Virtual Reality Without Vision: A Haptic and Auditory White Cane to Navigate Complex Virtual Worlds

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ABSTRACT

Current Virtual Reality (VR) technologies focus on rendering visuospatial effects, and thus are inaccessible for blind or low vision users. We examine the use of a novel white cane controller that enables navigation without vision of large virtual environments with complex architecture, such as winding paths and occluding walls and doors. The cane controller employs a lightweight three-axis brake mechanism to provide large-scale shape of virtual objects. The multiple degrees-of-freedom enables users to adapt the controller to their preferred techniques and grip. In addition, surface textures are rendered with a voice coil actuator based on contact vibrations; and spatialized audio is determined based on the progression of sound through the geometry around the user. We design a scavenger hunt game that demonstrates how our device enables blind users to navigate a complex virtual environment. Seven out of eight users were able to successfully navigate the virtual room (6x6m) to locate targets while avoiding collisions. We conclude with design consideration on creating immersive non-visual VR experiences based on user preferences for cane techniques, and cane material properties.

Author Keywords

Virtual reality; white cane; blindness; visual impairments; haptic feedback; auditory feedback; mobility, 3D audio

CSS Concepts

• **Human-centered computing~Human computer interaction (HCI)**; *Haptic devices*

INTRODUCTION

In recent years, virtual reality (VR) technologies have proliferated into the mainstream market with the promise of applications across industries; from entertainment, to healthcare and education. At the crossroads of applications, researchers have also begun introducing accessibility to VR content for people who are blind or low vision [5], [19], [21], [24], [39], [56], opening up VR applications to the quarter billion users that have currently limited to no access. Unlike interacting with stationary and mobile devices, VR often requires the user to move and orient for exploring and navigating a virtual environment.

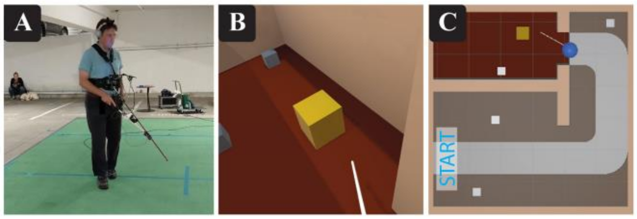

Figure 1. A) A participant navigates through the experimental game using the prototype haptic controller. B) Rendered first-person view of virtual environment (VE). C) Overhead map of VE with participant and cane (blue sphere with line).

To navigate during day-to-day activities in the real world, blind individuals typically use mobility aids, such as the *white cane* (also called a *long cane*). The cane conveys environmental information in the direct path of travel [7] by creating a three-dimensional spatial window. Navigating with the cane provides three sources of information: detection of obstacles, surface topography (e.g., textures and elevation), and foot-placement preview [3]. For navigation tasks, users may employ a variety of cane techniques as well as cane tips. Equally important to haptics is the sound feedback; often, users use echolocation cues resulting from their cane use or footstep sounds to determine the position and distance of objects [7].

In direct analogy, the use of a virtual white cane has previously been investigated for enabling blind users to interact in VR [5], [24], [27], [39], [56]. For example, Canetroller [56] implements a belt-mounted VR cane controller for blind users to perceive tapping feedback from virtual objects. Canetroller is built around a one degree-of-freedom magnetic particle brake that can stop horizontal cane swings in place combined with vibrotactile and auditory feedback, which showed the feasibility of supervised VR interaction for blind users in two sparse VR scenes.

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In this work, we venture into larger spaces and examine the ability of blind users to independently navigate and explore large $6m \times 6m$ virtual environments (VE) as shown in Figure 1. We enable this through our novel wearable cane controller that renders haptic feedback of surface shape, impact collisions, and textures, as well as spatialized audio based on the progression of sound through the geometry around the user. The multiple degrees-of-freedom enables users to adapt the controller to their preferred technique and grip style. Our VEs include walls and rooms, winding paths, and doorways, giving users ample freedom for moving around and exploring an unknown environment.

The controller renders two types of haptic feedback: 1) kinesthetic forces using a novel lightweight three degree-of-freedom brake mechanism. This allows users to interact with virtual objects to understand their shape; 2) tactile feedback using a voice coil actuator that conveys information about an object's surface properties (e.g., texture and perceptual hardness) or kinesthetic feedback that is too high in frequency for the brake mechanism to simulate. To produce audio feedback, we integrate a wave-based acoustic simulation to render geometry-aware sound effects. This enables users to sense effects such as occlusion of the audio source around a corner or get a sense of the dimensions for the surrounding space. We demonstrate its use with spatial audio beacons that represent landmarks that users managed to navigate to even when outside the direct line of hearing.

To evaluate the performance of our system for conveying diverse non-visual information, we created a VR scavenger hunt game. Targets were distributed across the indoor environment, where some of the targets had no direct line of audio to participants' initial location. Participants walked the indoor architecture while forming their understanding of the VE. Seven out of eight users were able to successfully navigate the VE to locate all five targets while avoiding collisions. Moreover, users' navigation performance increased with repeated play.

We make three specific contributions in this paper:

1. A wearable cane controller that renders human-scale force feedback corresponding to a virtual environment using a novel three-axis brake mechanism along with rendering surface textures during tapping and sweeping.
2. A simulation of virtual environments that renders physically-realistic audio effects modeled on the properties of the space, including geometries and materials.
3. An evaluation that demonstrates that blind participants were able to integrate the various feedback modalities to navigate and explore a virtual environment using their skills from navigating the real world with a white cane.

RELATED WORK

Several works have investigated ways of making VR applications accessible for the blind and visually impaired. These have employed a combination of multimodal feedback through audio and haptics, as well as augmentative sensory substitution approaches. We review several of these approaches in the following sections.

Acoustic Virtual Environments

Several prior work has explored using acoustics to enable non-visual navigation in VEs. In particular, much work has focused on the creation of accessible auditory desktop games [4], [31], [32], [41], [48]. These approaches approximate footsteps in the real world through keyboard navigation, and use text to speech to provide heading information, and distance estimation to obstacles.

Another line of work has focused on applications for navigation training with algorithms to render realistic sound effects. Maidenbaum et al. simulated a white cane that blindfolded sighted participants controlled with a mouse to obtain a single-point depth information (through sound) of the VE [26]. González-Mora et al. extended this to provide more information by also capturing the form and volume of the space in direct line of sight of the user [8]. Seki and Sato created a system where they could model sound reflections to convey the location of obstacles [51]. While these systems allowed users to navigate the VE by avoiding colli-

