Exploring Aural and Haptic Feedback for Visually Impaired People on a Track: A Wizard of Oz Study

Kyle Rector, Rachel Bartlett, Sean Mullan
University of Iowa
Iowa City, Iowa, USA
{kyle-rector, rachel-bartlett, sean-mullan}@uiowa.edu

ABSTRACT
Access to a variety of exercises is important for maintaining a healthy lifestyle. This variety includes physical activity in public spaces. A 400-meter jogging track is not accessible because it provides solely visual cues for people to remain in their lane. As a first step toward making exercise spaces accessible, we conducted an ecologically valid Wizard of Oz study to compare the accuracy and user experience of human guide, verbal, wrist vibration, and head beat feedback while people walked around the track. The technology conditions did not affect accuracy, but the order of preference was human guide, verbal, wrist vibration, and head beat. Participants had a difficult time perceiving vibrations when holding their cane or guide dog, and lower frequency sounds made it difficult to focus on their existing navigation strategies.

CCS Concepts
• Human-centered computing → Empirical studies in accessibility

Author Keywords
Accessibility; outdoor exercise; visual impairments; eyes-free; audio feedback; vibration feedback.

INTRODUCTION
Access to a variety of exercises is important for maintaining a healthy lifestyle, including being alone or with others, indoors or outdoors, or playing in individual or team sports. Organizations such as the United States Association of Blind Athletes [38] facilitate opportunities for blind or low vision athletes. There are team sports including Goalball and Beep Baseball, and adaptive sports (e.g. skiing [39]). Despite these opportunities, many people may be left out. For example, those who live in rural areas may not have enough players or equipment, and not everyone may be interested in team sports. Individual exercises can be easier to facilitate, but they have barriers including the low availability of local human guides [25]. Because of barriers to physical activity, people who are blind are more likely to be obese [5, 34] than people who are sighted.

For people who are visually impaired, there remain accessibility issues with public exercise spaces. Rector et al. [25] conducted an interview and survey study to explore how assistive technologies can enhance exercise, and found opportunities for future work including enabling rigorous outdoor exercise and making exercises spaces (including jogging tracks, swimming pools, and gyms) more accessible. We addressed these themes by conducting an exploratory study at public 400-meter jogging tracks, a public exercise space that allows for rigorous outdoor exercise. Although a 400-meter jogging track provides clear high contrast visual cues to stay in a lane, the tactile cues that a blind person would receive via their cane or feet only indicate whether you are walking on the track surface or not. Navigational feedback from ubiquitous computer-vision based technologies may be able to help people who are visually impaired walk in a track lane.

While navigation technology research exists for people who are visually impaired, results do not always generalize to public exercise spaces. The navigation tasks are often conducted in controlled settings, where the walking length is shorter (~20 meters) and the tolerance for error is higher (~2 meters) [12, 18], unlike our tasks (100 meters long 1.22-meters wide). Furthermore, longer distances cause greater veering for people who are blind or blindfolded [14]. We designed our feedback to be compatible with mainstream technologies that work in the track setting that includes distracting noises and weather conditions.

We present our findings from an ecologically valid Wizard of Oz study comparing how fast and accurately people who are visually impaired walk on a 400-meter jogging track with four different feedback conditions: 1) *Human Guide* (control), 2) *Verbal* feedback, 3) *Wrist Vibration* feedback, and 4) *Head Beat* feedback. Our work differs from previous navigation research (that uses a baseline of no feedback) by having a *Human Guide* baseline (chosen for safety) that is a superior approach to the technology conditions. We had participants qualitatively rate and rank the four conditions. Our work addresses the following research questions:

RQ1: How much do people who are blind or low vision veer when using sound or vibration feedback afforded by mainstream technologies compared to using a human guide when walking around a 400-meter jogging track?

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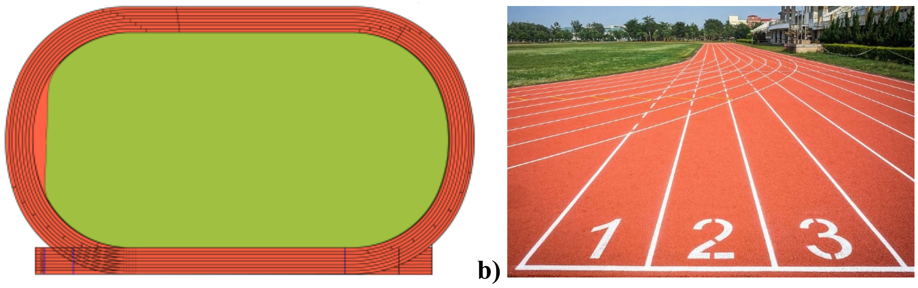

Figure 1. a) Aerial view of a 400-meter jogging track, where the inner lane is 400 meters long. One loop around Lane 7 is 446 meters long (Adapted from Photo by Martinvl CC BY-SA 3.0); b) ground view of a 400-meter jogging track from the perspective of a sprinting or hurdle start (Photo by Mk2010 CC BY-SA 4.0).

RQ2: How do people who are blind or low vision compare sound and vibration feedback to a human guide while walking around a 400-meter jogging track?

We discuss background and related research in accessibility of 400-meter jogging tracks, eyes-free exercise technologies, and navigation technologies. Then we describe our conditions and ecologically valid study with 14 participants. Finally, we present our findings and discuss their contribution to knowledge of navigation technologies in exercise settings.

BACKGROUND AND RELATED WORK

Below we discuss accessibility potential and issues of running tracks for people who are blind or low vision. We discuss research in anti-veering feedback for crosswalks and in open environments using technology and Wizard of Oz.

Blind and Low Vision Access to the Jogging Track

Most outdoor jogging tracks are 400 meters in length along the inside lane (Figure 1a). Each lane is 1.2 meters wide. Tracks have benefits for exercise over other outdoor spaces (e.g. sidewalks). First, collisions are less likely: most people run counterclockwise and use visual cues to stay in their lane. When a jogging track is open to the public, it is a controlled space for walking and running, meaning there are fewer obstacles than walking near cars, bikes, and pedestrians. Second, jogging tracks work in all weather conditions and are softer than sidewalks, reducing the chance for injury [6].

