Enabling People with Visual Impairments to Navigate Virtual Reality with a Haptic and Auditory Cane Simulation

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Figure 1. (A) A blind user wearing the gear for our VR evaluation, including a VR headset and *Canetroller*, our haptic VR controller. (B) The mechanical elements of Canetroller. (C) Overlays of the virtual scene atop the real scene show how the virtual cane extends past the tip of the Canetroller device and can interact with the virtual trash bin. (D) The use of Canetroller to navigate a virtual street crossing: the inset shows the physical environment, while the rendered image shows the corresponding virtual scene. Note that users did not have any visual feedback when using our VR system. The renderings are shown here for clarity.

ABSTRACT

Traditional virtual reality (VR) mainly focuses on visual feedback, which is not accessible for people with visual impairments. We created *Canetroller*, a haptic cane controller that simulates white cane interactions, enabling people with visual impairments to navigate a virtual environment by transferring their cane skills into the virtual world. Canetroller provides three types of feedback: (1) physical resistance generated by a wearable programmable brake mechanism that physically impedes the controller when the virtual cane comes in contact with a virtual object; (2) vibrotactile feedback that simulates the vibrations when a cane hits an object or touches and drags across various surfaces; and (3) spatial 3D auditory feedback simulating the sound of real-world cane interactions. We designed indoor and outdoor VR scenes to evaluate the effectiveness of our controller. Our study showed that Canetroller was a promising tool that enabled visually impaired participants to navigate different virtual spaces. We discuss potential applications supported by Canetroller ranging from entertainment to mobility training.

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INTRODUCTION

Virtual reality (VR) technologies are maturing quickly and have been widely applied to different fields by researchers and designers, such as entertainment [6,61], education [32,54], and social activities [62]. Researchers have recognized VR's potential in accessibility and developed various VR systems for training and rehabilitation for people with different disabilities [25], such as dyslexia [17,21], stroke [14,33], and ADHD [1,34].

While presenting great potential in a variety of use cases, current VR solutions rely mainly on realistic visual feedback to provide an immersive experience to sighted people, for whom the visual sense is dominant [38]. Most VR applications are not accessible for people with visual impairments (VIPs), preventing them from benefiting from this important class of emerging technologies [28].

Some prior research has explored VR experiences for VIPs. However, they either generated pure auditory virtual reality that has limited capability in describing the shape or specific layout of a virtual space [28,36], or provided simple haptic feedback with a joystick or a controller grounded by a robot arm that can only be used in a stationary situation (*e.g.*, [10,26,35]). To our knowledge, no VR experience has been created for VIPs that enables them to walk around the VR environment and achieve a good comprehension of the 3D virtual space.

To address this problem, we created *Canetroller* (see Figure 1), a wearable haptic controller that enables VIPs to physically navigate a VR world, thus providing them a more immersive VR experience. Since the white cane is the most common tool for blind people to navigate the real world, our controller simulates many white cane interactions, which allows users to transfer their cane skill from the real world into the virtual world. We describe the design of Canetroller, including a formative study with white cane users and orientation and mobility (O&M) instructors that inspired the design, a discussion of our haptic controller and VR system, and an evaluation with VIPs. Our results indicated that VIPs could successfully navigate and understand virtual scenes using Canetroller. We close by discussing potential application scenarios.

RELATED WORK

Auditory VR for People who are Blind

Most prior research in this area has focused on creating auditory VR for VIPs. Audio-based environment simulator (AbES) games allow blind users to interact with the virtual world through auditory feedback, *e.g.*, AudioDOOM [41], AudioMetro [40], and AudioZelda [37]. Studies showed that AbES games enhanced people's mobility skills when navigating the real-world space that was mapped by a virtual game [31]. Trewin *et al*. [50] further enhanced the accessibility of VR games by providing descriptions of the VR scenes and generating extra sound effects like footsteps. They also supported special commands such as auto-aim and auto-walk, where the system automatically completed an aiming and walking task and provided audio feedback indicating the current game status.

Purely acoustic VR solutions [11,12,44,48,49] induce presence and render virtual obstacles with sound rendering. For example, González-Mora *et al*. [12] created an acoustic VR space with a portable system that generated spatial audio to create the illusion that surrounding objects were covered with speakers emitting sounds depending on their physical characteristics (*e.g.*, color, texture).

Several audio VR systems also incorporated VIPs' real-world navigation strategies. For example, Picinali *et al*. [36] created an acoustic VR system that simulated the use of echolocation (the use of sound reflecting of objects to localize them) to help users better understand the virtual space. Virtual-EyeCane [28] used an acoustic-only white cane for interacting in VR. A user pointed the virtual cane to different objects and received audio feedback with different frequencies representing the distance to the virtual objects. In contrast to these audio-only solutions, our work combines both haptic and audio feedback to generate a more realistic VR experience.

Haptic VR for VIPs

Haptic sensation via white canes or body touch is the main channel for blind people to understand a physical space [13], with audio serving as a channel for complementary information. When navigating the real world, the white cane is commonly used for low-resolution scanning of the environment and to detect obstacles and identify distances. Similarly, legs and feet are used to feel the ground's surface, and the palm or fingers are used to precisely recognize the shape and texture of objects [13,22].

Prior research explored using haptic interfaces to help blind people navigate virtual environments. Although some researchers presented the virtual world in 2D and used passive tactile representations to provide the third-dimension information of a virtual object or space (*e.g.*, [18,20,27,56,60]), recent research has focused on creating 3D haptic virtual spaces using various desktop-mounted force feedback devices [9,16,22,35,45,57], such as PHANToM [63], Novint Falcon [64], and Geomagic Touch [65]. For example, MoVE [45] enables a blind user to touch a scaled virtual version of a space by using two PHANToM force-feedback devices with her thumb and index finger. Lahav and Mioduser [22,23] created a virtual environment that allowed blind users to get vibrations and attraction/rejection force feedback when navigating the space with a joystick. Jansson *et al*. [16] also rendered virtual textures and simple 3D objects with PHANToM and grooved surfaces with Impulse Engine 3000™. However, none of these systems allowed for free movement in space as all of them rendered a scaled model that needed to be explored via a probe or stylus. These scaled representations made it difficult for users to understand the virtual space [45] and build a consistent mental model [9].