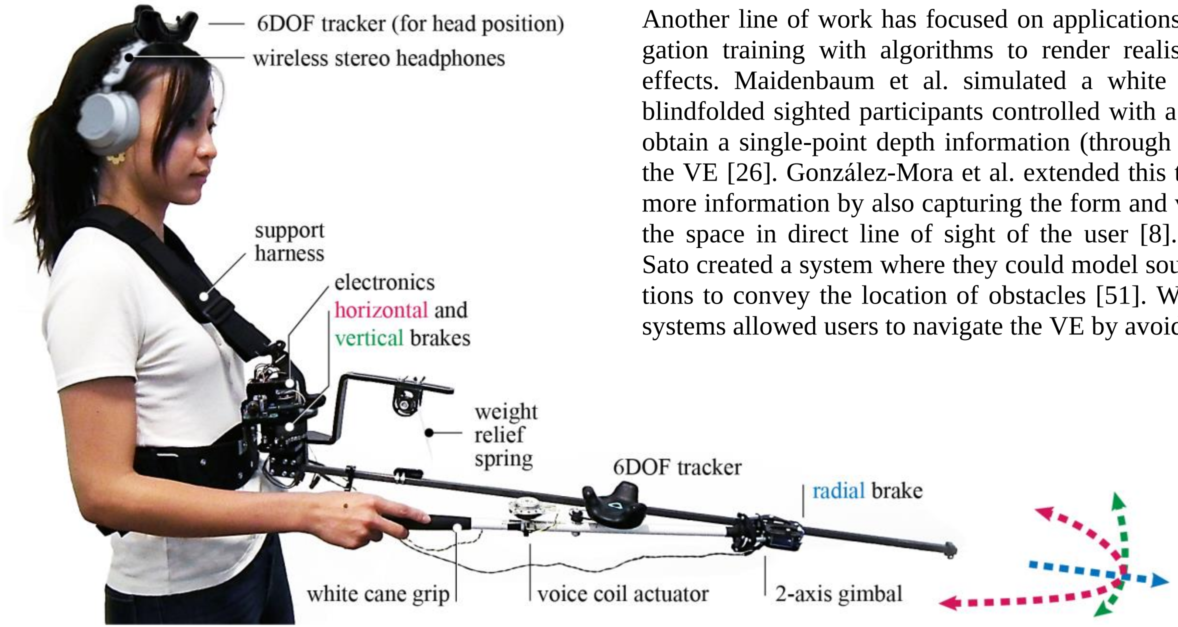


Figure 2. Components of our navigation cane controller. The controller renders force feedback in three orthogonal axes of motion, tactile feedback through a voice coil actuator, and spatialized audio effects through stereo headphones. 6-DOF trackers on the headphones and cane localize the user in virtual space and the belt fastens our controller to the body.

sions, the information is limited. Acoustics alone cannot convey the shape of the virtual geometry or the material properties; and more importantly for navigation, users lack feedback from their proprioceptive senses.

Recent advances in the gaming industry, have proposed efficient GPU algorithms that enable wave-based simulation of sound through virtual geometry with the purpose of increase game immersiveness and realism [30], [40]. Compared to traditional ray-based spatialized audio methods, wave-based acoustics is capable of capturing physics-effects such as occlusion, reverberation, and portaling; all of which are important cues for echo location [7].

Vibrotactile & Force Feedback Approaches

Prior work has complemented audio effects with various modalities of haptic feedback for increasing the immersiveness VEs. Several approaches have used traditional VR controllers with vibrotactile feedback to support interaction with virtual elements [14], [20]. These approaches offer users no distinction between surfaces and thus are limited in only being able to convey architectural geometry (i.e. walls and floor). Other work has extended the use of haptics to also convey kinesthetic forces using a variety of haptic devices [49], [56]. For example, Schloerb et al. used a Phantom haptic device to control the position of the user's avatar in the VE and provide force feedback from collisions with room walls [49].

Virtual Cane Controllers to Explore VEs

Other researchers have explored providing more intuitive navigation by creating simulations of a white cane [5], [19], [21], [24], [39], [56] used haptic systems that were grounded and did not allow users to physically move and explore the space. On the other hand, [56], [53] used mobile wearable systems. The work by Tzovaras et al. used a hand-worn exoskeleton that simulated contact forces from holding a cane. While large-scale force feedback was provided, the system was not able to render surface properties or realistic audio effects. Zhao et al. used a wearable cane (Canetroller) and is the closest solution to this work [57]. Canetroller only provides kinesthetic haptic feedback in one axis (i.e. stopping horizontal motion). Thus, Canetroller cannot provide meaningful feedback when holding the cane in different styles and support the techniques necessary to successfully navigate more complex spaces. This constrained applications to identifications tasks. Moreover, the approaches presented above made use of non-directional brakes that needed to be released to enable the user retraction of the cane, generating a sense of 'stickiness' of the obstacles.

We address these limitations by presenting a novel brake mechanism capable of rendering collision forces from the cane interactions in all axis. We demonstrate how these multidimensional cues complemented with physics-based audio rendering enables blind users to independently navigate large spaces.

Figure 3. A) Traditional cane grip centered-high, B) pencil cane grip centered-low, C) standard cane grip centered-low.

DESIGN RATIONALE

Several factors can vary in the use of the white cane for navigation: the techniques used to interrogate the environment, and the material properties of the cane shaft and tip and the position of the hand holding the cane grip. We review the differences in these factors and how they reveal important design choices in creating an adaptable cane controller for navigation in VR.

Cane Techniques

Different cane techniques are used to interrogate the environment depending on the situation [47], [56]. Two primary techniques most commonly used by blind travelers are the *two-point touch* technique (swinging the cane side to side, tapping either side in an arc) and the *constant contact* technique (sweeping the cane side to side while keeping the cane tip in constant contact with the walking surface) [13]. In both cases, the cane motion is within an arc slightly wider than one's shoulder length. This range of motion can be spanned by three orthogonal axes (polar coordinates) i.e. motion horizontally, vertically and radially where the cane collisions are contact constraints which occur as large instantaneous forces opposing the motion. Thus, a three-axis brake mechanism may be suitable to physically render virtual contact constraints.

Material Properties & Tip Styles

Cane tips tend to fall into five categories: pencil, marshmallow, ball, roller, and metal glide [1], [12]. The motion of the cane tip over a surface transmits sound and vibration from its tip to the hand that is holding the grip. As such, the cane's shaft and tip material properties both affect the haptic sensations felt and the audio effects transmitted [44], [36]. For example, a metal tip may amplify both the auditory and tactile high frequency vibrations felt by the user compared to a roller or pencil tip [12]. These properties are important to consider in rendering high fidelity tactile feedback and audio effects.

Grip & Hand Position

White cane users often vary the position of the hand holding the cane in relation to the midline of the body. Three common positions exist when holding the white cane: 1) held centered out in front of the body above the waist (*centered high*), 2) held below the waist (*centered low*), and 3) held to the side (*off-center*) [9],[16]. In addition, three grip styles are commonly used [36] (Figure 3): 1) *standard* grip where the grip is lightly held with the thumb and all other fingers except the index which lays flat across the grip; 2) *pencil* grip where the grip is held like a pencil; and 3) *tradi-*

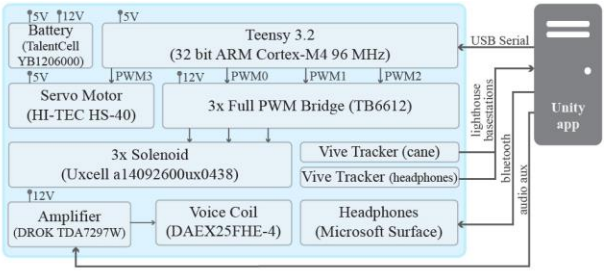


Figure 4. System Diagram of the controller electronics.

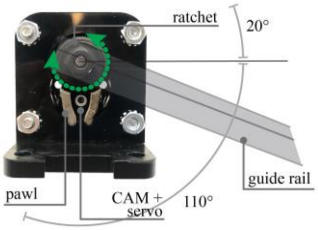


Figure 5. Vertical Axis Brake; a binary and bi-directional brake. Arrow shows the axis of motion. This mechanism consists of a ratchet with two pawls that can be selectively engaged to select a brake direction.

tional grip where the grip is held with the four fingers except the thumb, which lays flat across the grip. Depending on the navigation task, users will transition between positions and grips. These indicate the need for versatility in the controller's degrees-of-freedom such that various positions and grip styles are allowed.

Cane Length and Weight

A user's cane length is determined a priori based on the user's stride, walking speed, and reflexes [17]; typically ranging from 115 to 165 cm [13]. An appropriate cane length not only provides safety but also helps in distance estimation. As such maintaining consistency with a user's real-world cane is important to support virtual navigation. A cane must also be lightweight with its center of mass not too far from the grip, as differences in weight distribution can affect its use and increase user fatigue over time [44]. Typically, a cane's weight is in the range of 112-200g [13].