Accessible running tracks exist at schools for the blind. These schools may instrument the track with cables or metal bars (e.g., [33]) so people can hold onto them to stay in their lane. Unfortunately, these accommodations are uncommon at mainstream schools or other public venues. Blind runners can visit mainstream jogging tracks with a human guide with several techniques: 1) the two people connect via tether between the wrists or the waist, 2) the blind person walks slightly behind and holds the guide's elbow, or 3) the human guide gives a verbal commentary [37].

Prior research explored how to use aerial robots to guide people who are blind around a 400-meter jogging track [10]. Al Zayer et al. conducted a preliminary study with two people who are blind and found they were able to follow the sound of the drone in an indoor space [2]. The challenge with drones is that they may not be socially acceptable or legal in a public outdoor setting. An alternative to drones is to instrument the track with transmitters and receivers to give feedback via a belt [36]. There are open questions about how to make tracks accessible without instrumenting the space.

An overwhelming majority of jogging tracks are not accessible and there is no evidence that the majority of visually impaired people are visiting tracks independently. People who are visually impaired visit an adapted track or go with a human guide. One accessibility issue is that tracks have extra straight horizontal space at the beginning or end of the straightaways to accommodate for sprinting and hurdling events. If people who are blind follow the outside edge, they may walk into a corner without realizing it (Figure 1b). When considering the risks associated with navigation research in exercise spaces, a human guide is a better baseline condition than no feedback. Having no feedback entails a risk that is not justified by what we would have learned from the study.

Anti-Veering Feedback in Structured Environments

Researchers have explored the design of navigation feedback for people with visual impairments in structured environments, including at crosswalks. In an indoor simulated crosswalk setting, Guth had participants walk in a 2-meter wide, 20-meter long "crosswalk". Participants received audio feedback about the direction and distance of veering, and they veered less over the course of 20 trials [12]. Panëels et al. had nine participants walk 15 meters on tile and concrete and compared continuous tonal feedback against no feedback. When there was feedback, participants veered less [23].

Researchers have conducted crosswalk research in the wild. Diaz et al. developed a system using a convolutional neural network that analyzes video to provide real-time feedback [8], and plan to test with blind people in future work. Shangguan et al. implemented CrossNavi, a low-power system that analyzes video to guide blind people in zebra-striped crosswalks [29]. Ross and Blasch compared three types of feedback against no feedback (sonic "carrot", speech, and shoulder tapping). Tapping was the best approach in performance and preference [27]. Mascetti et al. evaluated two sonification approaches versus verbal feedback and found 2/3 of participants preferred sonification [22]. These methods have not been evaluated on a track and may not be compatible with exercise. There is little work on navigation feedback for longer, narrower paths. A straightaway or curve on a track is thinner (1.22 meters) and longer (100 meters) than common street crossing tasks. We explore how non-visual feedback applies to navigating such environments.

Navigation Feedback in Open Environments

Blind athletes have used the combination of technology and human help to navigate in outdoor environments. Recently, a blind kayaker used video chat to connect with a sighted person to ask about their surroundings [17]. Aira is a company that allows people to connect through their service to sighted assistance; one athlete used the service to complete the Boston Marathon [32]. These technologies are in nascent stages with technical glitches, so athletes rely on voice when the video fails. These technologies involve human help, but there is also an opportunity to learn about how automated feedback could enable independent exercise in public spaces.

Researchers have explored automated navigation feedback in open environments. Jones et al. used spatial audio to play music in the direction the user should walk [13]. NavCog [1] and NavCog3 [28] are robust systems that verbally provide information about points of interest and accurate turn-by-turn instructions for indoor environments. Magnusson et al. developed a system for blind people in the park, where the user points their phone at a point of interest to receive speech and vibrations [21]. Outdoor spaces present different challenges: the point of interest continually changes and people may want to keep their hands free and not pause while exercising. There is an opportunity to explore direction and turning feedback in an unstructured outdoor space where people who are blind can keep their hands free. For a comprehensive list of technologies used to help with navigation, Giudice and Legge present factors that affect navigation along with a survey of navigation technologies [11], and Roentgen et al. [26] provides an overview of 146 products, systems, and devices.

Wizard of Oz Navigation Feedback

Researchers have explored navigation feedback for people who are blind via Wizard of Oz for indoor navigation. Because of the large vocabulary needed (e.g. giving directions), Poláček et al. explored verbal commands [24]. Brady et al. explored verbal, sonification, and vibration feedback [3]. Fiannaca et al. [9] developed a system guiding people who are blind to doors in an open room. There is an opportunity to learn what feedback people who are visually impaired prefer in outdoor exercise settings. Wizard of Oz methods are appropriate to explore these preferences.

NAVIGATION FEEDBACK DESIGN

We designed three methods for providing veering feedback utilizing mainstream technologies for an outdoor public exercise setting. Our research goal was to conduct an early exploration of how these methods affect people who are visually impaired while walking in a public exercise space.

Unique Challenges of Jogging Tracks

Tracks are unique spaces in that they are both structured and unstructured. Tracks are structured with lanes indicated visually but unstructured because they are flat and wide. The task of staying in one lane is more difficult than most other tasks with wider paths and shorter distances (e.g. [12, 23, 27, 29]). Unlike navigation between two points, the purpose of walking on the track is exercise. With these factors in mind, we discuss the rationale behind the designs used in our Wizard of Oz study.

Feedback Methods

We developed three feedback methods taking into account the unique challenges of the track, related research, and the use of mainstream technology (as suggested by Shinohara and Wobbrock [30]). Two of our feedback mechanisms are audio and one is wrist vibration.

People need to be aware of their surroundings while exercising in a public space. To deliver audio feedback that does not interfere with hearing, we chose bone conduction headphones (suggested by [25]). We chose smartwatches for wrist vibration feedback with one on each wrist to indicate direction; the Blind Driver Challenge used a similar two-hand approach [15]. Sucu and Folmer [31] opted to have people steer away from, rather than towards, the vibration to appeal to intuition. Like Sucu and Folmer, we chose that people walk away from the wrist vibration to simulate approaching a wall or swimming lane line. We chose watches because most of our studies occurred during warmer seasons, but gloves could be a winter alternative.

