and the ability of individuals who are blind to compensate for the lack of visual sensory input, one has to ask whether differences in spatial mental constructs and navigation skill are solely due to *visual deprivation itself* (and related developmental factors such as the timing and profoundness of vision loss) or whether they reflect an impoverished or incomplete *acquisition* of necessary spatial information through other sensory channels. From a rehabilitation standpoint, perhaps what is missing is a better way to access, manipulate, and transfer acquired information—a gap that could be potentially closed through the use of appropriate technology. Here, we propose how the combination of computer-based virtual environments and neuroscience research may help answer these questions by developing scientifically testable training strategies aimed at improving navigation skill in individuals with severe visual impairment. The approach can be described as a user-centered, audio-based immersive and interactive strategy with the goal of developing novel and tractable rehabilitative approaches for improving spatial navigation, problem-solving skills, and overall confidence. Second, by observing brain-related activity associated with virtual navigation (using modern-day neuroimaging methodologies), we can begin to potentially uncover the mechanisms associated with navigation performance as well as how the brain adapts and carries out this task in the absence of sight.

Navigating Using Audio-Based Virtual Environments

With respect to navigation, information captured through sound is very important for developing a sense of spatial orientation and distance as well as obstacle detection and avoidance (Ashmead, Hill, & Talor, 1989; Rieser, 2008). Previous work with individuals who are blind has shown that spatial information obtained through novel computer-based approaches using sound (Ohuchi, Iwaya, Suzuki, & Munekata, 2006; Riehle, Lichter, & Giudice, 2008) as well as tactile information (Johnson & Higgins, 2006; Lahav, 2006; Pissaloux, Maingreaud, Velazquez, & Hafez, 2006) may prove useful for developing navigation skills. In parallel, many advances in computer technology have improved information accessibility in general. For example, many individuals with visual impairment are familiar with speech-based systems (e.g., screen readers or text to speech interfaces [TTS]) as well as contextual nonspeech information (e.g., alerts using associative and realistic sounds). With respect to contextual learning, virtual environments and simulations (e.g., flight simulators for pilot training) have received considerable interest as a novel means to interact with complex information using multiple frames of reference (e.g., egocentric vs. allocentric perspectives) and for the transfer of knowledge from one situation to another (Dede, 2009). In a series of ongoing studies, we have extended these concepts with the goal of developing audio-based virtual environments as a means to teach, motivate, and develop spatial navigation skills in individuals with severe visual impairment. Specifically, by interacting with auditory cues that describe and characterize a particular environment (e.g., using TTS to provide heading information or identifying an encountered obstacle) and the conceptual alignment of spatial features using audio-based information (e.g., using stereo spectral cues to help localize the spatial location of an object), a user with profound blindness can learn to navigate a relatively complex route (Sanchez & Saenz, 2006). Key to this approach is the fact that auditory-based spatial information is acquired sequentially, within context, and through a highly interactive interface that greatly engages a user to actively explore a given environment and construct a cognitive spatial map effectively and efficiently. Taken further, this then leads to the intriguing possibility that the spatial information acquired through virtual simulation can then be translated to overall enhanced navigation skill within real-world scenarios. In the subsequent sections, we describe a series of software-based applications that have been developed with these goals in mind as well the thought process that has evolved into our current lines of collaborative research in this arena.

AudioDoom

AudioDoom is an auditory-based computer game developed as a means to engage children with blindness in play and improve spatial navigation and problem-solving skills (Sanchez & Lumbreras, 1998). The game is loosely based on a popular "first-person shooter" computer video game called *Doom* (Id Software, Mesquite, TX). In this game, a player navigates through a predetermined labyrinth of walls and corridors, locating various items and avoiding monsters so as to find his or her way to an exit portal and start the next level. Key to succeeding in this game is to maintain an internal mental map regarding the spatial location of objects encountered and keep track of areas explored. Briefly, the auditory version of the game ("AudioDoom"; Sanchez & Lumbreras, 1998) works much the same way but involves the use of sound spectral cues (e.g., door knocks and footsteps) as a means to acquire contextual spatial information regarding one's surroundings during game play. Using a keyboard, mouse, or joystick, a gamer can move in any direction (stepping forward or turning right or left) and interact with the environment in a step-by-step fashion (i.e., through a series of sequential "encounters") so as to pass through a corridor, open a door, pick up treasure, and so on. The gaming structure organizes the level into several predetermined corridors, dead ends, and pathways, giving a sense of the entire area laid out over a three-dimensional space (Figure 1A). As the paths to be explored are constrained by the use of corridors rather than true open spaces, a player is able to maintain his or her sense of orientation and heading. Thus, played out in a corresponding three-dimensional auditory virtual world, the user builds a spatial mental representation based on these sequential and causal encounters within a goal-directed navigation framework (Sanchez & Lumbreras, 1998).