SYSTEM IMPLEMENTATION

Hardware

Based on the design rationale, we created a virtual cane controller prototype. An overview of the controller prototype and its components is shown in Figure 2. To interact in VR, the user wears our controller using the waist belt that mounts all components and puts on a pair of stereo headphones. The user holds and moves the controller at the grip much like an actual white cane. Our prototype provides three primary forms of sensory feedback: 1) large-scale shapes of virtual objects through a three-axis brake mechanism that renders kinesthetic feedback, 2) surface textures through a voice coil actuator that renders tactile feedback of contact vibrations, and 3) high-fidelity first echo and reverberations of sound in virtual geometries through a wave-based acoustics simulation.

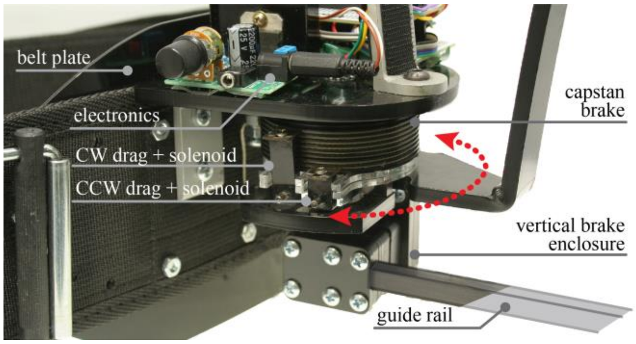


Figure 6. Horizontal Axis Brake. Arrow shows the axis of motion. This mechanism consists of a capstan with a helix-wound cord that when either side of the cord is tensioned, high output forces can be rendered bi-directionally.

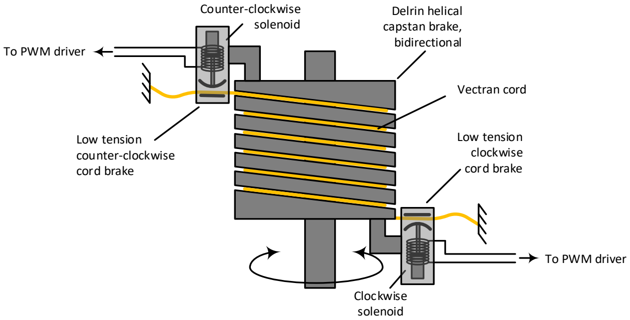


Figure 7. Schematic of the capstan brake mechanism. Two solenoid-actuated "shoes" exert a small friction to the cord against the capstan to prevent rotation.

Three-Axis Brake Design to Sustain Human-Scale Forces

The controller grip is connected to the belt-mounted prototype through a guide rail and a two-axis gimbal, such that the user can freely slide and rotate the cane when none of the brakes are engaged. Figure 3 shows the versatility in grip and cane positions afforded by this mechanism. A Teensy 3.2 microcomputer with a 32-bit ARM Cortex-M4 microcontroller drives the hardware electronics (Figure 4).

The three-axis brake is instrumented on the guide rail to prevent movement of the cane grip and thus provide force and torque feedback to the user. The horizontal and vertical brake mechanisms are rigidly mounted at the base of the belt on a ¼" Delrin plate, while the radial brake slides with the cane grip (Figure 2). The guide rail is made of a square carbon fiber rod to prevent bending and twisting.

To measure minimum and maximum brake torques and forces, the mechanism was rigidly mounted to an 80-20 aluminum frame. Each brake was then selectively actuated, and the resulting force was measured 30 cm away from the pivot point for torques and directly on the moving brake for linear force using a force gauge (Extech 475044).

Vertical Axis Brake. Figure 5 shows a close-up view of the vertical axis, binary and bi-directional, brake mechanism. The mechanism consists of a ratchet with 80 teeth per revolution and two spring-loaded pawls that can be selectively engaged to restrict rotation of the ratchet in one direction at

Brake Axis	Object Location	Action	Torque [Nm]
Horizontal	Disengaged		0.072
	Counter-Clockwise	Collision	> 4.504
		Moving Away	0.082
	Clockwise	Collision	> 2.655
		Moving Away	0.082
Vertical	Disengaged		0.024
	Top/Bottom	Collision	> 6.01
		Moving Away	0.028
			Force [N]
Radial	Disengaged		0.405
	Front	Collision	> 15
		Moving Away	0.81

Table 1. Unidirectional brake forces in the direction of the braking force and in the opposing direction. All measurements were taken 30 cm away from the pivot point.

a time. The ratchet in turn is coupled to the controller guide rail to restrict the user's motion. A micro servo (HI-TEC HS-40) actuates a CAM to engage and disengage either of the two spring-loaded pawls. This brake mechanism is asymmetric, and the user feels minimal resistance when the brake is disengaged (0.024 Nm). When either pawl is engaged, the user only feels resistance in one direction (greater than 6.01 Nm) but is free to move in the opposing direction (0.028 Nm). Table 1 shows the measured braking torques. The total range of motion is 130°.

Horizontal Axis Brake. Figure 6 shows an overview of the horizontal axis, bi-directional, brake mechanism and Figure 7 shows a schematic of its working principle. This design is based on an extension of the brake used by [53] in a handheld VR controller but with a variation to fit our application needs of a highly asymmetric brake behavior.

A capstan brake creates high output forces through an exponential gain increase of low input forces. The output braking force of a capstan+cord is governed by:

$$\text{OutputCordTension} = \text{InputCordTension} * e^{(\mu * \Theta)} \quad (1)$$

Where μ is the mutual friction between capstan and cord and Θ is the number of cord turns (radians). This braking device depends on the friction between a rotating capstan drum and fixed ends of the spiral-wound Vectran cord. The 3" diameter x 1" tall drum is made of acetal plastic (Delrin). 125 lb. Vectran cord and Delrin for the capstan were chosen for their mutual friction (static and dynamic with a very low stick-slip transition). This allows the brake to exert a low to high braking force and any force in between.

The capstan drum is also mounted to the vertical brake mechanism and the two rotate together. There is a 7.5 turn helix milled into the outside surface of the drum to retain the cord. The two ends of the cord are rigidly mounted to the belt plate including approximately 2mm of slack. This slack enables the capstan to rotate with very low friction when the brake is not actuated. At the two cord entrances of the capstan are small solenoid actuated "shoes" that exert a small friction of the cord against the capstan (Figure 7). As one solenoid is actuated, this small friction resistive force of the cord against the capstan is exponentially increased by Equation (1) and causes the other end of the cord to resist movement with a much higher force (tension). Since the end of the cord opposite the solenoid brake is attached to the belt, the capstan drum is difficult to rotate in that direction but easy to move in the other direction. This asymmetric or unidirectional brake behavior is desired, especially when the cane hits a barrier. The solenoid operation is nearly instantaneous, making the brake very fast acting. Table 1 summarizes the braking torques. CW and CCW braking forces are asymmetric due to the solenoid actuating the drag levers being located at different offsets from the pivot point and undesired flexion in the levers.

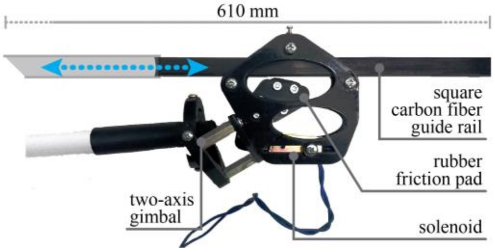


Figure 8. Radial axis brake; a binary and unidirectional brake. Arrow shows the axis of motion. This mechanism has an actuated friction pad that when in contact with the rail generates enough friction to engage and amplify the force to restrict sliding of the grip.