To enable a more intuitive exploration of the virtual space, other researchers have simulated aspects of white cane interaction in virtual reality [26,42,51,52]. For example, BlindAid [42] used PHANToM to simulate the force feedback generated by a white cane during navigation. HOMERE [26] is a multimodal VR system in which a cane controller connected to a robot arm was used to control the virtual cane and provide haptics of collision and texture. Although they simulated haptic aspects of cane interaction, these systems used a grounded controller, which prevented mobile navigation of the VR space.

The closest solution to ours is the work by Tzovaras *et al*. [51], which enabled a mobile VR experience by using a CyberGrasp haptic glove to generate force feedback to a blind user's fingers, providing the illusion that they are navigating the virtual space with a cane. The researchers further improved the system by asking the user to hold a real cane [52], with which the system can detect the user's grasp posture and provide corresponding force feedback through CyberGrasp. The system also provided 3D audio feedback. Although an evaluation showed that the system was useful for VIPs to navigate the virtual space, the current design could not prevent a user from penetrating virtual objects, which left much room for improvement. Moreover, no thorough analyses of the users' feedback were reported, making it difficult to assess the benefits and weaknesses of the system design.

Our work addresses the problems involved in prior work, by creating an immersive VR experience that enables mobile VIPs to navigate a real-world-scale virtual space using their cane skills coupled with spatial audio. Further, a brake mechanism on our cane controller addresses the object-penetration problem present in prior work.

"Smart Canes" in (non-virtual) Reality

Researchers have also augmented a physical white cane to improve users' navigation experience in the physical (non-virtual) world. Some have explored equipping real canes with sensors to detect far-away obstacles (out of the reach of a normal cane) and providing audio or vibration feedback to the user [29,30,46,55]. Others have added motors to the cane, providing navigation cues on the cane through force feedback to assist a visually impaired user to avoid obstacles and navigate more safely and efficiently [8,53]. Though some smart canes are commercially available for purchase, they have not been widely adopted, primarily because people need to know their cane will work 100% of the time and will never run out of batteries, experience a software crash etc. In contrast to this prior work, we do not enhance or replace the regular white cane used in the physical world, but focus on making VR accessible to VIPs using a novel controller that mimics white cane interactions.

The smart cane that is most related to our work is the contactless haptic cane [2–5], a short version of a white cane with ultrasound sensors and actuators. This cane did not physically contact objects but still provided users a haptic sensation similar to a real cane. This design could reduce the possible inconvenient environmental interactions caused by cane contact, which was valuable from a social perspective. Our VR system adopted the same "contactless" concept, which simulated the haptic feedback of the cane interaction, but used a short cane controller to avoid contact between the controller and the real environment reducing the effect of the real world on users' virtual experience.

FORMATIVE STUDY

To guide our design, we relied on two sources: 1) prior published work [58,59] that explored the navigation challenges and strategies for people who are blind, and 2) our own observations from a formative study with VIPs who rely on a white cane and with O&M instructors.

Formative Study: Method

We recruited seven VIP participants (3 female) whose ages ranged from 25 to 40 (mean=32.4) and five O&M instructors (all females) whose ages ranged from 26 to 49 (mean=34.2), as shown in Table 1-2. All VIP participants were cane users. Since V1 (also labeled as O1) was both a VIP and an O&M instructor, we included the interview questions for both VIP and O&M instructors in her study.

ID	Age/ Sex	Visual Condition
[1,2]V1	29/F	Ultra-low vision for ~10 years.
[1,2]V2	40/F	Blind since birth.
[1,2]V3	31/F	Blind since birth.
[1,2]V4	34/M	Blind since birth.
[1]V5	30/M	Legally blind since birth.
[1,2]V6	25/M	Ultra-low vision since birth.
[1,2]V7	38/M	Blind. He was legally blind since birth.
[2]V8	63/F	Ultra-low vision for 50 years.
[2]V9	51/F	Ultra-low vision, for ~5 years.
[2]V10	37/M	Low vision, for ~8 years.

Table 1. Demographic information of VIPs. Participants labeled with "[1]" participated in the formative study, and those with "[2]" participated in the evaluation study.

ID	Age/ Sex	Vision	Years teaching O&M
[1,2]O1	29/F	Ultra-low vision.	1.5 years
[1]O2	28/F	Sighted	2.5 years
[1,2]O3	49/F	Sighted	5.5 years
[1]O4	39/F	Mild low vision. Not legally blind.	8 years
[1,2]O5	26/F	Sighted	2 years
[2]O6	38/F	Sighted	14 years
[2]O7	26/F	Sighted	3 years

Table 2. Demographic information of O&M instructors. Instructors with "[1]" participated in the formative study, and those with "[2]" participated in the discussion on Canetroller.

With the VIPs, we first conducted an interview. We asked about their understanding of virtual reality and gave them a definition of VR in case they were not familiar with the concept. We then asked about their prior VR experience and their expectations of VR. We also asked about their use of the cane in real life. Then, we asked participants to navigate with their canes while we observed their cane strategies in five different scenarios. Participants were required to think aloud during the navigation. The scenarios include: (1) the experiment room with desks, chairs, and trashcans; (2) a corridor from the experiment room to an elevator; (3) an outdoor area surrounded by circular cement seating platforms; (4) a street crossing area with tactile domes; (5) a square sand sports pit surrounded by curbs, with two benches and a metal trashcan outside of the area.

