Exploring Bimanual Haptic Feedback for Spatial Search in Virtual Reality

BoYu Gao, Tong Shao, Huawei Tu, Qizi Ma, Zitao Liu and Teng Han

Abstract— Spatial search tasks are common and crucial in many Virtual Reality (VR) applications. Traditional methods to enhance the performance of spatial search often employ sensory cues such as visual, auditory, or haptic feedback. However, the design and use of bimanual haptic feedback with two VR controllers for spatial search in VR remains largely unexplored. In this work, we explored bimanual haptic feedback with various combinations of haptic properties, where four types of bimanual haptic feedback were designed, for spatial search tasks in VR. Two experiments were designed to evaluate the effectiveness of bimanual haptic feedback on spatial direction guidance and search in VR. The results from the first experiment reveal that our proposed bimanual haptic schemes significantly enhanced the recognition of spatial directions in terms of accuracy and speed compared to spatial audio feedback. The second experiment's findings suggest that the performance of bimanual haptic feedback was comparable to or even better than the visual arrow, especially in reducing the angle of head movement and enhancing searching targets behind the participants, which was supported by subjective feedback as well. Based on these findings, we have derived a set of design recommendations for spatial search using bimanual haptic feedback in VR.

Index Terms—Bimanual Haptic Feedback, Spatial Search, Controllers, Virtual Reality

1 Introduction

Spatial search is one of the common and important interaction tasks in VR [12, 17, 23, 30], and commonly consists of visual search and target selection phases. Users need to first perceive a spatial direction and then search for a target location in virtual environments. Visual search is essential and considered particularly challenging in spatial user interfaces such as menu selection [71], object manipulation [50, 53, 54], data exploration [52] and navigation [12, 17, 30] in VR. The broad searching area and distant/hidden/invisible targets add a burden to users in VR both physically and cognitively. Typically, visual search requires users to recognize spatial directions for localization and takes much longer times than target selection in spatial search [22, 79].

Existing approaches lean towards using multi-modal sensory cues such as visual, auditory and/or haptic feedback, which is more akin to the natural sensory input and process for users in the physical world. Specifically, previous research has proven the effectiveness of integrating vibrotactile feedback on head-mounted devices (e.g., an HMD) or handheld devices (e.g., a single controller) to increase the user's spatial perception of virtual environments, obstacles or invisible targets [4, 5, 12, 29, 52, 67]. Nonetheless, those vibrotactile cues are often explicit, either requiring extra hardware (e.g., extra motors on HMD) or only conveying limited information. There missed an opportunity to leverage bimanual haptic feedback, essentially provided by the controllers in both hands, to assist users with visual search in VR.

By employing bimanual haptic feedback through handheld controllers, users can utilize their two hands to represent right and left directions respectively. This makes it effortless for users to distinguish between them, thereby facilitating the process of recognizing spatial directions (e.g., front, back, left or right). Furthermore, using the body as proprioceptive reference, the vibration properties perceived by the two hands can be translated into cues for spatial search in VR, e.g., strong vibration denotes the front direction with the left controller, while weak vibration represents the back direction with the right controller. However, bimanual haptic design with VR controllers poses the following challenges. First, research on vibrotactile communication has shown that people can perceive directions through tactile stimuli rendered on one side of the body [69] and tap-on-the-shoulder (i.e., a vibrotactile stimulus on the torso links to an immediate percept of external direction) [19, 46], which is easy to understand but provides users with limited information. It is unknown whether there is a mapping between perceived vibration properties provided by handheld controllers (e.g., combinations of intensity, frequency, or duration) and spatial directional cues for users in VR and how it should be. Second, regarding the matter of active learning and memorisation by users, numerous studies have been conducted [15, 16, 58, 65]. Users need to learn and memorize mappings between vibration properties and spatial directions. It is unclear what is users' capability to do so. Third, bimanual haptic feedback may make exploration/manipulation with the hands even harder. For example, the use of bimanual haptic feedback could potentially hinder the user's ability to interact with and explore virtual environments. This is due to the possibility of excessive or inaccurate feedback interfering with the user's sensations and actions [3, 75]. Additionally, if the feedback is too strong or frequent, it may cause psychological discomfort [28], which can further impede exploration and interaction. Therefore, we need to carefully design feedback-related factors and parameters to alleviate this limitation as possible. Fourth, the performance of the proposed bimanual haptic feedback compared with existing conventional methods (visual [57], auditory [30, 60] and unimanual haptic [45, 52] cues) for spatial search in VR is also under-explored.