A capstan brake was chosen as opposed to the ratchet mechanism due to its fast actuation speed and brake force that can be modulated by varying the PWM signal used to actuate the solenoids. This flexibility is advantageous in the horizontal axis for generating different floor textures and geometry; for example, tactile domes in pavement crossroads, and crevices in the floor.

Radial Axis Brake. Figure 8 shows a close view of the radial axis, binary and unidirectional, brake mechanism and its components. The mechanism consists of a cantilevered rubber pad actuated by a solenoid (Uxcell a14092600 ux0438). When the solenoid is engaged, the rubber comes in close contact with the guide rail and generates enough friction to engage and amplify the braking force to restrict sliding of the grip cane in the distal direction. The total range of motion is 610mm. Table 1 summarizes the braking forces. Compared to the vertical and horizontal axis brakes, the radial brake can only restrict motion in one direction. For our system, this is adequate since there are rare scenarios where preventing motion of the cane in the direction towards the user is necessary.

Weight Distribution. The entire device weighs 1.87 kg. To reduce the load on the belt, users wear a shoulder harness which helps distribute the weight to the shoulders (Figure 2). However, due to the multiple components instrumented along the cane handle, the weight distribution of the cane is offset from the grip. Thus, we included a constant force spring (6.3N) attached between the guide rail and the waist-mounted belt to reduce the device's apparent weight. The controller with the voice coil, radial brake, and VIVE tracker together weigh 378 g. With the constant force spring, the perceived weight can be adjusted by moving the spring further or closer to the pivot point.

Power Consumption. A battery pack (TalentCell YB1206000) mounted to the belt is used to power the hardware electronics. The battery pack has two outputs: 1) 5V USB, 12000 mAh and 2) 12V, 6000mAh. The 5V USB output is used to power the servo motor; while the 12V output is used to power the solenoids for the remaining brakes and amplifier for the voice coil actuator. Table 2 summarizes power consumption requirements based on active components. A typical scenario with two axes engaged and texture rendering consumes 0.6A.

Brake States	Current [mA]
None engaged	45.0
One brake engaged	323.5
Typical use (2 axes engaged + voice coil actuator rendering tex-	600.0
Voice coil with highest frequencies	100.0

Table 2. Prototype power consumption.

Position Tracking

To track the position of the user in the virtual environment as well as the cane movements, we use an HTC VIVE Lighthouse system [10]. Two VIVE tracker v2.0 units are used, one attached to the stereo headphones worn by the user and another attached to the cane controller. The use of a head mounted display (HMD) for visual feedback is diagnostic and is optional.

Software

We developed an application developed in Unity 2019.2.0 to interface with the VIVE trackers and render the appropriate haptic and auditory feedback to the user based on their position and that of the cane. Brakes are selectively engaged depending on the dominant axis of the collision. Audio and textures are also played dependent on the impact velocity, and material properties of the colliding object.

Texture Rendering

Our three-axis brake mechanism described above proficiently portrays large-scale forces for shape discrimination but lacks the capability for rendering the high-frequency accelerations that occur upon contact collisions and sweeping of fine surface textures. Rendering impact forces has been shown be a better predictor of perceptual hardness compared to stiffness [14]. To address this, we connect an amplifier (DROK TDA7297W) to a voice coil actuator (Dayton Audio DAEX25FHE-4) capable of rendering a broad spectrum of acceleration frequencies [6], [23], [45].

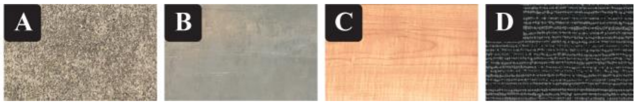


Figure 9. Sample material tiles used to record texture models and sound. A) Concrete, B) metal (aluminum), C) hardwood tile, and D) short carpet.

The impact vibration and texture frequencies rendered to the user were modeled based on data recorded in the real world of different sample surfaces (e.g., concrete, metal, plastic, hardwood, and carpet); samples are shown in Figure 9. For all recordings, we use a carbon fiber cane with a metal glide tip distributed by the National Federation for the Blind (NFB) [35]. We mount a triple-axis accelerometer to the end of a white cane shaft (ADXL335) and record tapping and sweeping motions on the sample materials [46]. We then converted the voltage to acceleration data using calibration constants. To generate a compatible audio signal, we reduced the three-axis signal to one using principal component analysis (PCA) to determine the axis with the largest signal energy [14]. Although more recent methods have been proposed for generating data-driven texture models that make use of vibrations in all three-axes [45], we chose this one for its simplicity and good fidelity [46].

Each virtual object is then tagged with a recorded tapping texture and sweeping texture. When the virtual cane moves across the surface of a virtual object, the tapping texture is played back through the voice coil actuator with its amplitude adjusted proportional to the impact velocity. In addition, if the cane sweeps on the object, the sweeping texture playback rate is rendered and modulated based on the speed of the cane tip. If the non-moving cane is simply in static contact with an object, we should expect and get no texture.

Sounds Effects and Wave-Based Acoustics Simulation

For sound effects generated from collisions and the sweeping motion of the virtual cane, we also recorded data from real-world material samples (Figure 9). The same NFB carbon fiber cane with a metal glide that was used for recording textures was used for recording the sound effects. Tapping and sweeping sounds were recorded with a microphone in an outdoor environment to mitigate sources of acoustic reflection. The recordings are then filtered to reduce background noise and clipped to retain only the relevant sound signal. For sound clips of sweeping motion, the ends of the sample are manually adjusted with a synthesizer to achieve smooth playback when looping.

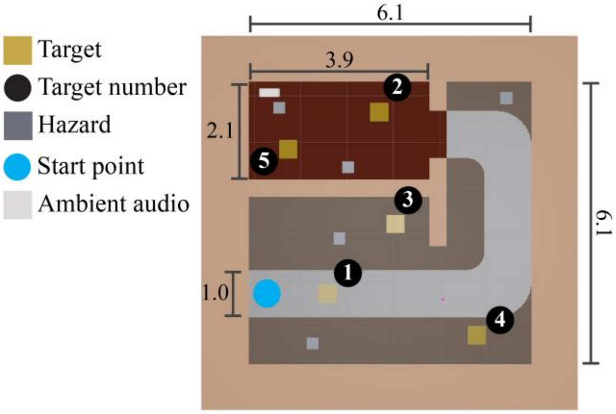


Figure10. Dimensioned game room drawing (in meters).

We integrated Project Acoustics [38] as the primary acoustics engine to render high-fidelity spatialized audio. This engine models sound wave effects (e.g., occlusion, reverberation, portaling) in complex room geometry [40]. The simulation is baked a priori with respect to the scene geometry. To accomplish this, all geometry in the virtual scene is first assigned absorption coefficients based on the desired material properties. The scene is then voxelized and the simulation is computed at discrete listener probes in the 3D space. The results are registered to the scene and at runtime interpolated based on the user's location and the nearest probe locations [40]. In addition to the spatialized audio, the volume is also modulated proportional to the impact velocity of the cane with collisions. The same workflow used for rendering textures is used in this case for determining which sounds effects are played.

Surface Foot Preview

With the components described above, we are only able to provide feedback to the user when they're in contact with the cane grip. No feedback is provided relative to the user's body. This means that a user lacks feedback from foot placement, for both texture and elevation changes. While the cane brake may be engaged to indicate the presence of an obstacle, the user is still able to move their body.

USER EVALUATION

To evaluate the fidelity of the cane simulation, we designed a scavenger hunt game in VR. Participants navigated the virtual environment using the cane simulation with two tasks in mind: 1) to collect targets, and 2) to avoid walking over hazards and virtual walls. Targets gave participants structure to navigate the virtual environment; and hazards and walls encouraged careful and intentional navigation.