With the O&M instructors, we conducted an interview, asking them about their prior knowledge of VR applications for VIPs, the potential of VR, and to describe standard cane skills, training techniques, and the main training scenarios. We also asked them to demonstrate different cane skills with a white cane we provided.

Formative Study: Findings

Experience with VR

We found most of our visually impaired participants had little or no prior experience with virtual reality and none of the O&M instructors had heard of any VR applications that were designed for VIPs. However, participants all showed great interest in VR and hoped they could be able to experience VR as sighted people could. As V3 said, "When listening to some VR examples, I wanted to know 'why cannot this be for us?'"

Expectations of VR

When asked about their expectations of VR, both VIP participants and O&M instructors envisioned VR to be a mobility-training platform, where users could simulate routes or unfamiliar environments to learn cane skills, prepare for travel, and further build confidence. Some VIPs wanted to use VR as an educational tool, and some even hoped that VR would be able to bring them equal access to all visual information that they could never perceive before. "If VR has a way to describe or make me feel sculptures, or if it is able to translate whatever everyone can see to tactile, [it would be great]" (V5). Interestingly, V7 wanted to use VR to build a new identity in which other co-users in VR would not know that he had any disabilities. Although not wanting his virtual avatar to appear different than others, V7 believed that a cane-like controller would be useful for him to navigate the virtual world because it could give him the simulation of what he was used to.

Cane Strategies

The O&M instructors identified four main cane use styles:

Two-point touch is swinging the cane from side to side and tapping the edges of one's walking path on either side in an arc slightly wider than one's shoulder [15]. It is used to protect both sides of the walker's body. Most participants used this strategy when they were walking fast in a relatively safe or familiar place.

Constant contact is sweeping the cane from side to side and keeping the cane tip in contact with the surface at all times [19]. This technique provides the most reliable detection of subtle surface changes at every point of the arc. Participants used it to conduct a thorough scanning of the environment. For example, we found that V1 primarily used two-point touch when navigating the corridor, but she changed to constant contact when she was getting close to the stairs.

Trailing is used to search for openings, objects, and surface changes along an edge, especially vertical surfaces such as a wall or curbs [66]. A VIP can "keep the cane at base of the wall, maintain the position, and travel along" (O5). In the outdoor circular area, V5 trailed along the cement seating platform and determined the area to be a circle.

Shorelining is another technique that uses touch and drag to travel along an edge. A person can repeatedly tap the edge she wants travel along, move the cane from the edge to the opposite side, and then drag the cane along the ground back toward the edge [66]. Compared with trailing, O&M instructors recommended shorelining because "it can protect the other side of your body" (O5). For example, we observed that V7 explored the square sand sports pit area by shorelining along the curbs around it.

Perceiving the Environment with the Cane

Compared with other navigation tools, such as GPS or guide dogs, a cane provided VIPs "more detailed information on what is immediately in front of them in the environment" (V7). During our observation, participants could perceive the shape, texture, material, and even the interior structure of an object (*e.g.*, hollowness) by using a cane. They used both the tactile and auditory feedback from the cane to perceive the environment. As V2 described, "we get the information from all the senses."

We found that participants used the tactile feedback to understand the position and shape of an object. For example, V5 could tell the object in front of him was a chair because he felt the shape of the wheels at the base by using the tactile feedback from the cane. Participants could also perceive the height of an object according to the contact point where the cane hit it. Some participants could perceive the texture by using a cane. V6 described how he perceived the texture of the carpet in the experiment room, "I know the floor is carpet because it feels like there's pattern to the carpet. I can feel the lines [on the carpet] with the cane." Besides tactile feedback, participants also used auditory feedback from the cane to determine the material of an object and even whether it was hollow.

Although some participants used their hands to feel details (*e.g.*, locating elevator buttons) or confirm the information they perceived from the cane, most participants indicated that they *avoided using their hands*, especially in unfamiliar places. For example, when V2 explored the sand sports pit area, she only used her cane to explore the surrounding objects (benches and trashcan), "See, I would never reach and touch that [trashcan]." The O&M instructors also recommended using the cane to explore an unknown space before touching it. This emphasized the importance of a cane in perceiving objects in an unfamiliar place.

Target Scenarios for Cane Training

There were four main scenarios that most O&M instructors emphasized for training students: rooms, hallways, stairs, and street crossings with curbs and tactile domes. Although VIPs need to get training in many important scenarios, the instructors indicated that "funding does not always allow ideal training amounts" (O4). This emphasized the potential of VR simulation in O&M training, which could generate different virtual scenarios to provide users sufficient training with a lower demand on resources.

Formative Study: Discussion

The formative study demonstrated VIPs' strong interest in virtual reality and its potential in orientation and mobility training. According to the VIPs and the O&M instructors, there were different cane skills that people could use to navigate different environments. For example, a cane user can use two-point touch to conduct a fast navigation, while using constant contact to have a thorough scanning of the environment. She can also use trailing or shorelining to walk along a wall or a hallway. Our VR system should

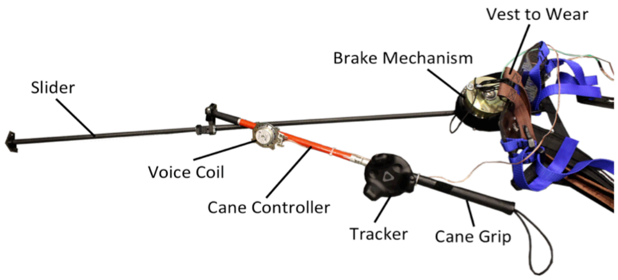

Figure 2. The mechanical parts of Canetroller, including the cane controller users interact with (bottom) and the haptic mechanism users have to wear to experience feedback (top).

support all these standard cane techniques to enable a visually impaired user to easily navigate the virtual space with their existing cane skills. Moreover, VIPs use both auditory and tactile feedback to perceive objects in the environment, suggesting the importance of multimodal feedback. The sensations our participants described included: the physical resistance when a cane touches an object, the tactile feedback when the cane sweeps on different textures, and the audio feedback when the cane interacts with the environment. Since VIPs have different preferences for cane types, we consider customizing the virtual cane (*e.g.*, the length) based on users' preferences.