We considered whether to play continuous or corrective feedback. Williams et al. [35] recommends giving constant information to aid in staying on course in wide-open spaces and minimal timely information in dense spaces. For the straightaways, we chose a hybrid approach: we initiate feedback only when the user is out of their lane and then give continuous feedback until they are back in their lane. We chose not to deliver continuous feedback at all times, particularly for wrist vibration, because people can be fatigued and desensitized with continuous vibrations [7]. On the curves, people have to "veer" several times to complete the task, so we chose to present minimal non-distracting feedback. We present our straightaway and curved feedback below. Table 1 (below) provides a summary of the feedback.

Feedback on Straightaways

We provide continuous feedback when a person is out of their lane and no feedback when they are in their lane. We were inspired by the tactile feedback that swimmers receive in a lap pool. If a swimmer veers out of their lane, they feel tactile feedback because their arm hits the lane divider. As a result, the swimmer moves away from the lane divider to continue swimming in their lane. A swimmer avoids turning away too much or else they may run into the lane divider on the other side. If the person is in their lane, they feel nothing at all. If they veer far out of their lane, they may receive feedback several times until they are back in their lane.

Human Guide

Our control condition is a researcher with experience as a human guide walking with the person. People chose to either

Task	Human Guide	Verbal	Wrist Vibration	Head Beat
Straightaway	Hold elbow or verbal cues	Correct Left Correct Right	500ms pulses on R wrist 500ms pulses on L wrist	60 bpm in R ear 60 bpm in L ear
Curve	Hold elbow or verbal cues	Left 45 Left 90 Right 45 Right 90	500ms pulse on R wrist 2x225ms pulses on R wrist 500ms pulse on L wrist 2x225ms pulses on L wrist	2 beats at 60 bpm in R ear 4 beats at 120 bpm in R ear 2 beats at 60 bpm in L ear 4 beats at 120 bpm in L ear

Table 1. Feedback design for the four conditions on straightaways and curves. R = right, L = left

hold the guide's elbow or walk alongside the guide who would verbally notify which way they started to veer.

Verbal

The probe delivers verbal feedback via bone-conduction headphones. If the person veers right, they hear *"Correct left."* If they veer left, they hear *"Correct right."* They hear the verbal commands until they are back in their lane. The verbal commands repeat at 0.77 Hz. Although spatial audio is more robust against cognitive load [16, 20] compared to verbal feedback, we chose verbal feedback because ambient noises (traffic, wind, and joggers) may impede one's ability to perceive direction via bone-conduction headphones.

Wrist vibration

The probe delivers wrist vibration via smartwatches. We chose a wrist vibration condition to explore non-aural feedback. If the person veers right, they feel a 500ms vibration on their right wrist every second. If the person veers left, they feel a vibration on their left wrist every 500ms. They feel the wrist vibrations until they are back in their lane.

Head beat

The probe delivers heartbeats via bone-conduction headphones. We chose the heartbeat as a hybrid between aural and tactile feedback. The sound is low frequency, so the bone-conduction headphones provide an auditory and tactile experience near the temples. If the person veers right, they hear/feel a heartbeat at 60 beats per minute (BPM), or 1Hz, in their right ear at 90DB. If they veer left, they hear/feel a heartbeat at 60 BPM, or 1Hz, in their left ear at 90DB. They hear/feel the heartbeats until they are back in their lane.

Feedback on Curves

For curves, we present minimal non-distracting feedback. The person takes 45-degree left turn segments once they start exiting the lane to their right to approximate a semi-circle. We give 90-degree left turn feedback when they veer too far right and provide right turn feedback if they veer too far left.

Human Guide

Our control condition was the same human guide who behaved the exact same as the straightaways. The human guide did not take 45-degree segments to maintain ecological validity of the baseline condition, giving a possible advantage over the technology conditions.

Verbal

The probe delivers verbal feedback via bone-conduction headphones. If a person veers right, they may hear *"Left 45"* or *"Left 90."* If a person veers left, they may hear *"Right 45"* or "*Right 90."* For example, if they veer left slightly, they would hear *"Right 45."* If they have veered to the right significantly, they would hear *"Left 90."* They only hear this feedback once. The wizard repeats this feedback manually only if their trajectory has not changed. We do not want people repeatedly turning 45 or 90 degrees while they are still out of their lane; they would eventually walk in a loop.

Wrist vibration

The probe delivers wrist vibration via smartwatches. If a person veers right, on their right wrist they feel either a pattern of 500ms of continuous vibration to signify a 45° turn a pattern of two 225ms vibrations separated by a 50ms pause to signify a 90° turn. If a person veers left, on their left wrist they feel either a pattern of 500ms of continuous vibration to signify a 45° turn a pattern of two 225ms vibrations separated by a 50ms pause to signify a 90° turn. For example, if they veer left slightly, they would feel one continuous vibration on their left wrist, but if they veer to the right significantly, they would feel two pulses at a faster pace on their left wrist. They only feel this feedback once. The wizard repeats this feedback manually if their trajectory has not changed.

Head beat

The probe delivers heartbeats via bone-conduction headphones. If a person veers right, they hear a 1-second clip of a heartbeat in their right ear at 60 BPM to signify a 45° turn or a 1-second clip of two heartbeats in their right ear at 120 BPM to signify a 90° turn. If a person veers left, they hear a 1-second clip of a heartbeat in their left ear at 60 BPM to signify a 45° turn or a 1-second clip of two heartbeats in their left ear at 120 BPM to signify a 90° turn. For example, if they veer left slightly, they would hear one heartbeat in their left ear at 60 BPM. If they have veered to the right significantly, they would hear two heartbeats in their right ear at 120 BPM. They only hear this feedback once. The wizard repeats this feedback manually if their trajectory has not changed.