In response to the aforementioned challenges, we designed and explored bimanual haptic feedback with various combinations of vibration properties for spatial search in VR. Based on the analysis of existing studies [1, 5, 28, 46, 52, 65], we selected two of three vibration properties (vibration type: continuous and pulse, vibration intensity: strong and weak, vibration duration: long and short) that can easily help distinguish the spatial directions to form four bimanual haptic feedback patterns (Fig. 1: Pattern 1, 2, 3 and 4) (see Section 3 for the details). In line with previous studies [12, 15, 16, 34, 35], spatial space was divided vertically into eight sectors, which represents eight directions (east, west, south, and north, as well as the intermediate directions of south-east, south-west, north-east, and north-west). The corresponding properties of bimanual haptic feedback patterns were mapped to eight directions in VR, e.g., Pattern 2: vibration types repre-

- *BoYu Gao, Tong Shao, Qizi Ma and Zitao Liu are with Jinan University, Guangzhou, China. E-mail: bygao@jnu.edu.cn*
- *Huawei Tu is with La Trobe University, Melbourne, Australia. E-mail: h.tu@latrobe.edu.au*
- *Teng Han is with Institute of Software, Chinese Academy of Sciences & School of Artificial Intelligence, University of Chinese Academy of Sciences. E-mail: hanteng@iscas.ac.cn.*
- *Corresponding author: BoYu Gao, Huawei Tu*

Manuscript received xx xxx. 201x; accepted xx xxx. 201x. Date of Publication xx xxx. 201x; date of current version xx xxx. 201x. For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org. Digital Object Identifier: xx.xxxx/TVCG.201x.xxxxxxx

sent front or back, and front with continuous, while duration indicates intermediate direction and long duration from the controller indicates target direction.

We then assessed the proposed four bimanual haptic patterns to explore how effectively they support the recognition of spatial direction by using spatial audio feedback in VR as a baseline. The results showed that Pattern 2 achieved the best performance in the recognition of spatial directions in terms of accuracy and efficiency. Subsequently, we compared Pattern 2 with three conventional feedback conditions (i.e., no additional feedback, visual arrow, and unimanual haptic feedback) using a spatial search task in VR. Pattern 2 achieved comparable selection times as the visual arrow, a common spatial search method in the existing works [33, 53, 72], with less movement overheads than the visual arrow in VR.

The main contributions of this work are two-fold. First, we explored four different bimanual haptic feedback conditions based on the selection of vibration type, vibration intensity and vibration duration for supporting spatial orientation perception in VR. Second, we demonstrated the effectiveness of the proposed bimanual haptic feedback on spatial search tasks in VR, through a comparison with conventional visual arrows and unimanual haptic feedback.

2 Related Work

2.1 Spatial Search in VR

Spatial search is a common and important interaction in VR [12, 17, 22, 23, 30, 53, 79]. For example, for an assembly task in VR, the time taken to search for the components to be assembled directly affects the overall completion speed [53]. The use of spatial depth information or landmarks can help the learning of spatial locations and then facilitate the searching process in VR , greatly enhancing the searching efficiency [20–22]. Previous studies also demonstrated that the field of view covered by current VR devices is still limited compared to that of the human eye. To search for or locate objects outside the field of view in VR, guiding techniques are needed to assist the users within the limited screen space [8, 36]. It is therefore worth improving visual search efficiency to enhance the performance of spatial search in VR. The following subsections summarizes the use of visual, auditory and haptic or multimodal cues to support spatial search in VR.

2.2 Cues for Spatial Search Tasks

Three common types of cues for spatial search in VR are summarized, including visual, auditory and haptic cues.