CANETROLLER

Guided by the findings from the formative study, we designed *Canetroller*, a haptic cane controller coupled with spatial audio feedback that allows VIPs to use their real-world cane skills to explore different virtual spaces.

Interaction Design

The design of Canetroller was inspired by real-world interactions with a white cane. To experience VR, a user wears a VR headset with earphones to hear 3D audio and holds Canetroller to feel haptic feedback as shown in Figure 1A. Canetroller is a wearable controller that consists of the five main parts shown in Figure 2: a brake mechanism that a user wears around the waist, the cane controller that the user holds and sweeps or taps as they would a real cane, a slider between the brake and the controller that imparts a horizontal physical resistance generated by the brake, a voice coil that generates vibrations to the controller for tactile feedback, and a tracker to monitor the cane controller's 3D poses. We designed Canetroller to be shorter (25 inches) than real canes (36–60 inches) to reduce the effect of the physical space on the user's virtual experience by inadvertently hitting real objects. Although

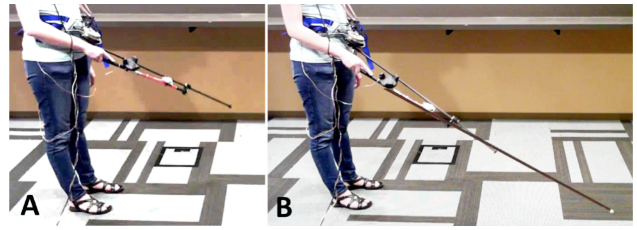

Figure 3. (A) Canetroller in use. (B) The overlaid image of the virtual cane (brown). Note that the virtual cane can be longer than Canetroller, usually as long as the VIP's real cane.

Canetroller is short, the virtual cane it represents in VR can be arbitrarily long as shown in Figure 3. We adjust the length of the virtual cane based on the user's height and how they hold the cane.

Canetroller provides three types of feedback: (1) *Braking:* When the virtual cane hits a virtual object horizontally in the left-right direction, the brake mechanism generates physical resistance that stops the controller moving towards the object. With this feedback, the virtual cane would not penetrate virtual objects, providing users precise perception on the boundaries of virtual objects. (2) *Vibrotactile*: When any part of the virtual cane contacts a virtual object (hits an object or sweeps on a surface), Canetroller generates vibrotactile feedback to simulate the corresponding hit or texture vibration that the user would feel in the real world. (3) *Auditory:* Our VR system generates spatial 3D audio feedback that simulates the sound of a real cane interacting with the real world. Our sound rendering depends on the surface type and collision speed. With this multi-modal feedback, our system supports different cane strategies:

Shorelining. When the virtual cane hits a vertical surface, *e.g.*, a virtual wall, in the horizontal left-right direction, the user can feel the physical resistance that enables them to perceive the boundary of the wall. They can also feel the contact vibration and hear the 3D sound, which simulate the collision between the cane and a wall. With this interaction, a blind user can walk along a virtual wall with Canetroller by using the shorelining technique (Figure 4A).

Two-point Touch. When the virtual cane taps on a surface, Canetroller generates corresponding vibration to simulate the tactile sensation. The user can also hear 3D tapping sound from the VR system. With this interaction, a user can conduct two-point touch on different virtual surfaces such as carpet, concrete, or tactile domes (Figure 4B).

Constant Contact. We also support constant contact

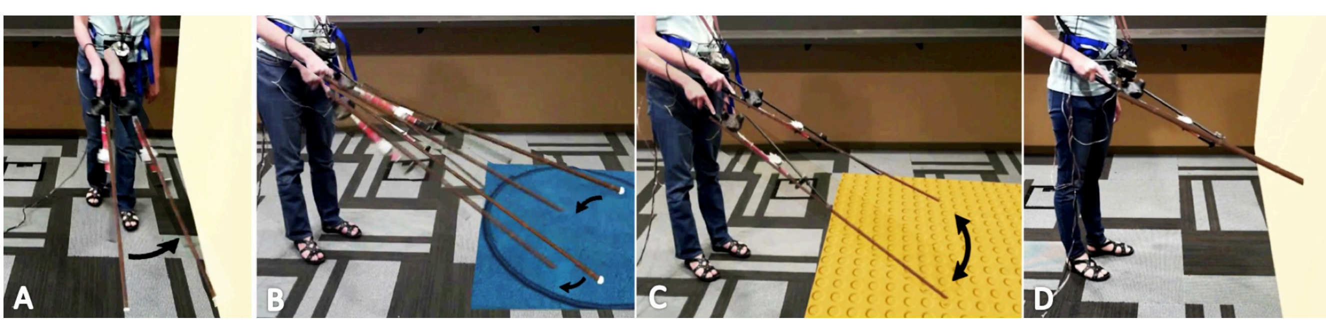

Figure 4. (A) A user walks along a virtual wall with shorelining. (B) The user uses two-point touch on a piece of virtual carpet. (C) The user uses constant contact on a piece of virtual tactile dome. (D) The user penetrates the virtual cane into a virtual wall.

rendered by generating tactile and auditory feedback that simulates textures of different surfaces (Figure 4C). Moreover, since tactile domes found at sidewalk crossings have bumps that would generate resistance when the cane sweeps across, we use the brake to generate short resistances at each bump, thus providing the user with the illusion that her cane hits the bumps. To make the experience the most realistic, we modulate the frequency of the braking resistance, and the speed and amplitude of the vibrotactile and the 3D audio feedback based on the virtual texture characteristics and the sweeping speed.