Evaluation goals

Through our evaluation, we wanted to understand if and how participants could explore the virtual world using our non-visual rendering. We were interested in two questions:

1) Does the simulation provide sufficient sensory information through both haptic and auditory channels to enable users to independently navigate and understand the space? In visual VR experiences, increased realism has been linked with improved acquisition of spatial knowledge [31]. We hypothesized that the multisensory feedback provided in the simulation could simultaneously give the environment semantic value and thus help users navigate. In particular, we wanted to understand if the wave-based acoustics simulation enabled participants to directly navigate towards audio beacons even if such beacons were outside a direct line of hearing; and if together with the haptic cues, participants would be able to understand both global geometry and local surface properties.

2) Can participants apply the same knowledge and skills in using their (physical) white cane to effectively navigate the VE using our virtual cane? Does our simulation provide enough realism (haptic, audio, grip, feel, etc.) for participants to employ the same techniques they use with a real cane to navigate the architectural landmarks in the game?

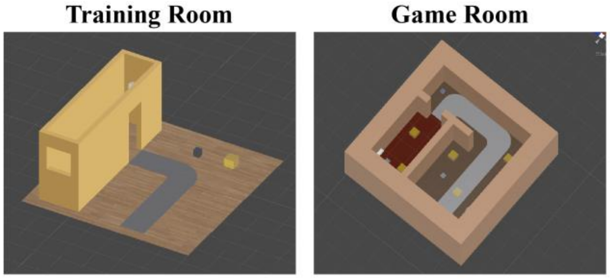
Game Mechanics

The virtual scavenger hunt was set in a virtual building with a walking area of $6.1m \times 6.1m$ (Figure 10) and two distinct spaces: 1) a small carpeted room of $3.9m \times 2.1m$ with a doorway and a radio playing a podcast, which we included to introduce an additional distinct localization cue; 2) an open *outdoor* area with a winding concrete sidewalk leading into the small room. Participants were told that the concrete sidewalk was a "safe zone" where they would not encounter hazards, although targets could appear anywhere. All walls were rendered as drywall material.

Participants' primary task in the game was to collect all five targets. Targets appeared sequentially once the previous target was collected. Figure 10 shows the location of each target numbered in the order in which they appeared. Targets emitted a distinct sound of techno music that acted as an audio beacon which participants could orient to. In addition, all targets were rendered as cubes (355.6mm per side) and sounded like drums when tapped. To collect a target, participants had to walk over it.

Participants were also told to avoid walking over hazards and colliding with virtual walls. Unlike targets, hazards did not emit beacon sounds. However, they did have a distinct shape and material that could be detected by the cane. Hazards were rendered as metal cubes (255mm per side). Tapping or sweeping against them resulted in a metallic clinking sound and texture rendering.

In addition to the sound effects from the cane tapping or sweeping across the various game elements, feedback was provided when a participant collected a target or collided with walls or hazards. Collecting a target played a reward sound of collecting coins. Colliding with a wall played a mild explosion sound. Colliding with a hazard played a more alarming cartoon-like explosion sound.



Training Room

Game Room

Figure 11. User study training and game virtual rooms.

Because the cane's brake was grounded to the participant's torso, it was not uncommon for the cane to pass into walls or other objects as participants walked or pivoted their bodies. To help resolve the confusion this could generate, whenever the cane was "inside" a virtual object or wall, our cane would "lock up" by activating all three brakes until the cane was outside the obstacle (usually achieved by physically walking or turning back). This helped participants to verify the location and solidity of objects and gave them an additional means of testing their environment with the cane.

Rationale

We conducted our evaluation as a scavenger hunt, as it left participants' exploration strategies mostly unconstrained, while game elements provided some degree of structure. Games have been used in virtual environments for implicit learning before [31],[26] as they lead to more immersive exploration. In designing the game layout, we included game elements based on the four APH mobility training techniques [47]: 1) detection (locating targets), 2) shorelining (avoiding virtual environment walls and following the sidewalk), 3) negotiating doors & stairs (navigating between rooms in the virtual environment), 4) negotiating obstacles and reorientation (avoiding obstacles).

Participants

Eight legally blind users (4 female, 4 male) were recruited for participation through mailing lists. Five participants were totally blind and three reported some light and shadow perception. Ages ranged from 25 to 70 with an average of 44.9 years. Only one participant had previously interacted with a VR system. All participants had received formal O&M training and used a white cane as their preferred navigation aid (with at least 5 years of experience). One participant used both a cane and a guide dog depending on the task. Four participants (P1, P2, P5, P6) used an NFB carbon fiber cane with a metal glide tip and the other four (P3, P4, P7, P8) used a folding aluminum cane with a Nylon pencil tip. Participants average cane length was $1.57m$ $(SD = 0.2)$.

Procedure

After arrival at the experimental location, participants received an overview of the session's activities and provided consent in accordance with our IRB. Following a brief pre-survey to gather demographic and other details related to cane use and VR experience, participants were fitted with our controller prototype and the length of the virtual cane was set to the same length as their real cane. We then walked participants through a brief orientation of the system by placing them in the *training room* VE (Figure 11).

Participants started inside the corridor (bottom left) where they could feel the walls on either side, and we demonstrated the experience of tapping and dragging against different surfaces and what happens when they passed through a wall with the cane or their body. They were then encouraged to walk along the corridor and find the doorway. After this, participants explored the different ground textures (concrete vs. wood) and we demonstrated the different sounds and textures associated with game elements (targets and hazards). Participants explored the training room until they were comfortable with the basic elements of the experience.

After training, the experimenter led participants to the start point of he game room. During the game, the first target was placed directly in front of the starting point to give participants some immediate feedback (Figure 10). After this, targets appeared sequentially and players navigated the VE to find them, attempting to navigate around walls and avoid hazards. The game concluded once participants acquired the fifth target. If time remained, we asked participants if they would like to play again. We recorded the position and orientation of participants' headsets and the cane, as well as all geometry they collided with.

At the end of the session, we removed the controller prototype and proceeded to a post-survey. We asked participants about their understanding of the VE, how they used the provided feedback, what things they needed to adapt to in contrast to using their real cane, and their overall experience with the system. The study lasted 1.5 hours.

Results

Overall Game Statistics

Seven out of the eight participants (excluding P3) were able to successfully find all five of the targets in the game. The experimenter suspended P3's game play after locating Target 4 due to time constraints in keeping the study within the allotted time. The average time to complete the game for the first trial was $572.3s$ $(SD = 287)$ and to find each target $106.0s$ $(SD = 119.9)$. Four participants (P1, P5, P6, P8) repeated the game for a second trial. Other participants were not able to complete a second trial due to time constraints. The average time to complete the game in the second trial was $218.2s$ $(SD = 51.1)$ and to find each target $43.6s$ $(SD = 30.3)$ (Figure 13).

Figure 12a shows a 2D histogram of position data points from trial 1 of all participants. Each point contributes 1/sampling rate to a histogram bin value such that the total value approximates the accumulated time spent in seconds. This plot reveals areas where participants spent more time, for example at the hallway corner and doorway. Figure 12b and Figure 12c show a comparison of the trajectories between trials. Users were faster and collided with fewer hazards and walls the second trial. For the trial 1, users hit

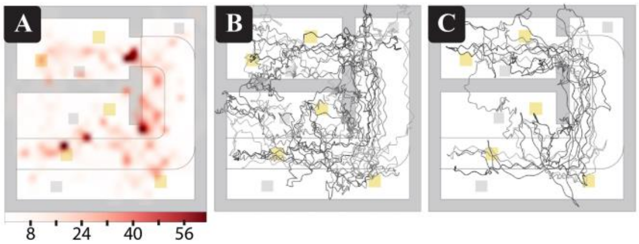


Figure 12. A) 2D histogram of position data points from trial 1 of all participants. Values represent time [seconds] spent at each bin. B) Trial 1 trajectories for users that completed two trials (P1, P5, P6, P8). C) Trial 2 trajectories for users that completed two trials (P1, P5, P6, P8).

on average 3.5 hazards $(SD = 2.8)$, and 12.4 walls $(SD = 7.2)$ (Figure 13). For trial 2, users hit on average 1 hazard $(SD = 0.8)$, and 6.2 walls $(SD = 2.6)$ (Figure 14).

