Investigating Three-dimensional Directional Guidance with Nonvisual Feedback for Target Pointing Task

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Abstract

While directional guidance is essential for spatial navigation, little has been studied about providing nonvisual cues in 3D space for individuals who are blind or have limited visual acuity. To understand the effects of different nonvisual feedback for 3D directional guidance, we conducted a user study with 12 blind-folded participants. They were asked to search for a virtual target in a 3D space with a laser pointer as quickly as possible under 6 different feedback designs varying the feedback mode (beeping vs. haptic vs. beeping+haptic) and the presence of a stereo sound. Our findings show that beeping sound feedback with and without haptic feedback outperforms the mode where only haptic feedback is provided. We also found that stereo sound feedback generated from a target significantly improves both the task completion time and travel distance. Our work can help people who are blind or have limited visual acuity to understand the directional guidance in a 3D space.

Keywords: Directional guidance, audio feedback, haptic feedback, 3D environment

Index Terms: Human-centered computing—Human computer interaction (HCI)—Empirical studies in HCI; Human-centered computing—Human computer Interaction (HCI)—Interaction techniques—Auditory feedback

1 Introduction

Directional guidance plays an important role for spatial navigation, and thus numerous applications were designed to provide users with directional information. For instance, arrow signs are commonly used to indicate the direction of a specific target destination. A navigation system is another example that shows step-by-step directional instructions on a map for pedestrians and drivers.

While visual cues are often used to provide directional information, visual guidance can be inaccessible for people who are blind or have low vision. Hence, various studies have been conducted to investigate directional guidance with nonvisual feedback to complement visual cues when these are limited or unavailable, mostly for people with visual impairments [3, 5, 6, 8, 12–14]. For instance, Strachan *et al.* [13] designed a navigation system called GPSTune, which is a portable navigation system with audio feedback where different volume is used to indicate the remaining distance and direction of a panning sound to convey the direction towards the target destination. Others also investigated audio feedback for conveying coordinates information or direction on a touchscreen device to people with visual impairments [8, 14]. On the other hand, some researches studied haptic feedback, particularly using wearable devices. Ertan *et al.* [3], for example, tried to help people with visual impairments to navigate a route while wearing a vest that could deliver 4 cardinal directions using vibration motors mapped to each direction. Similarly, Hong *et al.* [5] proposed a wrist-based haptic device which helps to find a target on a 2-dimensional surface (*e.g., a paper map*). While most of the studies had been conducted to provide directional guidance for people with visual impairments for physical environments, recent studies have developed cane controllers for people with visual impairments to navigate a virtual space [11, 16].

All these studies are found to be helpful for providing 2-dimensional directional guidance for spatial navigation (*e.g.*, way-finding, reaching to specific coordinates on a 2D surface). However, little has been studied on supporting 3-dimensional directional information with nonvisual feedback except for aiding camera aiming for people with visual impairments via audio feedback [1, 15].

To identify design implications for supporting 3D directional guidance with nonvisual feedback, we conducted a user study with 12 participants where they were asked to point a virtual target that appears in a random direction with a controller as shown Fig. 1. Three different types of nonvisual cues were provided: stereo sound whose source is the target, proximity-based discrete beeping sound and haptic feedback (*i.e.*, a beeping sound and a short discrete vibration from a controller, respectively) where the frequency becomes higher as users get closer to the target. As a result, we found that stereo feedback improves the task performance both in terms of the completion time and the travel distance. Moreover, findings revealed that proximity-based sound feedback helps with the performance regardless of the presence of haptic feedback. The performance was also reflected on participants' subjective preferences.

The contributions of this work are as follows: (1) empirical evidences that show effective nonvisual feedback types for 3D directional guidance, and (2) implications for designing future nonvisual directional feedback.

2 Related Work

Our work is inspired by prior studies for providing nonvisual directional guidance focusing on audio and haptic feedback.