WIZARD OF OZ USER STUDY

Participants and Study Locations

Inclusion criteria specified vision, hearing, and walking ability. Participants had to have low to no vision, such that a technology device could help them navigate the track. Participants needed to be able to hear in both ears and walk for at least 10 minutes without stopping. We had 14 participants that completed the study. 8 reported no vision, totally blind, or light perception only, 1 reported no central vision, and 5 participants reported low vision. 7 were females ages 24-72 (median: 55). We present their navigation method for the study and exercises in Table 2. No participants reported using a navigation feedback technology during exercise.

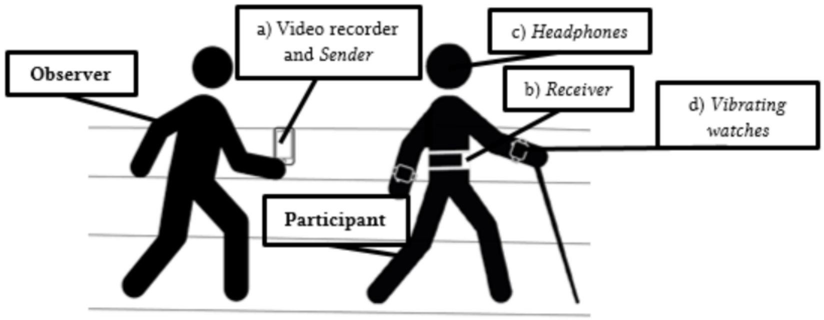

Figure 2. Observer and Participant on a straightaway. a) The observer holds two phones, one to record the participant from behind, and Sender to send commands in the Wizard of Oz study; b) the participant receives commands via the Receiver phone in the custom phone belt. The participant receives feedback via the c) bone conduction headphones or d) two vibrating watches.

Because travel was involved for the study, we met P3 at a track where the painting was in poor condition and therefore could not accurately measure time elapsed, and whether they were staying in their lane or walking parallel (or tangential) to the track. We collected qualitative data but cannot report quantitative results for this participant. We discovered that P4 could not hear out of both ears during the study procedure. We chose to keep the participant but omit the head beat condition from their study. We report quantitative data (n=13) and qualitative data (n=14). Table 6 shows tasks completed by blind and low vision participants.

We conducted the user studies at outdoor 400-meter jogging tracks with eight lanes (six lanes with P14) both in large and small cities. These tracks were located at schools, colleges, or universities. We received permission from the principal or athletic director at each location to run the user study. We chose jogging tracks because we wanted participants to experience feedback in an ecologically valid setting. This setting meant we encountered several aspects of using a public space including other people (2 participants), construction (4), physical education class or team (3), rubber track covers or tarps (10), high winds (5), fences (3), and pep rally music (1). Only two participants had others around, but this is likely because we needed to use most tracks during school hours to ensure staff members were on campus. Fewer people would be using the track at that time except for structured activity.

Device Configuration and Technical Implementation

The experimenter held two phones: 1) to record video from behind the participant for data collection and 2) to deliver feedback as a remote control via Wizard of Oz to the participant (*Sender;* Figure 2a). The participant wore an Android smartphone on their torso with a custom phone belt (*Receiver*; Figure 2b). We chose to affix the phone with a custom belt to simulate a future system that uses the phone's built-in camera to detect if a person is exiting their track lane. We developed an application in Android Studio using Java for the *Sender* and *Receiver* so that they could communicate with one another via WifiP2P due to public tracks not having Wi-Fi. Based on the command from the *Sender,* the *Receiver* either sent audio via Bluetooth to the bone-conduction headphones (Figure 2c) or sent instructions via Bluetooth to the LG G wristwatches (Figure 2d). We used Trekz Titanium bone-conduction headphones (20Hz – 20,000Hz). For the technology conditions (i.e., not *Human Guide*), the *Receiver* also logged the commands from the *Sender* as data.

To validate that the Wizard was delivering proper feedback, we had a separate researcher analyze the video footage from

P#	M/F	Age	Vision	Nav. Method	Indoor exercise	Outdoor exercise
P1	F	59	none	cane	treadmill	walk, tandem bike, swim w/others
P2	M	36	no central vision	vision	none	running in neighborhood
P3	M	24	low vision	cane	goalball, weights	running 2x/year w/others
P4	F	57	none	cane	treadmill, stretches	walking
P5	M	64	low vision	cane	rowing machine, treadmill, stationary bike	yardwork
P6	M	53	low vision	cane	none	gardening, walking
P7	F	24	low vision	cane	dance, cheerleading, ice skating	none
P8	M	72	none	cane	speedbag, taekwondo, boxing	speedbag
P9	M	67	low vision	cane	Stationary bike, weights	walking
P10	F	71	light perception	guide dog	none	walking
P11	M	63	totally blind	cane	walking	walking
P12	F	37	light perception	cane	treadmill, stationary bike, elliptical	tandem bike, trail running w/others
P13	F	46	none	cane	elliptical	swimming
P14	F	26	totally blind	cane	treadmill, stationary bike, weights	none

Table 2. Demographic information about the 14 participants in the Wizard of Oz study. "with" = "w/"

the *Video Recorder* (Figure 2a) after completing the studies. The second researcher practiced giving feedback with the Sender interface on two random participants' video footage (P9, P11) and then gave feedback on another two random participants (P4, P5). We could not include P1 or P2 in this validation because of a software bug: logging timestamps in seconds (instead of milliseconds). However, this bug did not affect our quantitative analysis. We compared the two logs of button presses and considered each command a match between Wizard and researcher if the receiver logged them within 3 seconds of one another with respect to the start time. With true negatives (neither researchers pressed any button in a 3-second time window), the agreement for Straightaways is 78% and Curves is 90%. The Cohen's Kappa accounting for randomness was 60% ("moderate agreement" [18]) and 75% ("substantial agreement" [18]) respectively.