Visual Cue Visual cues are one of the most commonly used methods for spatial search in VR [76]. Using the visual arrow is an easy-to-implement and intuitive method for spatial search in VR. For example, Schmitz et al. [57] evaluated the effectiveness of using a central arrow and peripheral blinking to direct and focus attention in a panoramic video. Wallgrün et al. [72] demonstrated that the arrow was the most popular, intuitive, easy to learn and use, aesthetically pleasing mechanism, compared with butterfly guides and radar, in 360° image-based educational VR application. Except for the visual arrow, Lange et al. [33] made an effort to minimize the loss of immersion by seamlessly integrating directional cues into VR scenes, proposing a technique using group motion in VR to direct the user's attention. In addition, Yoshimura et al. [82] developed attention-restoring visual cues for display when gaze tracking detects that student focus shifts away from critical objects.

Auditory Cue Auditory cues are also widely utilized for spatial guidance and search in VR [2, 6, 9, 55, 60, 80]. By leveraging spatial audio techniques, creating localization and orientation of sound sources within a virtual environment can provide cues for navigation and orientation to users [2]. For example, Binetti et al. [6] proposed simultaneously adding spatialized auditory cues fixed at the target location, so as to overcome the problem of reduced visual effectiveness at different depths. Even though the advantages of auditory feedback for guidance in VR were presented, compared with light effects, not all participants could pay attention to the direction of the sound [55]. However, one more advantage is that the viewer's visual attention can be guided by sounds sourced outside of the field of view [80]. Recently, Song et al. [60] showed that combined sonification using spatial and non-spatial could significantly reduce the errors in localization, but also lead to a higher task load.

Haptic Cue Haptic cues can be implemented through vibration actuators attached to the headset, controllers, gloves, belts, bracelets, glasses and footwear in VR. Such haptic cues usually assist the users in recognizing direction [18, 37, 42, 46, 47, 81], providing guidance [5, 11, 14, 25, 40], searching for visual targets [12, 17, 23, 30]. Haptic cues are all involved in the process of spatial search in the above three tasks, in particular, the design of haptic cues from many devices for directional and spatial guides can greatly benefit the process of visual search in VR. For example, Mirzaei et al. [42] proposed and evaluated a special haptic VR suite that uses vibrotactile feedback to indicate the direction of sound sources to deaf and hard-of-hearing users. Yamazaki et al. [81] aimed to improve the experience of VR shooting games by employing a 3D haptic guidance method using necklace-type and belt-type haptic devices. The vibrational system [15, 16, 31] was implemented to guide the user by placing multiple vibration units around the body. The wrist-worn [47, 49] and eyewear [46] devices were designed to offer directional cues via vibration information, so as to reduce cognitive load and increase processing speed for the user. The possibility of utilizing haptic information from the feet for spatial navigation was also presented [37, 70]. However, there is less known about the mapping of vibration properties from handheld controllers to spatial directions in VR.

2.3 Interaction with Bimanual Haptic Feedback

Existing studies proposed innovative methods and techniques to design bimanual haptic feedback, including the design of force and vibrotactile feedback rendering and hardware devices.

Several studies have explored novel approaches to provide force feedback with bimanual interactions. For example, Meli et al. [38] proposed substituting haptic stimuli with cutaneous stimuli only in robot-assisted surgery. Peer et al. [48] presented a mobile haptic interface for two-handed 6DOF manipulation, emphasizing its ability to achieve proprioception. Wang et al. [74] proposed MoveVR, a technology that enables realistic, multiple forms of force feedback in VR by varying the speed of movement, rotation, position, and the agent carried by an ordinary cleaning robot to generate tension, resistance, impact, and material stiffness force feedback.

Some studies developed robotic systems for bimanual haptic feedback, including robotic arms with haptics for large-scale motions [27] and a bimanual haptic system for explosive ordnance disposal [32], and a wearable haptic display that displays pressure and vibration on the palm of the hand for two-handed manipulation in VR [41], and they evaluated the ability of the proposed method to recognise the presence of virtual objects in both unimanual and two-handed manipulation.

Other studies have focused on natural bimanual 3D interactions with haptic feedback. For example, Strasnick et al. [61] introduced Haptic Links to create variable stiffness connections between handheld VR controllers. Murayama et al. [44] proposed SPIDAR-G&G, a new haptic interface for intuitive bimanual tasks. Ryu et al. [56] introduced GamesBond, grips that form virtual connections without physical links. The above existing studies demonstrated the benefits of bimanual haptic feedback for manipulation tasks in real-world or virtual environments.