2.1 Directional Guidance with Auditory Feedback

As for navigating a 2D surface, Leplâtre and Brewster [7] conducted a study about how audio feedback can help users to navigate a complex menu structure of a mobile user interface by mapping approximately 150 different sounds to distinctive functions and showed that participants who had sound feedback completed menu navigation tasks more successfully than others. Oh *et al.* [8] also investigated different sound parameters such as volume, pitch, and stereo sound for conveying 2D gestures on touchscreen devices to people with visual impairments and found that the best performance can be achieved when stereo sound and pitch are mapped to x and y coordinates, respectively. Similarly, Su *et al.* [14] presented the system called Timbremap that guides users' fingers on a touchscreen using auditory feedback to help people with visual impairments to explore a map or a floor plan where high pitched sound for upward direction and low pitched downward direction. Strachan *et al.* [13], on the other hand, introduced a system called GPSTune, a handheld audio navigation system for way-finding. This system is designed to reduce cognitive overload while moving by guiding users with

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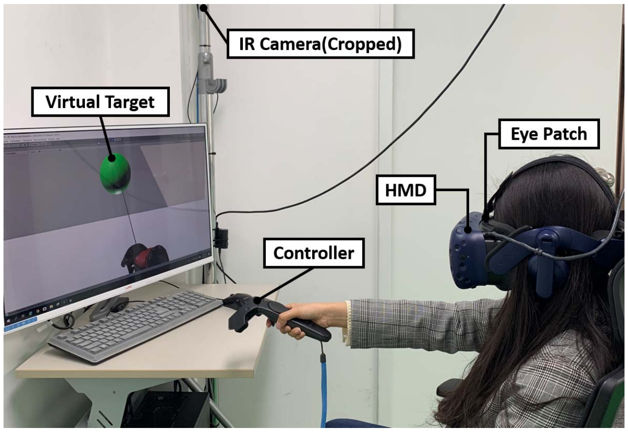

Figure 1: The experiment setup for our target pointing task with nonvisual feedback. Note that all participants wore an eye patch to prevent them from receiving any visual feedback while performing the task and that HMD was used for tracking participants' head orientation. Note that an external display in the figure was only visible to an experimenter.

audio feedback; volume for distance and direction of a panning sound for moving direction. Likewise, Zhao *et al.* [16] introduced Canetroller, a wearable VR controller, and showed the possibility of aiding people with visual impairments for navigation using auditory feedback in addition to haptic feedback.

While promising, these studies only inform 2D directional information on a 2D surface or way-finding with cardinal directions. Studies on 3D directional guidance with nonvisual feedback do exist for supporting camera aiming for people with visual impairments [1, 15]. However, they did not explore haptic in comparison to audio feedback in terms of task performance which differentiates our study with theirs.

2.2 Directional Guidance with Haptic Feedback

As for 2D guidance, Hong *et al.* [5] proposed a wrist-based haptic device for guiding hand for a path tracing task on a 2D surface (*e.g.,* a piece of paper, touchscreen). Likewise, Stearns *et al.* [12] developed an optical character recognition system with auditory and haptic feedback to help people with visual impairments to read printed text line by line with a finger-mounted camera. Researchers have also studied haptic displays to provide direction information for way-finding [2, 3, 6, 9]. For instance, Ertan *et al.* [3] designed a wearable haptic navigation guidance system to reduce the level of auditory attention needed for people with visual impairments. The system has a 4-by-4 array of micromotors embedded in the back of a vest and offers a user five different instructions: four cardinal directions and stop. Similarly, Van Erp *et al.* [2] proposed a vibrotactile waist belt to help people who are in a visually limited situation with waypoint-oriented navigation. The concept of the system was that the distance was converted into vibration rhythm and the direction was a map to vibration location. Also, NaviRadar [9] used vibration feedback to deliver directional information to users such as walking directions and the remaining distance to the next crossing via different intensity, rhythm, duration, and roughness of the vibration feedback. Unlike most of the studies with haptic feedback for providing directional guidance in horizontal space for way-finding, Katzschmann *et al.* [6] designed a smart white cane that can not only inform where obstacles are located both horizontal (left, right) and vertical directions (high, low) but also the distance using haptic feedback.

Although providing distance information is beyond the scope of this study, our goal is to provide 3-dimensional directional guidance in 3D space using both haptic and audio feedback.

Condition	Stereo	Beeping	Haptic
Beeping only w/ Stereo	On	On	Off
Haptic only w/ Stereo	On	Off	On
Beeping+Haptic w/ Stereo	On	On	On
Beeping only w/o Stereo	Off	On	Off
Haptic only w/o Stereo	Off	Off	On
Beeping+Haptic w/o Stereo	Off	On	On

Table 1: Six different feedback conditions tested in the study.