Study Procedure

Our study was within-subjects, so participants experienced all four conditions. The order of conditions was consistent between straightaways and curves. To be sure that walking experience or fatigue did not bias the conditions, participants completed different orders of conditions, determined by a 4x4 Latin Square. The independent variables were the four conditions *Human Guide, Verbal* feedback, *Wrist Vibration* feedback, and *Head Beat* feedback. Our dependent variables included behavioral measures: time elapsed for each walking task and percentage of time the participant was in their lane or making forward progress; and attitudinal measures: participants' ranking of conditions, comfort ratings, and willingness to use the condition again.

We helped participants put on the phone belt, headphones, and watches. We said, *"The objective is to stay in your lane. Imagine a physical wall to the right or left of the lane. If you start to hit a wall in real life, you would slightly correct your body to avoid the wall but still walk parallel to avoid hitting it again in the future. However, because the lanes do not have actual walls, instead:"*

- The voice will tell you which way to correct your body.
- We are playing a heartbeat in your right or left ear to indicate which wall you are hitting.
- We are vibrating your right or left wrist to indicate which wall you are hitting.

We played sounds or vibrations and asked the participants *"Based on this feedback, what would you do next?"* If the participants answered correctly for all the feedback options, we began the task. If participants were confused, we would provide clarification and test them again until they were able to distinguish the feedback instructions. This procedure took less than two minutes per condition.

Participants completed the straightaway tasks while using their primary mobility aid, which included cane, guide dog, or remaining vision. We gave participants the task to remain in lane 7 (or lane 5 for P14) because walkers are supposed to use the outer lanes. We guided the participant to the beginning of the straightaway and instructed them to begin when they heard *"Start"* (with recorded female voice) from their headphones or the guide. For the technology conditions, the experimenter walked 5 feet behind the participant, recorded video from behind the participant, and provided feedback using the *Sender* smartphone. The experimenter informed the participant that they would be walking behind them, but the experimenter walked quietly (a heel-toe gait) to avoid having their sound provide additional audio cues. In the guide condition, the guide recorded video footage pointed straight down the track whether or not the participant's feet remained in the lane. When the participants finished walking 100 meters, participants heard *"Stop"* from the headphones or the guide. We repeated the task again by walking along the track in the opposite direction. Before the curve tasks, we said, "*You can walk forward unless you are told otherwise. Similar to the straightaway conditions:"*

- The voice will give you literal instructions. The voice will tell you which way and how much to turn.
- Turn away from the heartbeat sound. We are playing a heartbeat in your right or left ear to indicate which wall you are hitting. The frequency of the heartbeat will indicate how much to turn.
- Turn away from the vibrations. We are vibrating your right or left wrist to indicate which wall you are hitting. The frequency of the vibration will indicate how much to turn.

We used the same procedure in the curves as for the straightaway tasks. We split the straightaway and curve tasks so the follow-up interviews could focus on one feedback design to avoid confusion. Because the curve always goes left on a 400-meter running track, we could not walk in the opposite direction. The experimenter would guide the participant across the field back to the beginning of the track curve. Because participants were walking in the outermost lanes, they ended up walking approximately 123 meters per task. In total, the participants walked over one mile.

After each condition (two walks each), we conducted an interview about their experiences. The interview asked participants for what they liked or disliked about the condition, suggestions for improvement, and used a Likert scale to determine participant comfort with the condition and likelihood of using the condition again. After the four tasks were completed (two walks for four conditions); we conducted an interview to learn how participants ranked the conditions in terms of their preference along with their rationale. We asked about how they felt about technology guiding them while on the track. The entire study took 90 minutes, and we compensated participants $20 for their time. All interviews were audio recorded and transcribed.

Data Measurements

A researcher (not experimenter) analyzed logs on the *Receiver* and the experimenter video footage to calculate:

- *Time Elapsed (TE):* Time to walk 100 meters for straightaways (123 meters for curves)
- *In Lane (IL):* % of TE that a person was in their lane. First, we measure the length of time in milliseconds that both participant's feet were inside the lane. We divide this measure by TE to calculate IL.
- *Forward Progress (FP):* % of TE that a person was in their lane or walking parallel to the track for straightaways (tangential for curves). The precision of the data is +/- 10°.

We measured IL and FP via human judgement of the video footage taken behind participants. From participant interviews, we collected:

- *Ranking of Conditions (Rank):* Rank the conditions from 1-4 where 1 is best and 4 is worst.
- *Comfort with the Condition Guiding Them (Comfort):* Rating from 1-5 where 1 is not at all comfortable and 5 is very comfortable.
- *Use Condition Again (Use Again):* Rating from 1-5 where 1 is not at all likely and 5 is very likely.

For track curves, the elapsed time may not reflect performance. If a participant shifted or veered out of their lane, there is a chance that they walked less than 123 meters because they took a shortcut (a chord). We include time elapsed for completeness. We removed P6 trial 2 and P11 because they had to leave the study early. We removed P1 trial 2 because of a failed attempt to walk with *Verbal*.

Data Analysis

We used the Shapiro-Wilk test for normality on all of our measures. We found that all collected data except *Head Beat* TE are not normally distributed. Therefore, we use the Friedman test to compare across all measures and Wilcoxon signed-rank test for pairwise comparisons. When comparing measures between the blind and low vision participants, we use Wilcoxon rank sum test. Because we are comparing between two groups of people with four different conditions, we applied Bonferroni correction, making alpha = 0.05/8 = 0.00625, to mitigate Type I error.

Two researchers conducted open coding on the entire set of interview transcriptions [4], creating codes for each of the four conditions. They coded for positive and negative aspects of each condition mentioned by the participants. They discussed and reached agreement on the list of codes.

RESULTS

Impact of Technology Conditions on Veering

RQ1 asks how much participants veer when using sound or vibration feedback as compared to a human guide. For both straightaways and curves, the differences in TE, IL, and FP were statistically significant when compared between the four conditions (Table 3).