Our current prototype only provides physical resistance in the horizontal left-right direction. Although the ideal device would support resistance in all three dimensions, mechanical engineering limitations forced us to only choose one, or else the device would have been too heavy and bulky to allow ergonomic use. We chose the horizontal braking based on the formative study, which indicated the horizontal feedback is the most common in identifying obstacles and spatial boundaries (*e.g.*, walls) when using different cane strategies, such as shorelining and constant contact. We did not leverage the physical floor to provide haptic feedback in the up-down direction because it would restrict the topology of simulated environments to only those that match the room's properties.

Since our brake cannot control the up-down or forward-backward direction, and our system cannot limit the user's body motions, Canetroller may still penetrate virtual objects in some circumstances (*e.g.*, when the user pokes Canetroller forward, or physically moves or rotates her body), making it difficult for users to understand the exact boundary of virtual objects or planes. Thus, we generate a "beeping" sound to warn the user if the cane penetrates a virtual object too deeply (*e.g.*, wall, carpet), or if the user moves outside the virtual space (Figure 4D).

Implementation

To build Canetroller, we combined two pieces of a folding cane to create a 24-inch cane controller. We used a Placid industries magnetic particle brake (Model B35) to generate the physical resistance and a Dayton Audio DAEX25FHE-4 voice coil on the controller to generate the vibration. A Vive tracker was attached to the controller to track its position. Our VR system used an HTC Vive headset to track the user's head position and orientation, thus generate 3D audio feedback. In typical operation, we do not render anything to the headset screen, but we can do so for debugging and demonstration to individuals without visual impairments. The system was implemented in the Unity game engine (v. 2017).

Our brake mechanism regards the user's body as the anchor, allowing a 360-degree rotation. We connect the center of the brake and the tip of the cane controller with a 35-inch slider. When a user sweeps the cane controller, the tip of the controller slides along the slider and drags the slider to rotate around the brake. We used a Pololu simple motor controller 18v7 to control the brake. We can make fine-grained adjustments to the flexibility of the brake's shaft rotation, thus controlling how easily the user can sweep the cane controller. If the brake is set to 100%, the brake shaft cannot rotate, so that the user cannot sweep the cane controller without rotating her body. In our VR system, this is used to render hard body collisions, *e.g.*, when the virtual cane hits a virtual object horizontally in the left-right direction. We release the brake when the tracker detects that the user starts to move the controller back. When the virtual cane sweeps on the virtual tactile domes, we set the brake to 30% in a short interval at each bump to simulate the resistance of hitting the bump.

To generate realistic vibrations upon collision, we attached a Pololu MinIMU-9 v5 embedded with a LSM6DS33 3-axis gyro and accelerometer to a white cane and recorded the acceleration data when this real cane came in contact with various objects. We used the equipped cane to hit different objects (*e.g.*, walls, metal tables, plastic trashcans) and sweep on different surfaces (*e.g.*, carpet, concrete, tactile domes) to record the corresponding accelerations. When sweeping the cane on different surfaces, we tried to sweep with a relatively constant speed of 200mm/s to reduce the effect of hand motions on the recorded acceleration data. We recoded the data at a sample rate of 1.4kHz.

We processed the acceleration data to generate an audio signal for input to the voice coil, using a simplified version of Romano et al.'s method [39]. We used a 10Hz high-pass filter to remove the effect of unwanted forces, such as gravity and hand motions during data recording. Since the human sensitivity to high-frequency vibrations is largely independent of directions [7], we combined the three-axis acceleration data into one-dimensional signal using a root sum square calculation, so our system could work with a single voice coil. We multiplied the signal with a constant factor (~0.005) to fit the voice coil's input range and upsampled it to 44.1kHz, which is a standard audio sample rate, for final use on the voice coil. We amplified this signal with a Velleman MK190 amplifier to drive the voice coil, making the vibrations even stronger.

To generate realistic 3D sounds, we attached a microphone to the cane tip to record the sound when hitting or sweeping on different surfaces. We removed recording noises with audio-editing software and then played back the sounds when the virtual cane produces corresponding interactions in the virtual world, modulating the sound depending on the virtual cane's speed. Unity rendered the 3D sound using the Microsoft Spatializer Plugin with a generic HRTF.

EVALUATION

We evaluated Canetroller with VIPs. Our goal was to evaluate the effectiveness of Canetroller and investigate how VIPs perceive different virtual environments by using the audio-haptic feedback from Canetroller.

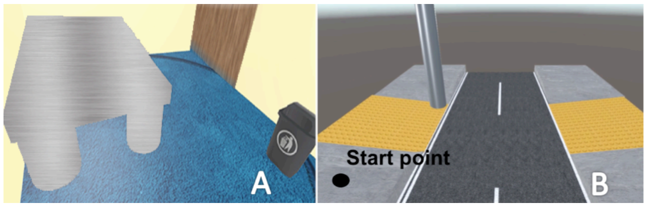

Figure 5. (A) Indoor scenario with a metal table, a trashcan, and a door. (B) Outdoor scenario of a street crossing with sidewalks, curbs, tactile domes, and a traffic pole.

Method

We recruited nine participants with visual impairments (5 females and 4 males) whose ages ranged from 25 to 63 (mean=38.7). All VIPs were cane users. Six of them participated in both the formative and system evaluation studies, as shown in Table 1.

Apparatus: Two VR Scenarios

The formative study indicated that both indoor and outdoor navigation are important scenarios for cane skill training. Thus, we designed two VR scenarios to evaluate our system: an indoor scenario with four walls as the boundary, a carpet on the ground, a closed door, a metal table, and a plastic trashcan (Figure 5A); and an outdoor scenario that simulated a street crossing with two cement sidewalks, curbs, two curb-cut ramps covered in tactile domes, concrete street, and a metal traffic pole (Figure 5B).