3 User Study

To investigate different nonvisual feedback designs to inform users with specific directions in 3D, we conducted a one-hour single-session within-subjects study with 12 participants where they were asked to point towards the direction of a target using a controller in a 3D virtual space given nonvisual feedback while blind-folded.

3.1 Conditions

We hypothesized that (1) multimodal feedback, beeping sound with vibration, performs the best when compared to a single mode feedback (*i.e.*, beeping only, vibration only) and that (2) an interaction effect exists between the presence of stereo sound and different combinations of feedback mode as stereo sound and beeping share the same auditory channel, unlike haptic feedback. Thus, we explored 6 different feedback conditions for providing 3D directional guidance (see Table 1) varying the followings:

- ***Stereo***: A pleasant music is played in a loop in the stereo mode where the target location is the source of the sound[1].
- ***Beeping***: A discrete beeping sound is played periodically from the top of a participant's head (mono) where the frequency of the sound becomes higher as the pointing direction gets closer to the target if within a range.
- ***Haptic***: A discrete and periodic vibration is delivered to users where its distance-frequency mapping is identical to *Beeping*.

3.2 Participants

We recruited 12 participants (10 females and 2 males). Their age was 23.83 on average (*SD* = 2.29; range 20-28). All participants had prior experiences with virtual reality and they were all right-handed. None of them had visual or auditory problems.

3.3 Apparatus

We developed a custom application using Unity2019.2.17f1 ran on a desktop computer for this study where the specifications were as follows: CPU of AMD Ryzen 7 1700 with RTX2080 graphic card and 16GB of RAM. A HTC VIVE Pro Eye and a handheld controller were used to track participants' head orientation and the pointing direction as shown in Fig. 1. Both stereo and beeping sound feedback[2] were played from the headset while haptic feedback was delivered by vibrating the controller.

The frequency of beeping sound and haptic feedback was defined based on Fig. 2(C)[3]. The frequency was set to 657*ms* for distances less than 4.5*m*, 365*ms* for less than 2.0*m*, and 263*ms* for less than 1.0*m*. For all conditions, the application provided an additional sound cue when the laser raycast from a controller had just entered a target as well as a continuous haptic cue while the laser raycast is pointing the target once entered. Finally, a ding-dong sound was

[1]Audio Spatializer SDK by Unity is used to implement this stereo sound.
[2]source: https://freesound.org/people/edsward/sounds/341871/
[3]We used C instead of the angular distance between A and B since θ changes depending on how participants' arm is stretched or bent.

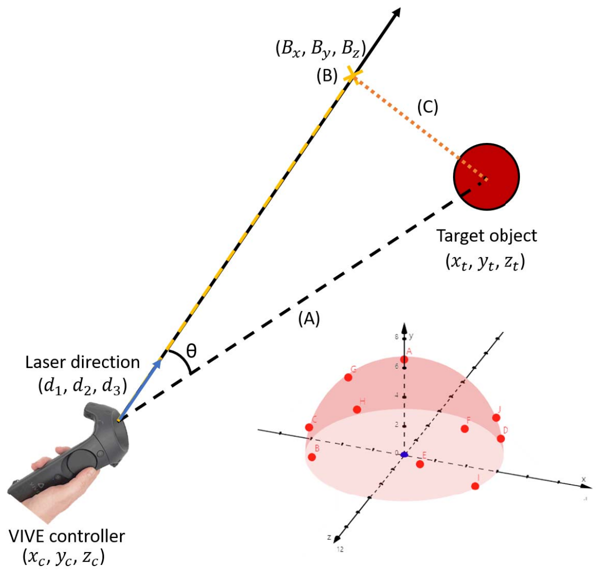

Figure 2: (A) The distance between the target center and the controller. (B) A point that has the same distance as *A* in the direction of the laser from the controller. (C) The distance between the center of the target and *B*. Red dots on a hemisphere shows target positions used during the task whose distances from the origin (participant) are identical.