On the straightaways, *Human Guide* allowed for smaller TE than other conditions (*Verbal* Z=29, p<1e-4, *Head Beat* Z=81, p<0.03, *Wrist Vibration* Z=81, p<0.02). There was also smaller TE for *Wrist Vibration* than *Head Beat* (Z=73, p<0.03). *Wrist Vibration* had higher FP than *Head Beat* (Z=192, p<0.01). On the curves, *Human Guide* allowed for smaller TE than *Wrist Vibration* (Z=44, p<0.04) and *Head Beat* (Z=55, p<0.05), but not for *Verbal.* There was smaller TE for *Verbal* than *Wrist Vibration* (Z=54, p<0.05). For straightaways and curves, *Human Guide* allowed for higher IL and FP than the technology conditions.[1]

However, the type of technology condition did not have an effect on IL (no pairwise comparisons statistically significant). This is true for both straightaways and curves. No other pairwise comparisons were statistically significant. Table 4 and Table 5 present medians across all participants for straightaways and curves. Table 6 below shows time elapsed, percent of time in lane, and percent of time making constructive forward progress for all participants.

People with low vision had higher accuracy than people who are blind on straightaways and curves (averages in Table 7). After applying the Bonferroni correction, level of vision only had a statistically significant effect on the FP for *Verbal* (W=21, p<0.00625) on the straightaway. There were also two effects on the curves with the *Wrist Vibration* with IL (W = 15, p<0.00625) and FP (W = 18, p<0.00625).

Participant Feedback

RQ2 aims to explore how participants compared sound and vibration feedback to a human guide. We found that condition type had a statistically significant effect on *Rank, Comfort, and Use Again* regardless of whether the tasks were on the straightaways or curves (see Table 8 below).

	Straight	Curve
IL	χ^2 (3, N=23) = 30.045**	χ^2 (3, N=20) = 27.929**
FP	(χ^2 (3, N=23) = 33.154***	χ^2 (3, N=20) = 27.929**
TE	χ^2 (3, N=24) = 13.368*	χ^2 (3, N=20) = 13.062*

Table 3. Statistical tests for measures In Lane (IL), Forward Progress (FP), and Time Elapsed (TE). Curve IL & FP are the same. (* = p<.005, ** = p<1e-5, *** = p<1e-6)

	Guide	Verbal	Vibration	Head Beat
IL (%)	100.00	61.64	63.90	60.48
FP (%)	100.00	82.62	87.87	79.44
TE (sec)	87.47	96.78	92.98	102.95

Table 4. Average measures for straightaways In Lane (IL), Forward Progress (FP), and Time Elapsed (TE).

	Guide	Verbal	Vibration	Head Beat
IL (%)	100.00	56.94	52.97	53.70
FP (%)	100.00	76.91	78.80	75.08
TE (sec)	105.01	111.14	118.79	114.52

Table 5. Average measures for curves In Lane (IL), Forward Progress (FP), and Time Elapsed (TE).

[1] Straightaways: *Human Guide* vs: *Verbal* (Z=210, p<1e-4), *Wrist Vibration* (IL: Z=190, p < .001, FP: Z=190, p<1e-4), and *Head Beat* (Z=210, p<1e-4). Curves: *Human Guide* vs: *Verbal* (Z=190, p<0.001), *Wrist Vibration* (Z=190, p<0.001), and *Head Beat* (Z=136, p<0.001).

P#	Gu. TE sec	Verb. TE sec	IL %	FP %	Vib. TE sec	IL %	FP %	Hea. TE sec	IL %	FP %	Gu. TE sec	Verb. TE sec	IL %	FP %	Vib. TE sec	IL %	FP %	Hea. TE sec	IL %	FP %
p1	100	109	4	19	88	49	79	98	27	48	81	188	6	13	102	30	38	119	5	13
p2	80	86	100	100	87	100	100	92	75	96	83	88	95	98	86	97	97	86	97	99
p4	90	96	18	60	118	13	53				115	100	14	45	109	14	57			
p5	87	90	100	100	88	98	100	86	100	100	90	99	98	98	99	100	100	97	100	100
p6	78	89	23	74	91	27	72	115	26	71	90	109	42	64	112	49	83	142	12	71
p7	81	99	98	99	93	100	100	96	80	95	103	111	99	99	112	100	100	104	100	100
p8	137	140	51	69	116	52	95	122	78	86	173	118	21	64	164	60	70	123	34	67
p9	88	93	100	100	91	46	95	86	78	92	97	96	69	86	99	55	93	99	68	93
p10	103	104	85	99	108	89	97	98	100	100	123	144	84	91	147	91	96	140	83	88
p11	88	110	52	67	107	65	89	165	18	62					133	27	100			
p12	59	89	43	72	75	50	81	106	34	51	91	116	39	68	160	24	60	135	18	50
p13	62	63	48	95	59	80	94	72	63	85	103	98	41	79	98	22	77	96	31	81
p14	83	90	51	87	90	61	87	100	47	69	104	104	41	79	119	17	55	133	24	62

Table 6. Time elapsed (TE), % in lane (IL), and % forward progress (FP) across two trials. We present straightaways on left and curves on right. Guide IL and FP are all 100%. White background = low vision, gray background = blind.

		Guide		Verbal		Wrist Vibration		Head Beat	
Level of Vision	Task	IL	FP	IL	FP	IL	FP	IL	FP
Blind	Straightaway	100.00	100.00	52.94	77.55	62.20	86.07	55.19	74.50
Low Vision	Straightaway	100.00	100.00	80.12	93.39	67.72	91.91	71.07	89.34
Blind	Curve	100.00	100.00	45.29	70.83	42.49	72.24	41.46	65.76
Low Vision	Curve	100.00	100.00	81.91	89.94	79.92	95.66	78.18	93.73

Table 7. Comparison for people who are blind or low vision: % in lane (IL) and % forward progress (FP).

Head Beat was a lower ranked condition. Looking at pairwise comparisons for *Rank* for both straightaways and curves, *Head Beat* was ranked lower than *Human Guide* (straight: *n.s.*, curve: Z=90.5, p<0.02) and *Verbal* (straight: Z=20, p<0.05, curve: Z=15, p<0.01). No other conditions had differences in ranking that were statistically significant.