In an early study, Sanchez and Lumbreras (1998) found that children who are blind ($n = 7$, aged between 8 and 11, all with early-onset and profound blindness) who played *AudioDoom* found the game very enjoyable (as assessed through the use of subjective questionnaires). Interestingly, supervising teachers also subjectively reported that blind gamers demonstrated improved cognitive abilities, problem-solving skills, and overall sense of self-confidence transferring to other areas of their course work (Sanchez & Lumbreras, 1998). However, perhaps even more interesting, was the fact that following play, the gamers were able to create tactile representations of the route they navigated in the game (e.g., using Lego® blocks; Figure 1B). Comparing their final constructions with the target virtual environment revealed that they were able to accurately represent the encounters and navigation route they followed (Figure 1C), suggesting a great degree of fidelity in the spatial cognitive maps generated following game play.

These observations reported during initial field testing of *AudioDoom* are important in terms of our overall discussion of navigation skill. Specifically, they demonstrate, first, that auditory information can provide for accurate cues that describe spatial environments and the relationships between objects and, second, that users of the game who have profound blindness can generate accurate spatial cognitive maps based on auditory information using an interactive and immersive virtual environment. Furthermore, the interactive and immersive nature of the game not only provides for a strong motivating drive but also demonstrates that spatial cognitive constructs can be learned implicitly and rather simply through causal interaction with the software.

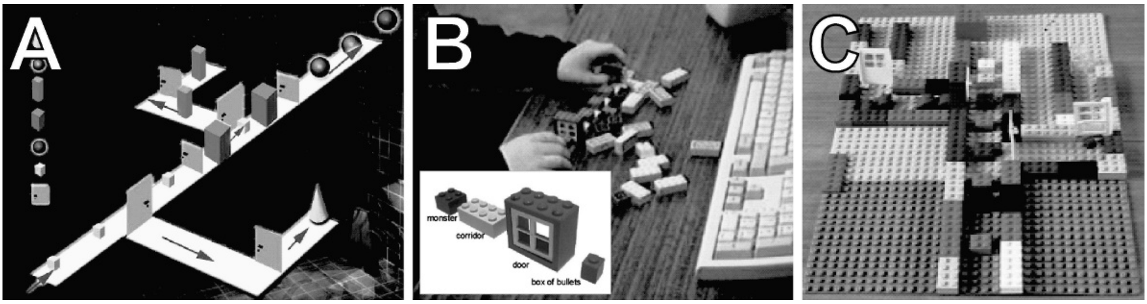

Figure 1. *Interacting with* AudioDoom*. (A) Figure depicting a target game level with corridors, doors, dead ends and objects. (B) After interacting with* AudioDoom*, a child is asked to create a model of the explored level using Lego*® *pieces representing different objects (inset figure). (C) The child's reconstruction of the level is an exact match of the target level depicted in (A). Figures modified from Sanchez and Saenz (2006).*

AudioMetro

In parallel to *AudioDoom*, another audio-based software interface has been developed with the goal of assisting users with visual impairment to organize and prepare a travel route before riding on the actual subway. This interactive software called *AudioMetro*, is based on the urban subway system of the city of Santiago, Chile, though, in principle, any subway system can be rendered (Sanchez & Maureira, 2007). Interacting with *AudioMetro* is based on a metaphor that simulates travel through a subway car. The metaphor considers notions of consecutive, transfer, and terminal stations and allows the user to simulate the experience of the entire voyage from start to finish. As with most urban subway systems, travel between two stations is sequential and along a specific line that covers both directions. Transfer stations consist of different levels with each specific line having its own level. In a typical session, the user has to first choose the departure and arrival stations of the voyage using an interactive menu (keyboard input and TTS interface; Figure 2). The software then automatically calculates the optimal route from the departure to the arrival station. In the second stage, the user travels virtually through the subway network, starting at the departure point, passing through consecutive stations, and making appropriate transfers until finally arriving to the desired destination. The software has an inherent sequential and unidirectional flow, allowing the user to explore the subway network and associated landmarks provided through audio feedback. As a result, users can familiarize themselves with the basic organization of the subway system and reinforce important concepts, such as the relative distance between stations, appropriate transfer points, platforms associated with each line, and key landmarks and facilities present at various stations.