Audio Provides Spatial Information and Realism

All participants had positive comments on the spatialized audio rendering engine. Participants commented how its realism immersed them in the space, "*The audio was super real that's why I thought there were people around me.*" (P6). It also provided information on participants' orientation, distances, and occlusions, "*From the target audio cue, I could know which direction to go and approximately how far I had to go*" (P8). "*The volume, depending on where you were helped a lot; because that's what I usually use* [in the real world]*"* (P5).

Metal Tip Users Perceive Greater Realism of the VE

Glide metal tip users performed better in all measures than plastic pencil tip users (Figure 13). All metal tip users (P1, P2, P5, P6) noted similarities of the vibrations and audio to sensations they were familiar with in the real world. "*What really set out was the tactile. It seemed so real, specially outdoors…The cement was spot on…"* (P2). *"Seems to me as much reality based as you can get"* (P5). *"The sweeping was very real. Audio was very real, it helped me locate where things might be..."* (P6). "[vibrotactile feedback] *changed in intensity depending on indoor vs outdoor. Like the outdoors on pavement the vibrations are harder…"* (P1). We return to this finding in the discussion.

Force Feedback Helped to Identify Architectural Geometry

When asked about their use of the force feedback generated by our three-axis brake, most participants (P1,P2,P5–P8) commented on its use for: 1) understanding the architectural geometry, and 2) finding open spaces to walk in (and knowing where NOT to walk). *"*[It helped me detect] *where barriers were, depending on the barrier type… How high does it go and how far across does it go. Is it straight up and down? Getting shape of things mostly"* (P1). *"I felt the clear entries where I didn't encounter walls"* (P5). "*When I couldn't move the cane I knew I was somewhere I wasn't supposed to be, compared to when it moved freely"* (P8).

Variety of Grips Employed with Some Adaptations Needed

Most users used the traditional grip with cane held off-center and some occasionally transitioned to holding the cane high above the waist. *"I did feel like it was pretty darn* [close to a real cane]*"* (P7). P1 and P2 preferred a pencil grip and commented on some of the difficulties in using this grip. P1 commented that it was not as easy to transition between grips and positions due to the brake apparatus. P2 and P3 also noted their grip's being quite similar to a real cane but having to adjust their hand slightly higher.

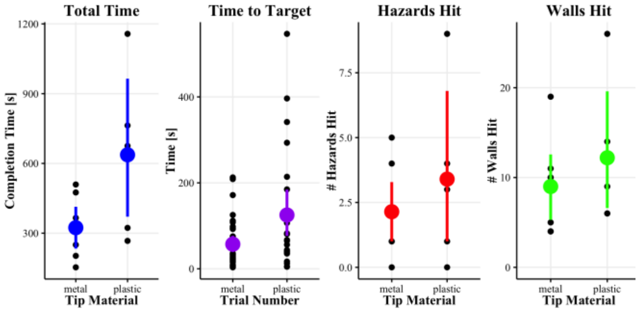


Figure 13. Overall game statistics grouped by cane material. Error bars represent 95% confidence intervals.

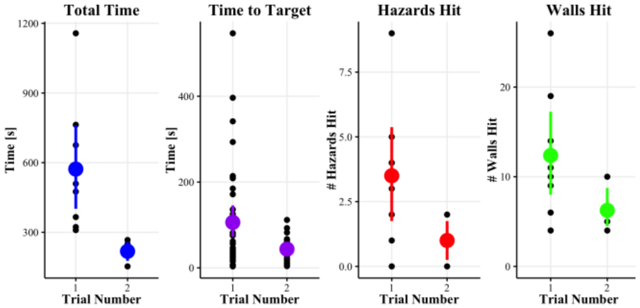


Figure 14. Overall game statistics grouped by trial. Error bars represent 95% confidence intervals.

Constant Contact and Two-Point Touch

All participants commented on using either constant contact or two-point touch for general navigation in the open spaces. *"When I use my cane, I don't glide, I usually do my tap motions. And that's what I did in the game, but I did glide a bit just to see. So, I did a little bit of both and they were both spot on"* (P2). *"Two-point touch I tried but I sometimes got lazy, so I ended up conveying that some in my cane technique by the end of it all*" (P6).

The Game was Fun, Interesting, and Challenging

Participants commented on their enjoyment while playing. *"It was challenging, and I enjoyed it. The 2nd time I enjoyed it even more. I wasn't a mad man on a mission"* (P6). *"It was dope!"* (P1). Users found the game relatable and challenging enough, *"It wasn't easy because I haven't had that experience, but it was in a way you could relate to it because it's a total body experience."* (P5).

DISCUSSION

Overall, the results of our evaluation show that our system provides a compelling VR experience for blind users through multimodal haptic cues and auditory feedback. As hypothesized, participants primarily used the kinesthetic force feedback to understand the architectural geometry of the VE, while the tactile feedback complemented with spatial audio conveyed more information about the local surface properties and geometry of materials.

An unanticipated effect was the sharp difference in performance between users of metal and plastic cane tips. Plastic tip participants had more trouble understanding the meaning of the tactile feedback, and generally performed worse. We assume this difference is largely due to the fact that we recorded sound effects and tactile feedback using a metal-tipped carbon fiber cane, so the simulation was unfamiliar to users of plastic-tipped canes. One participant commented, "*The cane was vibrating a lot for reasons I don't know*". Surprisingly, P4 (a plastic tip user) commented, "*The sensations are a little different. To me. It almost felt I had like one of those, I don't know if you've seen, the NFB canes that are really flexible.*" On the other hand, participants accustomed to using a metal tip in the real world found greater familiarity with the virtual cane and described the feedback as being "*spot on*" without much needed explanation. These insights highlight the importance of adherence to user preferences in cane styles and how they impact the amount of training or familiarization needed with a system. While we modelled only one type of cane, creating a library of different cane styles and material properties is certainly possible such that user preferences can be loaded at runtime in the same manner that the cane length is adjusted per user.

Similar to navigating the real world, we found that participants had more difficulty navigating narrow spaces, such as corners and doorways, especially when they were first getting used to the system (Figure 12). However, during subsequent times that they passed the doorway, they were able to navigate more efficiently. Differences were even more apparent for the second trial where participants were much quicker at finding all targets and reduced the number of collisions with the wall geometry and hazards.

An additional confounding variable was the time given to participants to navigate the game VE. Many participants mentioned their sole focus on finding the targets and less so in freely exploring. Linberg et al. showed that acquiring a survey representation requires a conscious effort from the user [25], one must be motivated to do so [34]. In our study, a high reward was placed on finding the targets but less so on exploration. This might have provided some bias for participants to not focus on forming a mental map of the space. This would be in line with Siegel and White's [52] survey knowledge theory where users first form knowledge of the content without structure, followed by route knowledge (egocentric), and last but less certain, a survey knowledge (allocentric). The decrease in navigation time and number of collisions provides evidence for participants' understanding of the VE structure and success in route tasks but not necessarily acquiring a survey representation.