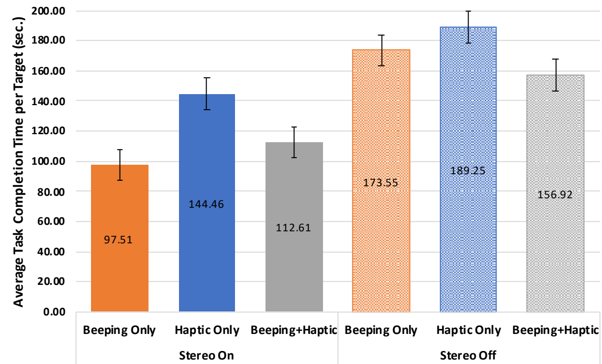

Figure 3: The average task completion time per target for each condition in seconds. Error bars indicate standard errors.

played if participants successfully triggers a button while pointing the target.

We logged all of the participants' input with timestamps and saved the logs as a csv file each time a participant completes a task with each target for the analysis.

3.4 Procedure

The study began by collecting participants' age, gender, and prior VR experience. After a briefing about the study, participants were asked to sit on a rotating chair at a fixed location so that they can change their facing direction in 360 degrees while seated. Then they were instructed to put on an eye patch before wearing the HMD to block their sight and hold a controller with their dominant hand. They were asked to find a virtual target that randomly appeared in various directions in 3D by listening to the directional feedback as quickly as possible while blind-folded. Once the raycast from the controller touches the target, participants could hear a positive sound feedback so that they can confirm the pointing direction by triggering a button on the controller (see Fig. 1). Prior to the actual task for each condition, participants were given a practice session with a single target to get familiar with each feedback design. As soon as they complete the practice, 10 targets appeared in a random order with the fixed shape and size (*i.e.*, a sphere with the radius of 0.5*m*) and distance (*i.e.* 6*m*) for each condition where the coordinates of the 10 targets were predefined to cover various directions as much as possible by sampling 10 coordinates from the surface of an upper semi-sphere as shown in Fig. 2. The order of the conditions was counterbalanced using a balanced Latin square design and we randomly assigned participants to orders and participants were allowed to take a break after completing the first three conditions. At the end, we collected subjective feedback regarding their experience with each condition.

3.5 Data and Analysis

A total of 720 data was collected from the study (12 participants × 6 feedback conditions × 10 targets). Two-way ANOVA was conducted to assess the interaction effect between *Feedback Mode* (3-level: beeping only *vs.* haptic only *vs.* beeping+haptic) and *Stereo* (2-level: on *vs.* off). Pairwise comparisons were examined with Bonferroni adjustments as post-hoc analyses whenever applicable. Subjective responses such as participants' preference and the reasons were collected as well.

4 Findings

We describe the findings to show the effectiveness of different feedback designs mainly in terms of task completion time, travel distance, and preference. Note that we were not able to find a significant effect of *y*-coordinate, the altitude, of the target on the task performance.

4.1 Task Completion Time

The result of task completion time is shown in Fig. 3. Two-way ANOVA with factors of *Feedback Mode* and *Stereo* revealed main effects. We found that the difference between three feedback designs were statistically significant ($F_{(2)} = 6.09$, $p = .002$, $\eta^2 = .017$). Pairwise post-hoc tests with Bonferroni adjustments showed that participants were slower when only haptic feedback were provided than *beeping only* and *beeping+haptic* feedback ($p = .003$ and $p = .002$, respectively). On the other hand, there was no significant difference between *beeping only* and *beeping+haptic* feedback. We also found that the average task completion time was significantly faster with stereo feedback than without it regardless of other feedback modes ($F_{(1)} = 41.28$, $p < .001$, $\eta^2 = .055$); 118.2 seconds with stereo feedback ($SD = 71.3$) and 173.2 seconds without stereo feedback ($SD = 147.5$). No interaction effect was found between the two factors.