To evaluate the usability and validity of this software, Sánchez and Maureira (2007) recruited seven participants (aged between 15 and 32, all legally blind and with varying degrees of residual visual function). In summary, the authors found that users of *AudioMetro* were able to initially plan their voyage and, over time, construct a mental representation of the overall organization and layout of the subway system and the interconnections of the various lines (as verified by tactile model construction). Furthermore, users were able to implement the knowledge gained by traveling independently throughout a series of test scenarios without the need of a guide present. Users also reported a greater sense of autonomy and competence in using the subway network (assessed using subjective rating scales) (Sanchez & Maureira, 2007). The results with *AudioMetro* suggest that audio-based interactive software can be used to access information as well as simulate and play out hypothetical scenarios that can potentially translate into enhanced navigation skills. Furthermore, these generated mental representations can be large scale and correspond to real-world environments. Finally, as with the case of *AudioDoom*, the use of gaming metaphors and the interactive and immersive nature of the software serve as powerful motivating incentives for their use.

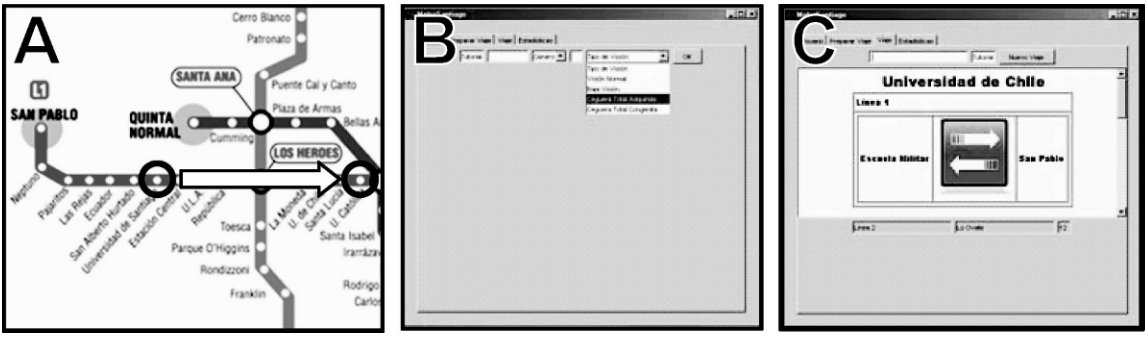

Figure 2. *Interacting with* AudioMetro. *(A) Section of the Metro map of Santiago, Chile. Travel from Universidad de Santiago to Santa Lucia station is indicated. (B) A user interface to select the desired origin and destination of travel. (C) Simulation of travel though the subway. Figures modified from Sanchez and Maureira (2007).*

Audio-Based Environment Stimulator

Building on and combining the strengths of the aforementioned software approaches, we then hypothesized that users with profound visual impairment who interact with a virtual environment that represents a real place (e.g., a building in a individual's school) can not only create an accurate cognitive spatial map of that place but may also potentially transfer this acquired spatial information to a large-scale, real-world navigation task. Key to demonstrating this premise would be to develop a flexible and modifiable software platform that leverages the advantages associated with both gaming metaphors and interactive virtual navigation. Following through with these notions, we are currently investigating the feasibility and effectiveness of using an audio-based virtual navigation software called *Audio-Based Environment Stimulator* (AbES) (Sanchez, Tadres, Pascual-Leone, & Merabet, 2009). This software is similar to those previously described in terms of its audio-based navigation and interactive capabilities but has the added feature of a floor plan editor that allows an investigator to generate virtually any physical space desired, including open rooms and corridors, multiple floors as well as furniture and obstacles (Figure 3). The software also incorporates various data collecting methods that can be used to assess behavioral performance (e.g., reconstruction of the route traveled, including the time taken to navigate to target, distance traveled, and errors made). The virtual environment is scaled so that each step is meant to represent one typical step in real physical space. Using a keyboard, a user explores the building virtually, moving through the environment and listening to appropriate spectral cues after each step taken (e.g., a knocking sound in the left stereo channel is heard as the player walks past a door on the left, and walking up stairs is associated with sequential steps of increasing pitch). Orientation is based on cardinal compass headings, with "north" defined in relative terms as the direction of forward movement as one enters the virtual space. Users have reported that they perceive their movement as "forward" in the virtual space, and thus the use of cardinal terms of direction is appropriate. The user also has a "where am I?" key that can be pressed at any time to access TTS-based information that describes his or her current location in the building, orientation, and heading as well as the identity of objects and obstacles in their path. As a proof of principle, pilot data from one test subject (early blind and aged 32 at the time of study) suggests that after approximately 40 to 60 minutes of interacting with AbES, the user was indeed able to survey and explore the layout of the building and locations of the target objects virtually. Furthermore, the subject was able to demonstrate a transfer of cognitive spatial knowledge in a real-world navigation task by locating objects found within a room in the actual physical building.