Bimanual haptic feedback could improve the efficiency of directional positioning for spatial search in VR. Operating controllers with both hands provides more perceptual channels [51, 56, 62], allowing users to intuitively perceive various interactive elements in virtual environments. Thus, it is worth investigating the design of bimanual haptic feedback for spatial search in VR.

3 Designing Bimanual Haptic Feedback for Spatial Search

This section introduces the design of four bimanual haptic feedback patterns for spatial search in VR, including the number of spatial sectors in the virtual space, and possible combinations of vibration properties for

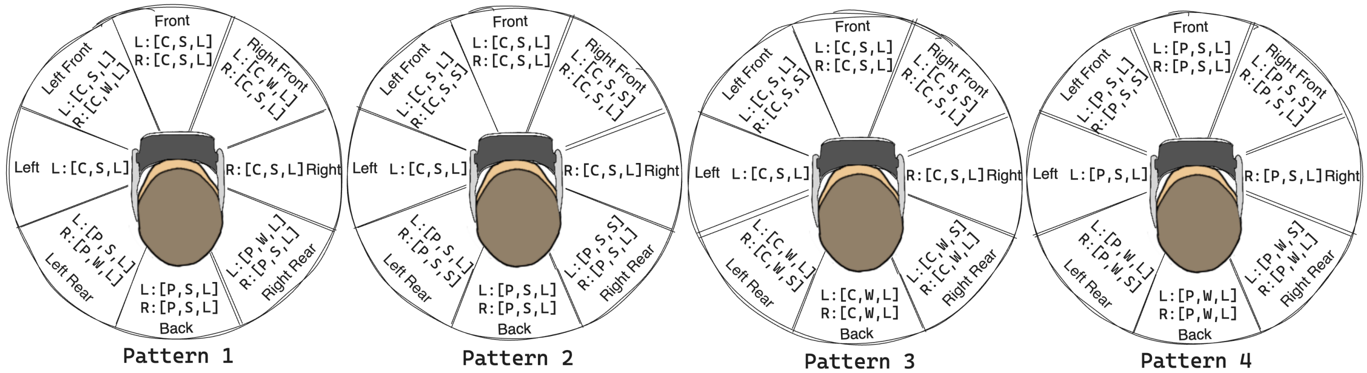


Fig. 1: Four types of bimanual haptic feedback patterns. The [Type, Intensity, Duration] denotes the parameter settings of vibration, where type denotes the types of vibration, C represents Continuous Vibration, P represents Pulse Vibration; Intensity denotes the strength of vibration, S represents Strong, W represents Weak; Duration denotes the duration of vibration, L represents Long, S represents Short. e.g. [C, S, L] means the vibration is Continuous, the vibration intensity is set to Strong, and the vibration duration is set to Long.

bimanual interaction with both handheld controllers and the mapping between the bimanual haptic patterns and spatial sectors.

Spatial Directions: Two main reasons for defining the eight sectors in the virtual space are summarized. First, humans navigate and orient themselves in the real world usually in eight directions: east, west, south, and north, as well as the intermediate directions of south-east, south-west, north-east, and north-west. The perception of our body's position in 3D space is often referenced to the orientation and position of the torso [15, 16]. Therefore, dividing the virtual space into 8 directions can align with natural human perception and reduce the learning burden for users. Second, navigation and spatial search with vibration feedback usually employ eight sectors for spatial direction segmentation [7, 12, 15, 16, 34, 35, 63]. More subdivision of directions can aid users in accurately perceiving directions. However, it could also increase the user's cognitive burden and reduce efficiency [16, 46]. Therefore, the use of 8 sectors satisfies the need for accurate navigation while maintaining simplicity and ease of operation.

Selection of Vibration Properties: The rationale for selecting vibration properties for the spatial directions is summarized as follows. First, the properties used to represent the spatial direction should be informative and easy to learn and recognize for users [46]. Second, the combination of vibration properties should avoid the interplay between each pair of properties. It is important to note that the consistent changes of frequency and amplitude should be avoided due to the interplay [13, 28, 43, 64]. For example, Tan et al. [64] demonstrated that, in practice, differences in distinguishable amplitude or frequency are limited by perceptual and cognitive factors associated with information transfer, such as familiarity with vibration. Thus, we only changed one variation for either frequency or amplitude at a time in our scheme. Third, to reduce the learning burden for users and increase generalization across different controllers (i.e., HTC VIVE Pro or Meta Quest 2), we have chosen only two values (small and large ones) for each vibration property [28]. Specifically, for vibration duration, we selected 300ms over 900ms as the most distinguishable signal length based on the results of Bial et al [5]. In terms of the intensity of the continuous vibration, we set it to 0.2 as weak and 1.0 as strong based on Prouzeau et al's Just Noticeable Difference experiments [52], with the implementation using Unity XRI's 'SendHapticImpulse' [68]. The intensity of pulse vibration is determined based on the existing experimental results [1, 65]. The pulse time interval is set to 125ms for strong and 500ms for weak.