4.2 Travel Distance

We also examined travel distance which is computed based on the sum of all distances between every two successive coordinates of a laser trace[4]. As shown in Fig. 4, the result is similar to task completion time. While no interaction effect was found to be significant, there were significant main effects of *Feedback Mode* ($F_{(2)} = 10.93$, $p < .001$, $\eta^2 = .030$) and *Stereo* ($F_{(1)} = 61.50$, $p < .001$, $\eta^2 = .079$). Pairwise post-hoc analyses with Bonferroni adjustments show that there is no significant difference between *beeping only* and *beeping+haptic* feedback, while the average distance with *haptic only* condition was longer than the two ($p < .001$ for *beeping only* and $p = .001$ for *beeping+haptic*). With stereo feedback, participants travelled shorter with the average distance of 58.7*m* ($SD = 47.9$) than without the stereo feedback where the average distance was

[4]The coordinates of *B* in Fig. 2 are used to compute the travel distance.

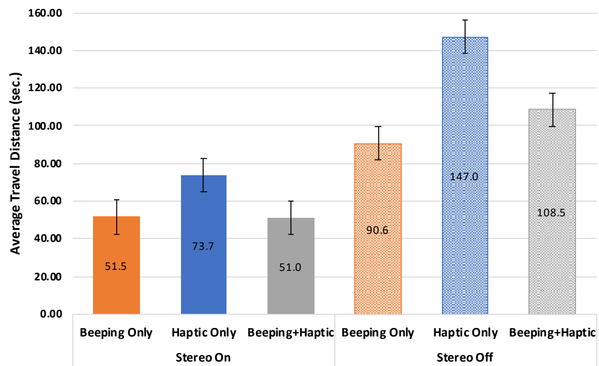

Figure 4: The average travel distance per target for each condition in meters. Error bars indicate standard errors.

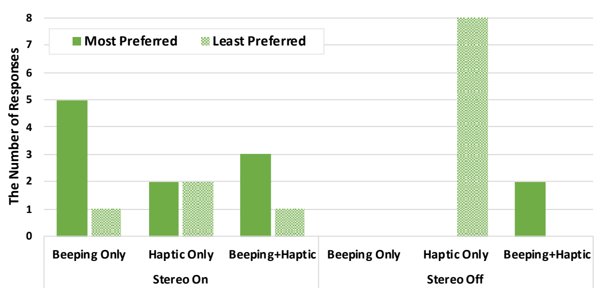

Figure 5: The number of responses for the most and least preferred feedback conditions for target pointing task in 3D (N=12). Most of the participants preferred having stereo sound.

115.3m (SD = 130.5). This is similar to prior finding that beeping sound feedback results in better accuracy than haptic feedback for line tracking task [12].

4.3 Preference

In the end, we collected participants' preference on feedback condition. As shown in Fig. 5, the majority of the participants (N = 10 out of 12) reported that they prefer having stereo sound feedback over no stereo sound, reflecting task performance. Indeed, 11 participants reported that stereo feedback was very helpful for understanding the approximate direction of the target relative to their head orientations, particularly for horizontal ones (*e.g.*, left or right). P2, however, mentioned that stereo sound is rather confusing than useful. In addition, we asked which feedback conditions participants favor. As a result, more number of participants responded that they prefer *beeping+haptic* over *beeping only* (N = 7 *vs.* 5); none of them chose *haptic* as their favorite. Participants who preferred beeping sound and haptic feedback in combination perceived that these are complementary to each other. On the other hand, the remaining participants believed that it is overwhelming or tiring to focus on two different sensory channels (N = 4) and that beeping sound is more intuitive (N = 3) than haptic feedback.

4.4 Trace Analysis

As a secondary analysis, we examined if there is a trend when searching for the correct direction of a target in 3D space and observed that participants had the tendency to scan the environment with their laser pointer in a horizontal direction as shown in Fig. 6. While the trend was more frequently observed when stereo feedback was given, the trend also existed even when stereo feedback was absent.

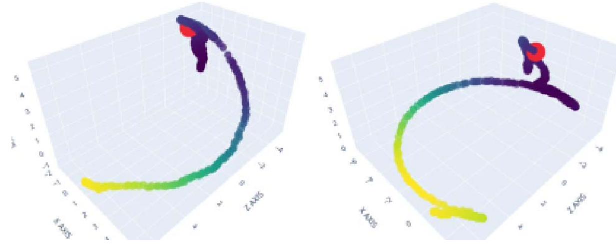

Figure 6: Example traces during target pointing task for P5 (left) and P9 (right) with stereo and beeping sound feedback that show the tendency of turning around in the direction of a horizontal space; the yellow color indicates the start of a trace and a red circle indicates the target.