In the outdoor scene, we played 3D environmental sound to simulate the traffic, enabling participants to distinguish street directions. In the real world, VIPs usually push the button on the traffic pole and listen for the traffic light to decide when to cross. To increase the realism of our VR scenario, participants pushed the virtual traffic button using a Vive controller's trigger button when standing on the curb-cut ramp. The system then generated a 3D traffic light sound to inform them when to cross the virtual street.

Procedure

We conducted a one-hour evaluation in a 4.5m x 5m room. With VIP participants, we first had a brief interview about their demographic information and their prior experience with VR. For safety reasons, we asked participants to walk around the real-world space of the experiment room to familiarize them with the real environment. We then introduced the hardware setup of our VR system, including the VR headset and Canetroller, and assisted participants in putting on the devices. Before experiencing the VR world, we customized the length of the virtual cane for each participant. We first set the virtual cane to the length of the participant's real cane, and then adjusted it based on how she held Canetroller. We continued with a tutorial session, an indoor scenario exploration session, and an outdoor scenario exploration session.

Tutorial: We started with a 15-minute tutorial session, in which we introduced all the features that Canetroller supported, including the three types of feedback, the different cane strategies the system supports, as well as the warning sound that indicates the virtual boundary. We guided the participants to interact with several representative virtual elements, including a wall with a door and two floor materials (*i.e.*, carpet, concrete). We also asked them to penetrate the virtual cane into the virtual floor deeply to hear the warning sound. We explained the different feedback and asked them to confirm whether they felt the feedback. Participants repeatedly practiced with Canetroller until they felt familiar with the system.

Indoor Scenario: Participants freely explored the virtual indoor environment with Canetroller. Before they started, we told them which virtual objects were in the virtual space, so that they would not struggle guessing what an object was when it was discovered. Participants were asked to think aloud, talking about what they felt, what they heard, what virtual objects they thought they had discovered, which parts confused them, and the reasons for their perception and/or confusion. When they had located all the virtual objects and felt confident about each object's position, we asked them to stand still and point to each object relative to their current position with their finger. We recorded whether they correctly pointed out each object.

Outdoor Scenario: Participants needed to cross the virtual street using Canetroller. All participants started their exploration at the same location on the left sidewalk, facing the traffic pole (Figure 5B). We first informed them that they were on a sidewalk and asked them to identify the position of the street and the direction of the traffic based on the 3D traffic sound. If they did not identify it correctly, we told them that the street was on their right side, so they could understand in which direction they should cross the street. We then asked them to walk forward along the sidewalk, locate the tactile domes and the traffic pole, trigger the traffic light sound with the Vive controller, and finally cross the virtual street. They also needed to identify the sidewalk on the other side to confirm that they had successfully crossed the street. Participants thought aloud during the whole process, describing how they identified different virtual objects and crossed the street.

At the end of both the indoor and outdoor scenarios, we asked participants to score eight questions from a presence questionnaire from 1 to 7 (Table 3), evaluating how realistic the VR experience was. We derived this questionnaire from the Igroup Presence Questionnaire (IPQ) [43] and removed vision-related questions. Since participants needed to think

Q1	In the VR world I had a sense of "being there".
Q2	Somehow I felt that the virtual world surrounded me (1 is fully disagree, 7 is fully agree).
Q3	I felt present in the virtual space.
Q4	I was completely captivated by the virtual world.
Q5	How real did the virtual world seem to you (1 is not real at all, 7 is completely real)?
Q6	How much did your experience in the virtual environment seem consistent with your real-world experience (1 is not consistent at all, 7 is very consistent)?
Q7	How real did the virtual world seem to you (1 is about as real as imagined world, 7 is indistinguishable from the real world)?
Q8	The virtual world seemed more realistic than the real world.

Table 3. Modified presence questionnaire (adapted from [43]**).**

aloud and answer our questions about their VR experience during the exploration, we removed questions on awareness of the real world from the questionnaire as well.

We finished the user study with an interview, asking participants about their impressions of each type of feedback, the most important feedback for them when perceiving the virtual space, how they would improve the system, and the potential applications they thought Canetroller may enable.

Results

Our study demonstrated that Canetroller enabled VIPs to explore and navigate the VR world.

Effectiveness of Canetroller

In the indoor scenario, all participants could locate and identify all the virtual objects (the door, the metal table, and the trashcan) using Canetroller. Eight out of nine participants correctly pointed out the locations of all the objects at the end of the indoor session, indicating that participants could build accurate mental models of the 3D virtual space with Canetroller. V6 said, "This is cool, because it does let you create a good physical mapping on your space." V3 was the only one who did not fully understand the virtual room layout. Although she pointed out the virtual door and table correctly, she built a linear mental model, saying the trashcan was in the same line with the door and table.

In the outdoor scenario, six participants could distinguish the traffic direction, locate the tactile domes and traffic light, and successfully cross the virtual street with little assistance from the experimenter. However, the other three participants (V2, V4, V8) had difficulty distinguishing the traffic direction through the 3D traffic sound. Although they correctly identified most virtual elements (*e.g.*, the tactile domes, the traffic light), they could not decide in which direction to cross the street without assistance.

Sense of Presence in the Virtual World

In accordance with the standard presence data analysis for IPQ [67], we evaluated the average Spatial Presence (SP: Q2, Q3), Involvement (INV: Q4), Experienced Realism (REAL: Q5, Q6, Q7, Q8), and a general item that assesses the general "sense of being there" (G: Q1) for both indoor and outdoor VR scenarios based on participants' scores in the presence questionnaire. Figure 6 shows the average scores to SP, INV, and REAL on three axes, and the general item G as a bow on the left. We found that participants had a high spatial presence in both the indoor and outdoor VR scenarios, indicating that VIP users could use Canetroller to physically experience the 3D virtual space.