Participants felt most comfortable with the *Human Guide.* On the straightaways, participants gave *Guide* higher *Comfort* ratings than *Verbal* (Z=3.5, p<0.05)*, Wrist Vibration* (Z=3, p<0.03), and *Head Beat* (Z=3.44, p<0.03), with no significant differences between the technology conditions. On the curves, participants gave *Guide* higher scores than *Wrist Vibration* (Z=2.5, p<0.04) and *Head Beat* (Z=3.5, p<0.02).

The *Use Again* ratings were less conclusive, with *Human Guide* likely better and *Head Beat* likely worst. On the straightaways, participants gave higher *Use Again* ratings to *Guide* than the technology conditions (*Verbal:* Z=4, p<0.03, *Wrist Vibration:* Z=1.5, p<0.05, *Head Beat:* Z=2.5, p<0.007) with no significant differences between the technology conditions. On the curves, participants gave a worse *Use Again* rating to *Head Beat* than *Human Guide* (Z=3, p<0.008), with no differences between the other conditions.

Level of vision had no statistically significant effect on the rankings or ratings. Upon analyzing the means and medians, we found that the rankings, order of comfort scores, and order of use again scores from top to bottom had the same order: 1) human guide, 2) verbal, 3) wrist vibration, and 4) head beats (Table 9 below). Below, we report the themes uncovered by two researchers (Table 10 below) to support the rankings, ratings, and quantitative measures for each condition.

Human Guide

Human Guide had the greatest number of positive themes and fewest negative themes. The participants had experience walking with a companion or human guide and no experience with the technology conditions prior to our study, so it was reported as the most familiar of the conditions (Natural & familiar): "It [walking with a Human guide] feels more natural" (P2). The human guide had experience guiding people who are blind in walking settings, so they were able to accomplish the task effectively (Accurate & trustworthy) while also being themselves (Social & fun). P13 touched on both of those points: "It [Human guide] was fine. It was enjoyable to walk with someone because you stay together, and you chat, and you are not going to go out of the lane." One negative aspect is that they are dependent on a human guide, with whom it may not be easy to coordinate. Participants mentioned that not all guides are equal—some are worse than others. P5 discussed how the guide was harder to trust than the technology: "Those [technologies] I knew I could rely on, but a person, I don't. […]." When asked why, P5 mentioned why human guides in general are not as reliable: "They are a common person and […] like to see what's in a storefront, they are selfish for walking."

Verbal

Participants appreciated that the verbal instructions were detailed (Clear distinguishable instructions): "I felt very comfortable with it telling me to go right or left" (P1). Participants felt like it was natural because it resembled a GPS or mobile talking applications (Personal). P10 distinguished the *Verbal* from the *Head Beat*: "It just seemed a little more personal. That's funny because a computer cannot be personal, but it is." We used short verbal statements, but participants felt that they were too long and gave suggestions including

Sentiment	Human Guide	Verbal	Wrist Vibration	Head Beat
Positive	• Social & fun • Accurate & trustworthy • Natural & familiar • Immediate feedback	• Personal, resembling talking app or GPS • Clear, distinguishable instructions	• Easy to feel if placed correctly • Not aurally distracting	• Not interfering
Negative	• Dependent • Not all guides are equal	• Must pay attention (cane/conversation could interfere) • Feedback too long	• Cane interferes with wrist vibrations • Socially unacceptable with two watches	• Too quiet • Wind & loud sounds degrade quality • Feedback "too late" • Must pay attention (to distinguish feedback)

Table 10. Positive and negative themes about each condition based on participant's interview responses.

"remove the word 'correct'." (P14, Feedback too long). We chose bone-conduction headphones to allow participants to hear their surroundings, but participants reported needing to focus on the sound (Must pay attention). P7 commented: "since I was so focused on this [Verbal condition] I wasn't so focused on my cane." P4 mentioned a concern with the Verbal condition while with others: "If there's someone walking with you and you're talking you might miss the cues."

Wrist Vibration

Participants reported that *Wrist Vibration* gave participants the best opportunity to listen to their surroundings (not aurally distracting): "you didn't have the ear distractions" (P6). To ensure they could feel the vibrations, we placed the watches on the participants' wrists by making sure the strap fit properly and having them remove personal watches (Easy to feel). P12 reported, "They [the vibrations] are very strong which is good, so you can't miss them". However, seven participants suggested the improvement of increasing the intensity. There was a challenge for cane users, who noted that the cane running along the track would compete with the vibration feedback (Cane interferes with vibrations). P3 stated, "I lifted the cane because sometimes my hand would be vibrating." Finally, several participants felt that two watches were socially unacceptable (Socially unacceptable): "I wonder if you get criticism from people if you have two watches" (P10). An alternative is to wear a single watch with different types or locations of vibrations to distinguish the feedback. However, there may be a steeper learning curve to infer the direction of the turn based on a vibration pattern or location than having the right and left wrist indicate direction.

Tasks	Rank	Comfort	Use Again
Straight	χ^2 (3, N=14) =8.657*	χ^2 (3, N=14) =9.286*	χ^2 (3, N=14) =13.165**
Curve	χ^2 (3, N=14) =9.857*	χ^2 (3, N=14) =8.938*	χ^2 (3, N=14) =11.138*

Table 8. Friedman test for straightaways and curves comparing *Rank*, *Comfort*, & *Use Again*. (*= p<.05, **=p<.005)

Head Beat

Head Beat was the lowest ranked and rated condition with the most negative themes. The head beat sounds did not interfere with other sounds because the sounds were of low frequency (Not interfering). P8 appreciated the heartbeats: "it's not being intrusive, it's not overwhelming, [and] it gives me enough of a cue and it doesn't tie up anything else." However, participants felt that the sounds were too quiet against the weather and other sounds (Wind and loud sounds): "If you are in any kind of traffic and the wind, [...] you are not going to hear it" (P11). Having the elements such as wind interfere with aural feedback is consistent with Williams et al.'s research with outdoor navigation [35]. Participants report the feedback arriving "too late" even though the Observer sent signals to the Participant consistently in the study. Participants also had to interpret the feedback to make the correct action (Must pay attention). Six participants suggested changing the type of sound and five participants suggested making them louder.