Although further analysis is needed, this could be due to natural target search behaviour which is to turn around to scan the surrounding environment. Also, higher frequency of the trend with stereo sound can be explained by the design of the stereo sound which is easier to know if the target is on the left or the right side rather when compared to pointing a target that is high above the participants. Thus, participants tried looking for the target by rotating their horizontal orientation to narrow down the search space and then make fine-grained adjustments afterward. Note that we found no performance difference between targets where their vertical coordinates were higher than 3m and the rest that were below.

5 Discussions

Here we summarize our findings and present design implications learned from the study.

5.1 Complementing Stereo Sound with Beeping

As stereo sound is known to be effective for conveying spatial information for way-finding [4], we confirmed that stereo sound is a useful cue for providing directional guidance in 3D space as well. However, our findings also suggest that stereo sound is not sufficient for fine-grained target searching task when a user wishes to find the direction towards a specific object rather than a walking directions where an approximate cue is sufficient. Fortunately, we found that additional proximity-based beeping sound feedback can help users point a specific target. Reflecting on our findings, we suggest using stereo and beeping sound in combination for providing 3D-directional information.

5.2 Single Versus Multimodal Feedback

We expected that stereo with haptic feedback would outperform stereo with beeping sound feedback as feedback provided in the same modality is known to cause cognitive overhead or distractions interfering with each other sharing the same channel [10]. Indeed, Hong *et al.* [5] also showed that haptic guidance with 4 vibration motors had better performance than that with 8 motors. However, our findings imply that multimodal feedback with sound (either stereo sound or beeping sound feedback) and haptic is not that informative. Yet, it is important to investigate haptic feedback for conveying directional guidance as there are circumstances where audio feedback is not appropriate nor safe (*i.e.*, having a conversation, crossing a busy street). Thus further study is needed to explore diverse design patterns for haptic feedback.

5.3 Two-Step Guidance

We did not consider users' natural search behavior for pointing a target in 3D space at all when designing nonvisual feedback. However, the analysis of participants' trace suggests that two-step directional guidance could be a natural way to convey directional information in 3D space where the first step is to deliver the horizontal direction followed by the second step to provide vertical direction towards the target. Although further investigation is needed to confirm the trend, in this way, we can provide a single type of feedback at a time, ideally beeping sound feedback rather than a haptic feedback, so that users can pay more attention to finding either the horizontal or vertical direction. Yet, one should consider additional overhead as users would need to stop and continue when changing their scanning direction whereas the current version allows users to point a target with the shortest distance.

6 Limitations

As a single-session controlled lab study, our study has several limitations. Fist of all, although the target population for this nonvisual directional guidance is people with visual impairments, the participants we recruited for this study were sighted participants. While blind-folded, since people with and without visual impairments may vary such as performance and preference, the findings may not be applied to people with visual impairments. Also, while we used a HMD to track the orientation of participants' head, it is possible that the form factor (i.e., weight) of the device may result in different findings compared to a natural setting where a headset is used to convey the audio sound instead of a heavy head-mounted device with a visual display. It could have different results when doing the searching task in a real situation. In addition, while we had a discrete set of range for mapping feedback frequency and the distance to provide a stronger noticeable difference to users, continuous feedback could have been more ideal. Lastly, while we were able to find significant results even with the limited sample size, we plan to conduct this study again to collect sufficient data to generalize the findings of the user study.

7 Conclusion and Future Work

We have conducted a user study with 12 participants where they were asked to point a virtual target in 3D space as quickly as possible while blind-folded while providing various directional feedback. The findings showed that the proximity-based beeping sound with or without haptic feedback, and stereo sound generated from the target location significantly improve the nonvisual target pointing task performance in terms of the completion time and travel distance while haptic feedback was found to be relatively ineffective for conveying the directional information. Based on the lessons learned from this study, we plan to explore additional design spaces for audio and haptic feedback more in-depth (*e.g.*, tone, volume, and pitch for the sound and intensity, duration, rhythm for the vibration) and conduct another user study with people with visual impairments. In addition, we will extend this work by applying nonvisual feedback designs for finding a real object in an actual 3D physical space and assess if our findings from a virtual space can be generalized to a real environment.

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