Mapping between Properties and Directions: For the bimanual haptic feedback pattern, the overall design of the scheme was to distinguish the eight directions by the vibration differences between front-back and left-right. The proposed four bimanual haptic patterns are described as follows (Fig. 1).

Pattern 1 distinguishes forward and backward by vibration type (continuous, pulse), with continuous vibration representing the front side and pulsed vibration representing the rear. The left side and right side are differentiated via vibration intensity between the two controllers. For example, if the target direction is on the left side, the left controller will enable a stronger vibration intensity than the right controller.

Pattern 2 distinguishes forward and backward by vibration type (continuous, pulse) which is consistent with Pattern 1. The left side and right side are differentiated via vibration duration between the two controllers. For example, if the target direction is on the left side, the left controller then has a longer vibration duration than the right controller.

Pattern 3 distinguishes forward and backward by the intensity of the continuous vibration, with the intensity of the continuous vibration being stronger for the forward direction and weaker for the backward direction. The left side and right side are discerned by the difference in vibration duration between the two controllers, which is consistent with Pattern 2.

Pattern 4 distinguishes forward and backward by the intensity of the pulse vibration, with the intensity of the pulse vibration being stronger for the forward direction and weaker for the backward direction. and left side and right side are discerned by the difference in vibration duration between the two controllers, consistent with Pattern 2 and Pattern 3.

4 Experiment One: Comparison of Bimanual Haptic Feedback for Spatial Direction

The objective of this experiment is to comprehend users' perception of various combinations of vibration properties for four types of bimanual haptic feedback and to identify the optimal combination based on both objective and subjective evaluations. To achieve this, we crafted four distinct bimanual haptic feedback patterns, incorporating combinations of vibration type, intensity, and duration of vibration. To reduce the workload on the participants and to avoid memory confusion between different patterns, we utilized a between-subject design to assess the performance of each pattern in aiding participants to easily perceive specific spatial directions. We also compared it with the use of spatial audio from existing work [30, 60].

4.1 Participants

We recruited 50 participants (10 female) from the local campus, aged from 22 to 27 (M: 24, SD: 3.6). Only 15 participants who had experience using VR devices were randomly assigned into 5 groups. However, none of them had experience with bimanual haptic feedback in VR. All participants had a normal or corrected-to-normal vision and no hearing or touch-related impairments.

4.2 Apparatus

We used an Meta Quest 2 headset device (refresh rate of 90 Hz and a resolution of 1440 × 1600 pixels per eye) with two handheld controllers for the experiment. The vibration properties with controllers were implemented using Unity XR Interaction Toolkit [68]. We designed the auditory conditions based on [30], which include white noise in combination with the spatial sound system that comes with Unity 2021.3.0, "spatial blend" set to 1 (full 3D), and Bose QC35II stereo noise-cancelling headphones (NC off). The headset was connected to a computer with an Intel core i7 8700 CPU (3.2GHz), 16GB RAM and a Geforce GTX-1060 graphics card. The experiment program was developed with Unity 2021 in C#.

4.3 Task Design

The task design followed an existing work [60], which studied the performance of determining directions through the aid of spatial audio. The experimental design in [60] involved participants verbally stating the corresponding direction when perceived through auditory cues, which was then recorded by an experimenter. A limitation of the design is that task completion time is hard to calculate. Therefore, when adopting the experiment design in [60], we modified it to use controller-based selection to calculate the user's completion time, so as to evaluate the performance of correctly selecting the spatial directions after perceiving the different bimanual haptic feedback patterns. The eight directions buttons and a start button on the virtual plane were shown in the VR environment (Fig. 2). The size and position of the buttons were the same for all feedback conditions. The button size was set to 0.5 × 0.5 metres, and the distance between the buttons and the experimenter was 2 metres. The participants were asked to select the corresponding direction using ray-casting by pressing the trigger of the controller.