DISCUSSION

From this Wizard of Oz study, we learned that while the technology conditions were not different in their effect on a person's ability to stay in their lane or make forward progress that participants expressed a preference in the ordering of the four choices: human guide, verbal, wrist vibration, and head beat. The descriptive statistics may indicate that people with low vision did a better job staying in their lane than people who are blind; presumably, because they were using the vision they had to determine the track lines. The Wizard of Oz system helped people who have low vision remain in their track lanes or make constructive forward progress because the lighting conditions or weather had an impact on the person's ability to see the track lines.

Tasks	Participant Responses	Guide	Verbal	Wrist Vibration	Head Beat
Straightaway	Ranking (1 = best, 4 = worst)	1.93	2.21	2.57	3.29
Straightaway	Comfort (5 = very comfortable, 1 = not at all comfortable)	4.86	4.29	3.93	3.92
Straightaway	Use Again (5 = very likely, 1 = not at all likely)	4.93	4.29	3.93	3.62
Curve	Ranking (1 = best, 4 = worst)	1.86	2.36	2.43	3.36
Curve	Comfort (5 = very comfortable, 1 = not at all comfortable)	4.77	4.23	3.85	3.54
Curve	Use Again (5 = very likely, 1 = not at all likely)	4.77	4.31	3.92	3.23

Table 9. Median rankings and ratings of the four conditions for both straightaways and curves.

This is an early step in providing non-visual feedback in exercise spaces with rough terrains, and with our careful design decisions, we were able to gain insights on outdoor feedback design. While Ross and Blasch determined that haptic (shoulder tapping) was the most effective approach compared to sounds and speech [27], our findings differ; we found that cane users did not perceive the vibration feedback as well. We believe the cause of this difference was texture: we conducted studies on the track with polyurethane pebbles as opposed to an indoor space with a smooth floor (e.g. [12, 23]). We also chose the wrist as the locus of stimulation versus the shoulders. We recommend when designers and developers use vibrations in exercise spaces with rougher terrain, that the *vibrations are pronounced or only on one wrist.* This way, a person can use their cane or guide dog and still perceive feedback. Secondly, we found that wind and loud noises (including physical education classes and football pregame music) reduced the ability to hear the *Head Beat* condition, but that the *Verbal* condition did not suffer. We recommend *louder, or higher frequency sounds* be used in these spaces. Another reason to follow these guidelines is so the user can focus solely on their current navigation techniques instead of having to pay attention to vibrations or sounds.

Comparison to other navigation research

This research is different from other research in anti-veering for people who are visually impaired (e.g. [12, 23, 27, 29]) because the tasks in this study have narrower paths and longer distances. We used solely commodity technologies due to our research occurring in an outdoor public space. Our results show that there are gaps between in one's ability to navigate in this type of shared exercise space with mainstream technology as compared to a human guide. Our study did not attempt to demonstrate that these feedback mechanisms are better than a baseline of no feedback as in other research articles (e.g. [23, 27]). Due to the more difficult nature of our tasks, we chose safety as a priority. Ethically, we could not have a baseline of no feedback to demonstrate a true "win" for our different non-visual feedback designs.

Limitations

While we were careful to control for fatigue and learning effects by counterbalancing the conditions, and embrace the outdoor setting, there were limitations to our study. One of the priorities while using public tracks was maintaining the quality of the space, so we kept our study equipment minimal. As a result, we did not create walking traces of the person's path because we did not want to instrument the public (school) tracks. Instead, we were able to use the video footage to calculate participant's performance. We did not provide feedback on objects or barriers. However, a user's cane serves as obstacle detection and a guide dog serves as obstacle avoidance. We intend the technology conditions to complement one's existing, familiar navigation skills to provide extra information. We had 14 participants (not a multiple of 4), so we did not have an even distribution on the Latin Square. The reader should interpret the quantitative results with the imbalance in mind. Finally, we did not adjust the sound characteristics of *Verbal* or *Head Beat* based on preliminary user experience with the bone-conduction headphones (suggested by Mascetti et al. [22]).

Future Work

We recognize that while the technology conditions have the potential to help people with low vision walk on the track, further work is necessary to provide better feedback for blind people. These challenges are in line with a recent publication by the New York Times in 2017 that wearable technologies have the potential to assist blind runners, but they are facing challenges including inaccurate notifications, and unreliability [19]. Further work in this research can make other spaces accessible including swimming pools and or completing drills in a gymnasium.

One research direction is to help people who are blind determine if they have corrected their trajectory too little, too much, or accurately. Anecdotally, what we observed on a straightaway, for example, "correct right" could mean different amounts of turning. One person may make a subtle 30° turn, another person may make a larger 45° turn, and another person may take a side step and slightly adjust his or her direction. Giving timely, informative feedback on someone's turn status while in motion is a challenging research problem. The verbal vocabulary may need to be increased, or some combination of verbal with informative sounds that are *compatible* with outdoor spaces.

Another direction of future research is exploring the hybrid approaches to feedback that combine computers and humans. *Human Guide* was by far the best condition in our study, but human guides can also be more difficult to recruit [25]. Blind athletes have shown interest in connecting with remote human guides (e.g. [17, 32]). Researchers could study what types of verbal commands are most helpful for different types of exercises. Researchers could use the verbal commands to train human workers who have less experience with guiding or inform better automatic systems if the person cannot pay for such a service.

CONCLUSION

We designed and compared three different mainstream technology conditions to a human guide to explore navigation feedback for people who visually impaired while walking on a 400-meter jogging track. By conducting an ecologically valid study in a public outdoor space, we learned that while human guides are superior, there is a potential for these feedback designs to assist people with low vision on the track. We found that while participants walked with the same amount of accuracy between the three technology conditions that the participant preference was human guide, verbal, wrist vibration, and head beat. We presented qualitative factors that affected the user experience including outdoor noises, terrain of the space, and weather. These technology conditions provide insights for future outdoor exercise technologies for this population. We hope our work will contribute to the design of multimodal feedback mechanisms for exercise in public exercise spaces and in different terrains.

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