LIMITATIONS & FUTURE WORK

In this work, we approximate the region of interaction of a white cane as three orthogonal spanning vectors and create a wearable brake system grounded to the user's body. While several benefits arise (i.e., high asymmetric force brakes and a mobile system), there are also limitations. The controller cannot stop the user's body motion, so that when feedback passes undetected users may still walk into virtual objects. We mitigated this by providing audio feedback when users collided with the walls. We are also not currently able to render feedback to users' feet, which would convey cues such as elevation changes and ground textures.

Our prototype models one particular type of cane, carbon fiber with a metal glide tip, as we recorded audio and textures from real-world materials. Our results show the need for expanding this library. In addition, our prototype cannot adjust texture and impact feedback depending on where along the cane a collision has occurred. A collision at the tip generates a different vibration profile compared to impact higher up the cane. One approach towards this could be the use of multiple synchronized voice coil actuators.

Participants navigated the game VE by physically walking with a mapping of 1:1 between the real and the virtual. However, an interesting question arises on how we might enable even larger-scale navigation (e.g., of cities where a 1:1 mapping is likely not feasible) using established techniques in visual applications such as teleportation and walking speed gains [1]. Finally, given that users are navigating in VR, interesting augmentations could be explored to enhance not just realism but user presence [50].

Prior work has shown survey knowledge can be attained through exploration of VEs [37], [20]. Our study provides evidence of participants' understanding of the VE structure and acquisition of a route representation. In future work, we would like to study survey knowledge acquisition by comparing training in a VE and subsequent navigation and assessment of standard O&M metrics in an equivalent real-world environment.

CONCLUSION

We described a prototype experience for enabling non-visual exploration of large VEs. This experience comprises a wearable controller simulating a white cane commonly used by people who are blind or have low vision. Our controller renders human-scale force feedback using a novel three-axis brake alongside surface texture associated with tapping and sweeping. Our controller plugs into a VE where we render physically realistic audio effects that are modeled on the geometry and material properties of the VE. We evaluated this experience through a user study in which eight blind participants used our system to navigate and explore a virtual game using only their senses of hearing, touch, and O&M skills. Our work extends the state of the art in haptic simulations for VR and is particularly promising for opening up further research on the accessibility of VR for people who are blind or have low vision.

REFERENCES

[1] Parastoo Abtahi, Mar Gonzalez-Franco, Eyal Ofek, and Anthony Steed. 2019. I'm a Giant: Walking in Large Virtual Environments at High Speed Gains. *In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (CHI '19). Association for Computing Machinery, New York, NY, USA, Paper 522, 1–13. DOI:https://doi.org/10.1145/3290605.3300752

[2] Grace Ambrose-Zaken. 2005. Knowledge of and preferences for long cane components: A qualitative and quantitative study. *Journal of Visual Impairment & Blindness*, 99(10), 633-645.

[3] B. B. Blasch, Steven J. LaGrow, and W. R. De l'Aune. 1996. Three aspects of coverage provided by the long cane: Object, surface, and foot-placement preview. *Journal of Visual Impairment and Blindness*, 90, 295-301.

[4] Erin Connors, Elizabeth R. Chrastil, Jaimie Sánchez and Ltfi B. Merabet. 2014. Action video game play and transfer of navigation and spatial cognition skills in adolescents who are blind. *Frontiers in Human Neuroscience*, 133.

[5] Edoardo D'Atri, Carlo Maria Medaglia, Alexandru Serbanati, Ugo Biader Ceipidor, Emanuele Panizzi and Alessandro D'Atri. 2007. A system to aid blind people in the mobility: A usability test and its results. *In Second International Conference on Systems* (ICONS'07) (pp. 35-35). IEEE.

[6] Massimiliano Gabardi, Massimiliano Solazzi, Daniele Leonardis and Antonio Frisoli. 2016. A new wearable fingertip haptic interface for the rendering of virtual shapes and surface features. *In 2016 IEEE Haptics Symposium* (HAPTICS) (pp. 140-146). IEEE.

[7] Nicholas A. Giudice. (2018). Navigating without vision: principles of blind spatial cognition. *Handbook of behavioral and cognitive geography.* Edward Elgar Publishing.

[8] José L. González-Mora, L. Rodriguez-Hernandez, L. F. Rodriguez-Ramos, L. Díaz-Saco, and N. Sosa. 1999. Development of a new space perception system for blind people, based on the creation of a virtual acoustic space. *In International Work-Conference on Artificial Neural Networks.* (pp. 321-330). Springer, Berlin, Heidelberg.

[9] William Henry Jacobson. (1993). The art and science of teaching orientation and mobility to persons with visual impairments. *American Foundation for the Blind*.

[10] HTC Vive. Retrieved September 13, 2019 from https://www.vive.com/us/.

[11] Dae Shik Kim and Robert Wall Emerson. 2012. Effect of cane length on drop-off detection performance. *Journal of Visual Impairment & Blindness*, 106(1), 31-35.

[12] Dae Shik Kim, Robert Wall Emerson and Amy B. Curtis. 2010. Ergonomic factors related to drop-off detection with the long cane: Effects of cane tips and techniques. *Human Factors*, 52(3), 456-465.

[13] Dae Shik Kim, Robert Wall Emerson, Kooroosh Naghshineh and Alexander Auer. 2017. Drop-off detection with the long cane: Effect of cane shaft weight and rigidity on performance. *Ergonomics*, 60(1), 59-68.

[14] Julian Kreimeier and Timo Götzelmann. 2019. First Steps Towards Walk-In-Place Locomotion and Haptic Feedback in Virtual Reality for Visually Impaired. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (CHI EA '19). Association for Computing Machinery, New York, NY, USA, Paper LBW2214, 1–6. DOI:https://doi.org/10.1145/3290607.3312944

[15] Katherine K. Kuchenbecker, Jonathan Fiene and Günter Niemeyer. 2006. Improving contact realism through event-based haptic feedback. *IEEE Transactions on Visualization and Computer Graphics*, 12.2, 219-230.

[16] Steven J. LaGrow, B. B. Blasch and William De l'Aune. 1997. The effect of hand position on detection distance for object and surface preview when using the long cane for nonvisual travel. *RE: view*, 28(4), 169.

[17] Steven J. LaGrow and Marvin J. Weessies. 1994. Orientation and mobility: Techniques for independence. Palmerston North, New Zealand: Dunmore Press.

[18] Orly Lahav and David Mioduser. 2001. Multisensory virtual environment for supporting blind persons' acquisition of spatial cognitive mapping–a case study. In *EdMedia+ Innovate Learning*. Association for the Advancement of Computing in Education (AACE), 1046-1051.

[19] Orly Lahav and David Mioduser. 2004. Exploration of unknown spaces by people who are blind, using a multisensory virtual environment (MVE). *Journal of Special Education Technology*, 19, 3, 15-23.

[20] Orly Lahav and David Mioduser. 2008. Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind. *International Journal of Human-Computer Studies*, 66(1), 23-35.

[21] Orly Lahav, D Schloerb, S Kummar and M A Srinivasan. 2011. A virtual map to support people who are blind to navigate through real spaces. *Journal of Special Education Technology*, 26, 4.

[22] Orly Lahav, David W. Schloerb and Mandayam A. Srinivasan. 2015. Virtual environments for people who are visually impaired integrated into an orientation and mobility program. *Journal of Visual Impairment & Blindness*, 109(1), 5-16.

[23] Nils Landin, Joseph M. Romano, William McMahan and Katherine J. Kuchenbecker. 2010. Dimensional reduction of high-frequency accelerations for haptic rendering. In *International conference on human haptic sensing and touch enabled computer applications*, pp. 79-86. Springer, Berlin, Heidelberg, 2010.