We designed a learning mode to assist the participants in learning and memorizing the corresponding bimanual haptic feedback patterns or spatial audio patterns in our experimental setup. In the learning mode, participants clicked on any of the buttons representing the eight directions, and the corresponding bimanual haptic feedback or spatial audio was activated. At the same time, we verbally explained the feedback effect corresponding to that direction. This can facilitate the participants to quickly learn and remember the corresponding feedback patterns.

During the formal experiment, the participants were required to use the ray-casting selection technique to click on the start button using their dominant hand, which activates the corresponding feedback. The task required the participants to quickly identify the corresponding direction based on the feedback and click on the corresponding button to complete the experiment. The response time and the accuracy of selection for each participant in each trial were recorded.

4.4 Task Procedure

This task was divided into three phases. Firstly, each participant was asked to fill out a demographic questionnaire before the experiment began. This process was crucial in gathering relevant information about the participants.

The second phase consisted of two parts: a learning mode and a formal testing mode. Initially, participants were briefed about the overall procedure and objectives of the experiment. Following this, they were introduced to the association between bimanual haptic feedback patterns and the selection of spatial directions in the learning mode. In the training phase, participants needed to practise either haptic or auditory feedback conditions. The participant was asked to select any of the eight directions with the ray-casting selection, which triggers bimanual haptic feedback or spatial audio in the corresponding direction. Additionally, the experimenter received verbal explanations about the corresponding feedback effect in that direction to aid their quick memorisation of bimanual haptic feedback patterns. We understand that each participant may differ in performing practice tasks, so we allowed them to have sufficient time to learn and practice until they felt confident. The practice was checked based on their self-evaluation; participants generally could become skilled after training.

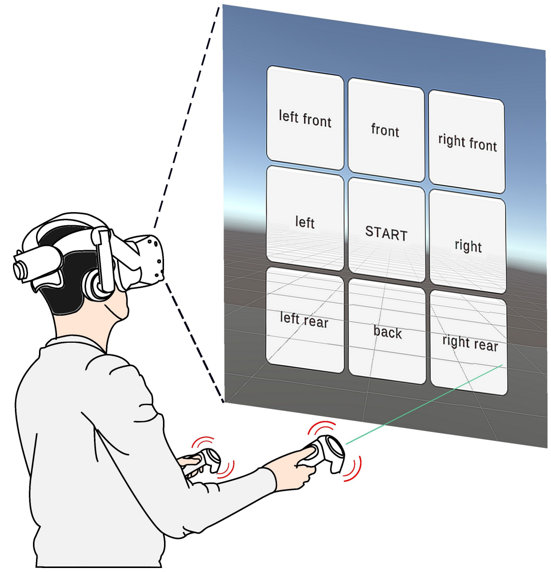


Fig. 2: Virtual scene for Experiment one: the use of bimanual haptic feedback from two controllers held by participants for 8 directions.

Table 1: Average selection times and accuracy for different feedback conditions.

Feedback Conditions	Median Trial Time	Mean Trial Time (SD)	Selection Accuracy (SD)
Pattern 1	2.37	2.42(0.53)	0.96(0.20)
Pattern 2	2.22	2.29(0.58)	0.98(0.15)
Pattern 3	2.47	2.55(0.52)	0.98(0.15)
Pattern 4	2.81	2.86(0.60)	0.94(0.24)
Auditory(g-HRTF)	3.04	3.13(1.10)	0.57(0.50)

In the formal testing mode, participants, divided into one of five experimental groups, were asked to initiate the experiment by clicking the start button using ray-casting, thereby activating the corresponding feedback. They were then required to quickly identify the corresponding direction based on the feedback and confirm their choice by clicking the corresponding direction button. Each trial was carefully recorded, noting the time taken by each participant to confirm their choice and the accuracy of their selection. The participants were encouraged to make their selections as quickly and accurately as possible. Each participant in their assigned experimental group was expected to complete 64 trials (4 (blocks) × 8 (directions) × 2 (each direction repeated twice)). The eight directions in each block were presented randomly, with each direction appearing only twice in each block.