Another unique feature is the fact that AbES can be played in two modes: "directed navigation" or a "game" (or "open exploration") mode. In directed navigation mode, a facilitator places the user in any location in the building and directs the individual to a target destination so as to simulate the navigation and exploration of the building. In the game mode, the user interacts with the virtual world on his or her own (i.e., without a facilitator) with the goal of exploring the entire building in order to collect hidden gems while avoiding roving monsters that can potentially take the gems away and hide them elsewhere (Figure 3B). Thus, in either mode, users interact with the virtual environment to gain spatial information and generate a cognitive map of the spatial surroundings. However, given the implicit nature of acquiring spatial information through gaming, we have speculated that the construction of these cognitive spatial cognitive maps may prove to be different, depending on the mode of play. In other words, AbES played in game mode is in effect designed to promote full exploration of the building, thereby maximizing creativity and to encourage the development of "higher-level" spatial skills (Blasch et al., 1997). By comparison, we hypothesize that individuals who interact with AbES in directed navigation mode will generate spatial constructs that are limited to the actual routes encountered and as defined by the facilitator. This latter point is of particular importance not only in terms of generating cognitive spatial maps but also with regard to safety. It would be reasonable to assume that individuals who have a more "robust" cognitive spatial map of their surroundings are more likely to be flexible in their spatial thinking and thus can come up with alternate routes for navigation when needed as opposed to relying on rote memory alone. Current work is now aimed at investigating these hypotheses by assessing how well individuals are able to transfer their acquired spatial information from the virtual to the real physical environment and as a function of the mode of acquiring that information.

Combining Technology and Neuroscience: Watching the Brain in Action

As mentioned in the introduction, it is generally believed that in the absence of sight, an individual develops compensatory strategies by using their remaining senses more effectively so as to remain functionally independent (Carroll, 1961; Wagner-Lampl & Oliver, 1994). In line with this view, mounting scientific evidence now suggests that these adaptive skills develop in parallel with changes occurring within the brain itself (Bavelier & Neville, 2002; Pascual-Leone, Amedi, Fregni, & Merabet, 2005). It is now established that these changes implicate not only areas of the brain dedicated to processing information from the remaining senses such as touch and hearing but also regions of the brain normally associated with the analysis of visual information (Merabet, Rizzo, Amedi, Somers, & Pascual-Leone, 2005; Theoret, Merabet, & Pascual-Leone, 2004). In other words, understanding how the brain changes in response to blindness ultimately tells us something about how individuals compensate for the loss of sight. This "neuroplasticity" or "rewiring" of the brain may thus explain the compensatory and, in some cases, enhanced behavioral abilities reported in individuals who are blind, such as finer tactile discrimination acuity (Alary et al., 2008; Van Boven, Hamilton, Kauffman, Keenan, & Pascual-Leone, 2000), sound localization (Ashmead et al., 1998; Gougoux et al., 2004; Lessard, Pare, Lepore, & Lassonde, 1998), and verbal memory recall (Amedi, Raz, Pianka, Malach, & Zohary, 2003).