[24] Anatole Lécuyer, Pascal Mobuchon, Christine Mégard, Jérôme Perret, Claude Andriot and J. P. Colinot. 2003. HOMERE: a multimodal system for visually impaired people to explore virtual environments. In *Proceedings of IEEE Virtual Reality*. IEEE. (pp. 251-258).

[25] Eric Linberg and Tommy Garling. 1983. Acquisition of different types of locational information in cognitive maps: Automatic or effortful processing? In *Psychological Research,* 45, 19–38.

[26] Maruricio Lumbreras and Jaime Sánchez. 1999. Interactive 3D sound hyperstories for blind children. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems (CHI '99).* Association for Computing Machinery, New York, NY, USA, 318–325. DOI:https://doi.org/10.1145/302979.303101

[27] Shachar Maidenbaum, Shelly Levy-Tzedek, Daniel-Robert Chebat and Amir Amedi. 2013. Increasing accessibility to the blind of virtual environments, using a virtual mobility aid based on the" EyeCane": Feasibility study. *PloS one 8,* 8, e72555.

[28] Shachar Maidenbaum and Amir Amedi. 2015. Non-visual virtual interaction: Can Sensory Substitution generically increase the accessibility of Graphical virtual reality to the blind? In *2015 3rd IEEE VR International Workshop on Virtual and Augmented Assistive Technology (VAAT)*. IEEE. pp. 15-17.

[29] Mayer L. Max and Jesse R. Gonzalez. 1997. Blind persons navigate in virtual reality (VR); hearing and feeling communicates reality. *Studies in health technology and informatics*. 39, 54-59.

[30] Ravish Mehra, Nikunj Raghuvanshi, Lauri Savioja, Ming C. Lin, and Dinesh Manocha. 2012. An efficient GPU-based time domain solver for the acoustic wave equation. In *Applied Acoustics*. 73(2), 83-94.

[31] Frank Meijer, Branko L. Geudeke, and Egon L. Van den Broek. 2009. Navigating through virtual environments: Visual realism improves spatial cognition. In *CyberPsychology & Behavior*. 12(5), 517-521.

[32] Lofti B. Merabet, Erin C. Connors, Mark A. Halko and Jaime Sanchez. 2012. Teaching the Blind to Find Their Way by Playing Video Games. PloS one 7, no. 9 (2012): e44958.

[33] Richard Mettler. 1998. Cognitive learning theory and cane travel instruction: A new paradigm. DIANE Publishing.

[34] Shannon D. Moeser. 1988. Cognitive mapping in a complex building. In *Environment and Behavior*. 20, 21–49.

[35] NFB Canes. Retrieved August 9, 2019 from https://www.nfb.org/programs-services/free-white-cane-program. *NFB canes.*

[36] Kiyohiko Nunokawa, Y. Seki, Shuichi Ino and K. Doi. 2014. Judging hardness of an object from the sounds of tapping created by a white cane. In *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, pp. 5876-5879.

[37] Makoto Ohuchi, Yukio Iwaya, and Yôiti Suzuki. 2006. Cognitive-map forming of the blind in virtual sound environment. Georgia Institute of Technology, 2006. http://hdl.handle.net/1853/50588.

[38] Project Acoustics. 2019. (3 March 2019). Retrieved September 6, 2019 from https://aka.ms/acoustics.

[39] Ludek Pokluda and Jiri Sochor. 2003. Spatial haptic orientation for visually impaired people. In *Eurographics*.

[40] Nikunj Raghuvanshi and John Snyder. 2018. Parametric directional coding for precomputed sound propagation. *ACM Trans. Graph.* 37, 4, Article 108 (July 2018), 14 pages. DOI:https://doi.org/10.1145/3197517.3201339

[41] Nikunj Raghuvanshi, John Snyder, Ravish Mehra, Ming Lin, and Naga Govindaraju. 2010. Precomputed wave simulation for real-time sound propagation of dynamic sources in complex scenes. *ACM Trans. Graph.* 29, 4, Article 68 (July 2010), 11 pages. DOI:https://doi.org/10.1145/1778765.1778805

[42] Reardon, S. 2011. Playing by ear. *Science*, 333(6051), 1816.

[43] Anthony E. Richardson, Daniel R. Montello and Mary Hegarty. 1999. Spatial knowledge acquisition from maps and from navigation in real and virtual environments. *Memory & Cognition*. 27(4), 741-750.

[44] Mark D. Rodgers and Robert W. Emerson. 2005. Human factor analysis of long cane design: Weight and length. *Journal of Visual Impairment & Blindness*. 99(10), 622-632.

[45] Joseph M. Romano and Katherine J. Kuchenbecker. 2011. Creating realistic virtual textures from contact acceleration data. In *IEEE Transactions on Haptics*. 5(2), 109-119.

[46] Joseph M. Romano, Takashi Yoshioka and Katherine J. Kuchenbecker. 2010. Automatic filter design for synthesis of haptic textures from recorded acceleration data. In *2010 IEEE International Conference on Robotics and Automation*. IEEE. pp. 1815-1821.

[47] Sandra Rosen. Long Cane Techniques: Study Guide. Retrieved August 9, 2019 from https://tech.aph.org/sbs/04_sbs_lc_study.html#12

[48] Jaime Sánchez and Mauricio Sáenz. 2010. Metro navigation for the blind. In *Computers & Education.* 55(3), 970-981.

[49] David W. Schloerb, Orly Lahav, Joseph G. Deslogeand Mandayam A. Srinivasan. 2010. BlindAid: Virtual environment system for self-reliant trip planning and orientation and mobility training. In *2010 IEEE Haptics Symposium*. IEEE. pp. 363-370.

[50] Martijn J. Schuemie, Peter Van Der Straaten, Merel Krijn and Charles A. Van Der Mast. 2001. Research on presence in virtual reality: A survey. In *CyberPsychology & Behavior*. 4(2), 183-201.

[51] Yoshikazu Seki and Tetsuji Sato, T. 2010. A training system of orientation and mobility for blind people using acoustic virtual reality. *IEEE Transactions on neural systems and rehabilitation engineering*. 19(1), 95-104.

[52] Alexander W. Siegel and Sheldon H. White. 1975. The development of spatial representations of large-scale environments. In *Advances in Child Development and Behavior*. New York: Academic Press. Vol. 10, (pp 10–55).

[53] Mike Sinclair, Eyal Ofek, Mar Gonzalez-Franco, and Christian Holz. 2019. CapstanCrunch: A Haptic VR Controller with User-supplied Force Feedback. In Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology (UIST ’19). Association for Computing Machinery, New York, NY, USA, 815–829. DOI:https://doi.org/10.1145/3332165.3347891

[54] Dimitrios Tzovaras, Georgios Nikolakis, Georgios Fergadis, Stratos Malasiotis and Modestos Stavrakis. 2004. Design and implementation of haptic virtual environments for the training of the visually impaired. In *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. 12, 2, pp. 266-278.

[55] David Waller, Earl Hunt and David Knapp. 1998. The transfer of spatial knowledge in virtual environment training. *Presence*. 7(2), 129-143.

[56] Wai Yu and Stephen Brewster. 2002. Multimodal virtual reality versus printed medium in visualization for blind people. In Proceedings of the fifth international ACM conference on Assistive technologies (Assets ’02). Association for Computing Machinery, New York, NY, USA, 57–64. DOI:https://doi.org/10.1145/638249.638261

[57] Yuhang Zhao, Cynthia L. Bennett, Hrvoje Benko, Edward Cutrell, Christian Holz, Meredith Ringel Morris, and Mike Sinclair. 2018. Enabling People with Visual Impairments to Navigate Virtual Reality with a Haptic and Auditory Cane Simulation. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI ’18). Association for Computing Machinery, New York, NY, USA, Paper 116, 1–14. DOI:https://doi.org/10.1145/3173574.3173690