In the final phase, participants were interviewed post-testing. The entire experiment took an average of 10 minutes per participant.

4.5 Metrics

During the experiment, we collected data on task accuracy, and task completion times, and conducted post-experiment interviews to gather participants' subjective experiences and preferences. Task accuracy refers to the number of tasks correctly performed by the participants. Task completion time denotes the duration from the start of the experiment to its completion.

4.6 Results and Analysis

We used the Shapiro-Wilk method to test the normality of the experimental data, and removed about 1% outliers. Outliers were values that differed from the mean by more than three standard deviations. When experimental data satisfied the conditions of normality, the data were analyzed with repeated-measures ANOVA with post-hoc tests using the Bonferroni correction. As the selection accuracy did not meet the

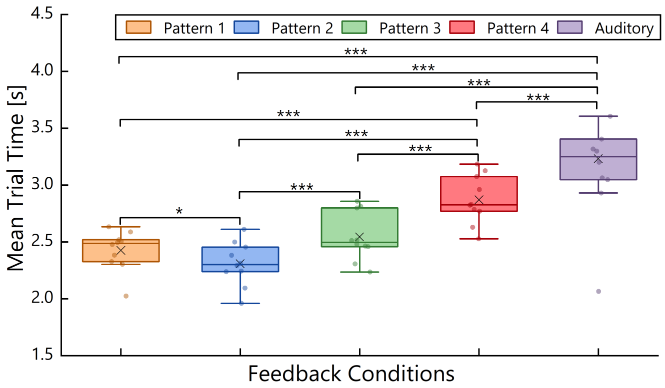


Fig. 3: Boxplots of selection times for all feedback conditions.

Table 2: Average selection times for different feedback conditions in eight spatial directions.

Directions	Pattern 1	Pattern 2	Pattern 3	Pattern 4	Auditory
Front	2.27(0.54)	**2.25(0.52)**	2.54(0.50)	2.82(0.47)	3.32(1.04)
Back	2.53(0.55)	**2.36(0.45)**	2.69(0.63)	3.07(0.52)	3.38(1.15)
Left	2.08(0.38)	**1.96(0.58)**	2.25(0.42)	2.44(0.53)	2.31(0.79)
Right	2.07(0.37)	**1.84(0.45)**	2.23(0.44)	2.45(0.60)	2.43(0.68)
Left Front	**2.43(0.46)**	2.53(0.67)	2.64(0.45)	2.75(0.48)	3.17(1.03)
Right Front	2.61(0.56)	**2.48(0.58)**	2.74(0.55)	2.78(0.47)	3.59(1.25)
Left Rear	2.62(0.42)	**2.39(0.43)**	2.61(0.44)	3.24(0.48)	3.29(1.02)
Right Rear	2.78(0.49)	**2.54(0.52)**	2.67(0.45)	3.31(0.60)	3.52(1.04)

normality test, we used Friedman's test to analyse the differences in selection accuracy between the conditions. The Mauchly sphericity test was conducted for each condition.

Then we examined the learning effects between the four blocks. Due to significant differences between block 1 and block 3, and between block 1 and block 4 (both $p < 0.05$), we selected the data of block 2, block 3 and block 4 for subsequent experimental analyses (Table 1, Fig. 3 and Fig. 5).

Task Completion Time A significant main effect was found on selection time for feedback conditions ($F_{4,45} = 14.126, p < 0.001, \eta^2 = 0.557$). Post-hoc two-by-two comparisons showed significant differences between each of the two conditions ($p < 0.05$), except for no significant difference between Pattern 1 and Pattern 3 ($p = 0.068$).

For each direction, the results showed that there was a correlation between repeated measures ($p < 0.001$), and multivariate analysis indicated that there was a correlation between the directions and the conditions ($F_{28,315} = 2.928, p < 0.001$). The descriptive results for each direction are shown in Table 2 and Fig.4. Among the eight directions, Pattern 2 did not exhibit significant differences compared to Pattern 1 ($p > 0.05$) in all directions, except for the right direction, where it showed a significant difference compared to Pattern 3 ($p = 0.031$). For Pattern 2 and Pattern 4, there was a significant difference ($p < 0.05$) between all directions except the direction left ($p = 0.107$), left front ($p = 0.218$), and right front ($p = 0.282$).