We compared participants' presence data between the indoor and outdoor scenarios, finding no significant differences for any variables with Wilcoxon Signed-Rank Tests. Participants' interview data echoed this result, showing that their preferences varied when comparing the two VR scenarios. Four participants (V1, V2, V8, V10) felt

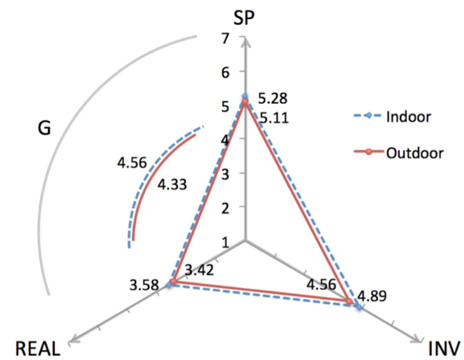

Figure 6. Radar diagram that shows the participants' average presence data in the indoor and outdoor VR scenarios.

the indoor scene was more realistic, four participants (V3, V4, V6, V9) had a more immersive experience in the outdoor scene, while V7 did not have a preference.

Multi-Modal Feedback from Canetroller

Braking Feedback. All participants felt that the physical resistance helped them understand the boundary of virtual objects. V9 felt excited about feeling the physical resistance when hitting the virtual wall: "I feel [the virtual cane] hit the wall! It feels like you are hitting up against something. I can tell the direction of this wall. Neat!" With the physical resistance, V7 could even distinguish the shape of the virtual trashcan by tapping around it with Canetroller: "Maybe this is the trashcan. It seems like a squarish type."

Vibrotactile Feedback. Most participants liked the vibrotactile feedback and used it to perceive texture. As V2 mentioned, "I feel the vibration different. I think [the simulation of] the texture is really neat, to distinguish between carpet and concrete." V1 and V6 specifically liked the feeling of sweeping on the virtual tactile domes, which were simulated by both the vibrotactile and the physical resistance. As V6 explained, "The feeling is really convincing. [I felt] I was just touching it. As you sweep through them you feel each individual bump." Some participants also noticed the change of vibration when they changed the speed of sweeping Canetroller. "When I swept it really fast one time, it vibrated much more" (V10).

Auditory Feedback. Participants relied on the auditory feedback to distinguish the materials, thus helping them decide what a virtual object could be. For example, V4 used the 3D audio to identify different virtual elements in the outdoor scene: "This is the traffic light because it's metallic sounding. And the street is on the right because I hear the concrete." However, some participants had difficulty distinguishing some specific sounds, which resulted in trouble identifying corresponding virtual objects. For example, in the indoor scene, V3 could not distinguish the sound difference between the wall and the door, so it took her a long time to finally identify the virtual door. As she mentioned, "[The sound] really did not feel that much different. That [difference] should be like stronger."

Dominant Modality. We asked participants which feedback was most critical for them to perceive different information in the virtual space. Participants' preferences varied. Two participants (V6, V9) felt that the physical resistance was the most important because it enabled them to understand the boundaries and build a good sense of the virtual space. "[The physical resistance] was the way to create the boundaries between various virtual objects. When perceiving minor details, the sound cannot convey that, it cannot convey that you are in that boundary at that specific moment. The force made it realistic." Three participants (V4, V8, V10) said they relied more on the audio feedback when exploring the virtual world. The other four VIPs indicated that the different feedback modalities were equally important and the combination created the best VR experience. "I think it's really a combination. The metal legs of the desk and the door proved very realistic sounding. The force is very important for perceiving the wall. The vibration of the domes was also good that I could feel a larger bump versus the roughness of the road" (V1).

Exploration of the Virtual World

Three participants (V1, V6, V8) used Canetroller to understand the size of virtual objects. For example, after locating the three table legs, V1 reported that the size of the table should be big: "It's a big desk, because I found two legs and then a while later I found that third leg."

V6 also used Canetroller to perceive the height of different virtual objects. When he located the table leg, he moved the cane controller up along the table leg and discerned the height with the cane: "So it could actually have a perceivable height!" He was also able to distinguish the height difference between virtual objects. When he found the trashcan, he mentioned, "That has some height, less height than the table, though."

When exploring the virtual world with Canetroller, participants used the same cane strategies as in the real world. They usually used shorelining along the virtual wall to locate the virtual door, and used constant contact to scan the virtual space to discover virtual objects. Some participants wanted Canetroller to support more cane strategies; for example, V1 tried to use a pencil grasp (*i.e.*, holding the cane vertically like a pencil [66]) in the indoor scenario because she thought it was a small and crowded environment: "I would probably be more likely to hold it in more of a pencil grasp in the inside. People tend to use their canes in a lot of different ways depending on the environment. So, for a small room, I would not typically have my cane straight out in front of me [like what I did with Canetroller]."

Environmental Sounds

We found that the simulated environmental sounds had a strong effect on participants' experience in the VR world. Participants who preferred the outdoor scene all indicated that the environmental traffic sound made the VR world more realistic. As V4 mentioned, "It feels like [real], it was nerve-racking in terms of 'Oh, am I going to get run over by this car while I'm crossing the [virtual] street?'"

Participants suggested adding more environmental sounds to the VR experience. When navigating the VR space, V1 and V4 wanted to hear the echo from the environment, which is a common strategy blind people use to estimate the size of space and the distance to an object (*i.e.*, echolocation [47]). As V4 explained, "I didn't have a good sense of direction where I was at [in the real world]. I can hear roughly where the wall is at, by the way it blocks off sound in the real world. I didn't have that in the VR world."

Potential of Canetroller for VIPs

All VIPs believed that Canetroller had strong potential. They were excited about Canetroller making the VR world inclusive. As V9 mentioned, "It was exciting to … be able to do [VR] as a blind person using [Canetroller]... it was inclusive. I enjoyed getting to participate in something… that sighted people get to do."