Evidence of functional and compensatory recruitment of visual areas to process other sensory modalities in the absence of sight has resulted largely from neuroimaging studies (Theoret et al., 2004). Modern brain imaging techniques such as functional magnetic resonance imaging (fMRI)[1] can identify areas of the brain that are associated with a particular behavioral task. Navigation skill, for example, has been extensively studied in sighted individuals (Maguire et al., 1998), and key brain structures that underlie this skill have been identified (such as the hippocampus and parietal cortical areas). However, very little is known as to how these

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[1] Neuroimaging techniques such as fMRI allow us to follow more closely and objectively phenomena related to behavioral performance at the level of the human brain. Unlike standard MRI images that give high-quality anatomical images of the brain, *functional* MRI takes advantage of the fact that when a region of the brain is highly active, there is an oversupply of oxygenated blood to that region. By measuring the relative amounts of oxygenated and deoxygenated blood, it is possible to determine which regions of cortex are more active for a given task over a time scale of a few seconds. This signal is then analyzed to generate images of the brain that reflect regions of the brain implicated with the behavioral task being carried out (see Logothetis, 2008).

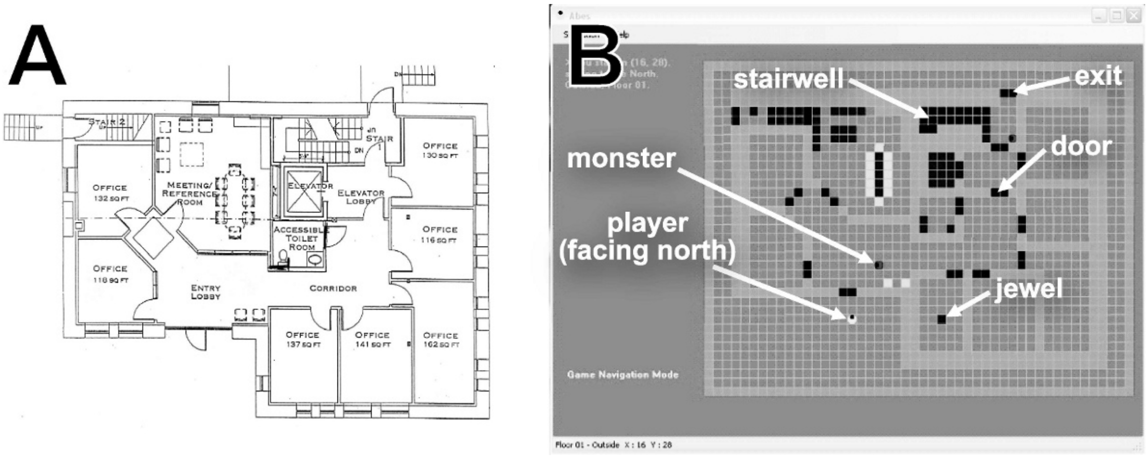

Figure 3. *Real and virtual worlds with AbES. (A) Actual floor plan of a target building. (B) Virtual rendering of the floor plan in AbES game mode showing various objects the user interacts with.*

same corresponding areas of the brain relate to navigation performance in individuals who are blind and as a result of the neuroplastic changes that follow vision loss. To help uncover this issue, we have adapted the AbES game so that it can be played within an fMRI scanner (Figure 4A). Again, as a proof of concept, we have shown that interacting the AbES within the scanner environment (testing with a sighted individual) leads to selective task activation of specific brain areas related to navigation skill. Specifically, when the subject listens to the auditory instructions describing his or her target destination, we observe brain activity localized within the auditory regions of the brain. When that same person is asked to randomly walk through the virtual environment (i.e., without any goal destination), we find brain associated activity within sensory-motor areas related to the key presses of the hand. However, when the same person is now asked to navigate from a predetermined location to a particular target, we see a dramatic increase in brain activity that implicates not only the auditory and sensory-motor regions of the brain but also regions of the visual cortex (to visualize the route) and frontal cortex (implicated in decision making), parietal cortex (important for spatial tasks), and hippocampus (implicated in spatial navigation and memory) (Figure 4B). As a next step, work is currently under way comparing brain activation patterns associated with virtual navigation in sighted (through sight and through hearing alone) with that in individuals with profound blindness (early and late onset). Of particular interest will be the role of the visual areas as they relate to plasticity and overall navigation performance. For example, does greater visual cortex activation correlate with strong navigating performance regardless of visual status and/or prior visual experience? Furthermore, how do activation patterns and brain networks change over time as subjects continue to learn and improve in their overall navigation skills? Are there specific areas or patterns of brain activity that can help identify "good navigators" from those patterns that typify poor navigation? These as well as many other intriguing questions await further investigation.

Conclusions and Future Directions

O&M training remains a mainstay in blind rehabilitation, and with systematic and rigorous training, individuals with visual impairment can gain functional independence. It is important, however, that training strategies remain flexible and adaptable so that they can be applied to novel and unfamiliar situations. Further, training must be tailored to a person's own strengths and weaknesses to address their particular challenges, needs, and learning strategies. The creative use of interactive virtual navigation environments such as the software approaches presented here, as well as other strategies (e.g., tactile representations; Ungar, Blades, & Spencer, 1995; see also Blasch et al., 1997), may provide for this flexibility and supplement

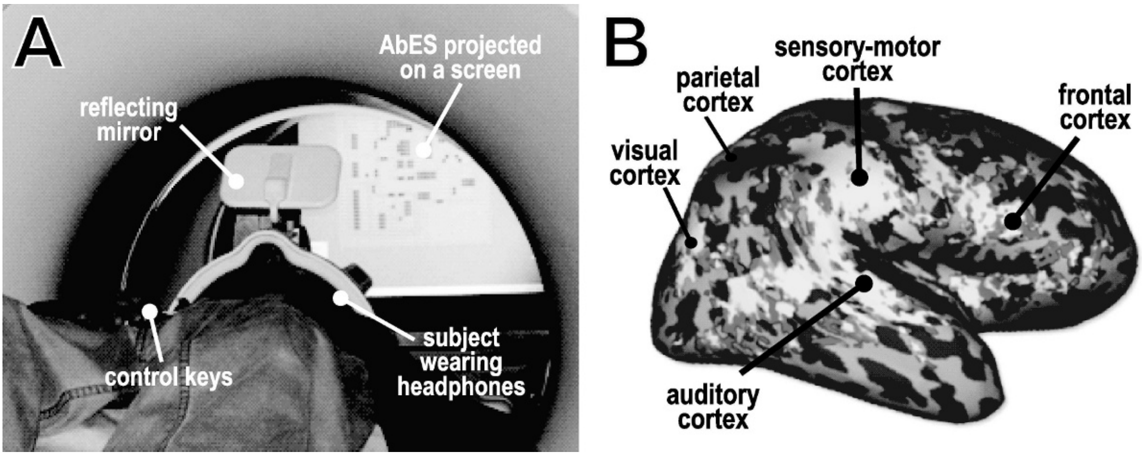

Figure 4. *Brain activity associated with navigation. (A) Sighted subject lying in the scanner and interacting with the AbES navigation software. (B) Activation of cortical areas while actively navigating with AbES. Areas implicated with active navigation include sensory-motor areas and auditory cortex as well as frontal, visual, and hippocampal (not shown) areas.*

current O&M training curricula. Certainly, that there may be substantial differences between the behavioral gains obtained though virtual compared to real physical navigation. For example, virtual navigation training within a controlled environment allows for the opportunity to play out multiple scenarios while potentially alleviating associated stress and risk issues. Conversely, there may be inherent advantages associated with the actual execution of physical movements in real-world situations that ultimately translate into enhanced motor planning and eventual consolidation of O&M task-related skills. We reiterate that we are not advocating for a replacement of current rehabilitative techniques with virtual training. Rather, we propose an adjunctive strategy that not only draws on the benefits of high motivational drive but also provides for a testing platform to carry out more controlled and quantifiable studies, including neuroscience-based investigations.

We have described a series of interactive audio-based computer software and virtual environments designed to serve as novel rehabilitative approaches to improve spatial navigation, problem-solving skills, and overall confidence in individuals with visual impairment. We continue to investigate the feasibility, effectiveness, and potential benefits of learning to navigate unfamiliar environments using virtual auditory-based gaming systems. In parallel, we are developing methods of quantifying behavioral gains as well as uncovering brain mechanisms associated with navigation skill. A key direction of future research will be to understand what aspects of acquired spatial information are actually transferred from virtual to real environments and the conditions that promote that transfer (Peruch, Belingard, & Thinus-Blanc, 2000). Furthermore, understanding how the brain creates spatial cognitive maps as a function of learning modality and over time as well as an individual's own experience and motivation will have potentially important repercussions in terms of how rehabilitation is carried out and, ultimately, an individual's overall rehabilitative success.

Moving forward, future work in this arena needs to continue employing a multidisciplinary approach drawing in expertise from instructors of the blind, clinicians, and technology developers as well as neuroscientists, behavioral psychologists, and sociologists. By further promoting an effective exchange of ideas, we believe that ultimately this will lead to an enhancement of the quality of life of individuals living with visual impairment and enhance our understanding of the remarkable adaptive potential of the brain.

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