When asked about desired VR applications, most participants mentioned mobility training and learning new environments. As V2 described, "I think it has potential. If I can learn about a room in a certain building through virtual world before I go over there ... It may provide me with a summary of the room, it will provide much value to me ... in place of me just go there and explore it myself." Some participants also wanted to use Canetroller for fun, experiencing a fantasy world. V6 was excited about VR games: "I definitely can see a lot in gaming environments. If you could touch a car with your cane when it's going, like a superman, that is cool!"

DISCUSSION

The user study demonstrated that Canetroller is a promising tool for VIPs to explore and navigate virtual environments. With only a few minutes' tutorial, in the indoor scenario, eight participants built an accurate mental model of the room and correctly located all virtual objects; in the outdoor scenario, six participants successfully navigated along the virtual sidewalk and crossed the street without assistance.

O&M instructors also saw promise in Canetroller. We demonstrated and discussed the potential of Canetroller with five O&M instructors (Table 2), and received positive feedback: "It is pretty cool. I would have been very skeptical before, but now I see that [Canetroller] provides [a] really good experience" (O3). All instructors agreed that Canetroller could be used in O&M training, especially simulating some scenarios that may have risks, such as the street. "It can be used with students who might be nervous about crossing a particular busy street. Let's try it this way first… without having the risk of hitting by [a] car" (O1). Moreover, O3 felt Canetroller would be good for outreach for blindness awareness, by simulating blindness in VR.

The most novel part of Canetroller is the use of the wearable brake mechanism to generate physical resistance for preventing virtual cane penetration in a mobile situation. Prior VR haptic controllers for VIPs either allowed only stationary use by grounding the controller on the desk or floor, or providing force feedback to the user's hand through haptic gloves, which could not physically stop the virtual cane penetrating virtual objects. Our wearable brake mechanism addressed this by using the user's torso as an anchor to physically halt the user's hand movement. This design allowed users to physically walk in the VR space, and enabled them to have a precise perception on the boundaries of different virtual objects, thus providing a more immersive VR experience.

However, our current prototype only provided physical resistance in the horizontal left-right direction. According to the user study, it would be helpful to provide physical resistance in other directions. For example, participants encountered difficulty perceiving the change of surface height (*e.g.*, the slope of the domes) because of the lack of physical resistance in the vertical direction. V6 suggested, "If it's a little bit higher up on the ground, I hope I would actually have to lift the cane to feel the rise and change in height." Moreover, without physical resistance in the forward-backward direction, participants could not receive accurate location information by poking Canetroller at a virtual object. For example, V9 was able to approximately triangulate the corner by hitting the two virtual walls; however, she could not locate the specific position of the corner. V9 mentioned, "I know that was a corner, but it did not feel like a corner exactly. It felt like there was an actual space between the two walls. With a real cane, you can actually poke into the corner." In the future, we should improve the brake mechanism, providing three-dimensional, or at least two axis braking feedback to enable users to perceive the virtual boundaries with more flexible cane movement.

The limited size of our physical VR space (~22 m^2) was challenging, especially for the outdoor scenario. Since the virtual street and sidewalk were much narrower than those in the real world, some participants reached the other end of the room quickly without having enough time to locate the domes and sidewalk with Canetroller. This diminished the immersive experience. V1 mentioned, "The indoor was a lot more realistic than the outdoor and I think part of that is because of size. The street is very narrow so it's very easy to [ignore the curbs]." The O&M instructors emphasized the importance of creating a big enough space for mobility training. "The space is kind of small. It needs to be physically larger so that people will have more space to practice and learn the dimensions of the street that is more similar to real life" (O3). Interestingly, O7 suggested using a button to trigger a virtual translation in the VR world. When the user released the button, she could still use Canetroller to physically explore the nearby virtual space. Although the virtual space can be infinitely large, the physical room will always be limited. In the future, we will design and evaluate different interaction techniques that enable the user to explore a big VR space within a small real-world room.

The hardware setup of Canetroller also had limitations. Most participants noted that it was too heavy (the cane controller held by the user weighed 0.44 kg and the brake-vest-slider apparatus worn on the waist weighed 2.1 kg) and had a different feeling than the real cane. Moreover, the short length of the cane controller changed participants' holding posture. Since the tip of Canetroller did not rest on the ground, participants needed to spend energy to hold the cane controller up, which sometimes led to over-compensation, resulting in the tip of the virtual cane floating over the virtual ground. However, we envision that this problem could be addressed by creating a brake mechanism in the up-down dimension. If we are able to impart a vertical physical resistance, we would also be able to add a constant force spring to reduce the perceived weight of the Canetroller to that of a real cane.

We evaluated Canetroller with an indoor exploration and an outdoor navigation task, demonstrating the basic usability of our system. There are many other possible approaches that can be used to investigate people's VR experience, for example, a quantitative analysis on the users' mental model by tracking their exploration path and asking them to reconstruct the VR space [24].

We evaluated the immersion of Canetroller with the Igroup Presence Questionnaire. Because we are the first to use this scale for VIPs (and had to modify some questions to suit this audience), we cannot easily compare these scores to prior work. Instead, we collected these scores to serve as an anchor for comparison with future work. We hope that others creating VR for VIPs will find our modifications to the questionnaire useful, and will begin to build up a set of scores for comparison for this user group. Moreover, since Canetroller is such a new experience, the novelty effects could impact our participants' scores. Future work should conduct a long-term evaluation to reduce this impact.

CONCLUSION

In this paper, we presented Canetroller, a haptic controller that simulates white cane interactions, enabling people with visual impairments to navigate a virtual environment by transferring their cane skills into the virtual world. We started with a formative study to understand VIPs' cane strategies, and distilled implications to guide the design of Canetroller. We also evaluated the effectiveness of Canetroller with indoor and outdoor virtual scenarios, showing it to be a promising tool to enable visually impaired users to explore and navigate the virtual world. Canetroller has potential in different areas, such as entertainment, O&M training, and environment preparation. We hope our work can inspire researchers and designers to design more effective tools to make VR more inclusive.

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