Selection Accuracy Post-hoc tests using Wilcoxon sign-rank and Bonferroni-Holm corrections showed significant differences between the auditory feedback and each of the other patterns ($p < 0.001$). Pattern 4 exhibited significant differences between Pattern 2 ($Z = 2.915, p = 0.004$) and Pattern 3 ($Z = 2.23, p = 0.026$).

Regarding the accuracy for each direction, in the case of the auditory condition, except for the easily distinguishable left and right directions, the accuracy was generally low for the other directions, which is also in line with the existing studies showing that sound is difficult to be distinguished in the confusion cone [60, 73] (Front, Back, Left Front, Right Front, Left Rear, Right Rear). The confusion cone represents the directions or regions known to have more localization errors when using generic Head Realited Transfer Function (g-HRTF) [78] for localization. As for four bimanual haptic feedback patterns, except for slightly lower accuracy in the left-front and left-rear directions for Pattern 4, there were no significant differences in accuracy among these conditions in each direction.

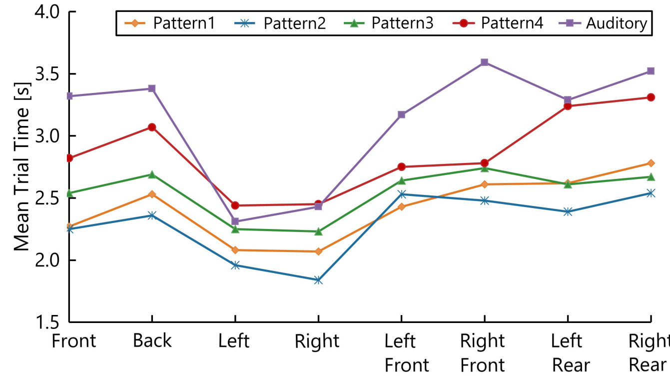


Fig. 4: Average selection times for different feedback conditions in eight spatial directions.

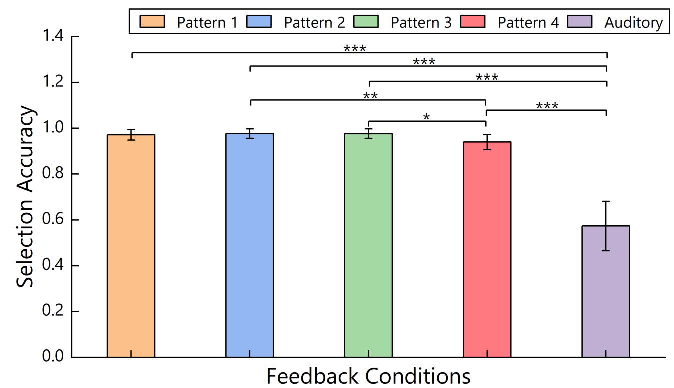


Fig. 5: Average selection accuracy for all feedback conditions. Error bars represent standard deviation.

Overall, Pattern 2 performed the best in terms of selection time and accuracy ($M: 2.29, SD: 0.58, Acc = 98\%$), while Auditory performed the worst ($M: 3.13, SD: 1.10, Acc = 57\%$).

Subjective Feedback In our post-study interviews, we observed that all participants reported no learning difficulties for the bimanual haptic patterns. Regarding the variation type (continuous and pulse vibrations) in bimanual haptic feedback, participants found that they were the easiest to distinguish. The participants also pointed out that they were more likely to notice differences in vibration duration than vibration intensity. It was also noted that the perception of the amplitude of the vibration varied among participants. When the experiment was performed continuously, some people would perceive their hands as being numb, therefore might perceive the controller as vibrating weakly, even if there is no vibration at all. As for the auditory condition, all participants reported that only the left and right could be differentiated.

4.7 Discussion

Our experimental results show that the four bimanual haptic feedback patterns we have proposed showed a large improvement in accuracy and speed compared to spatial audio feedback (g-HRTF), which meets our expectations, as it is known that the use of g-HRTF auditory feedback leads to difficulties in localisation. Although it can be improved by using p-HRTF, this modality requires personal customisation and calibration using specialised equipment [24, 39, 77]. This was confirmed by the subjective feedback from participants, who reported that they could only distinguish between left and right.

From the time-to-distinguish graphs (Fig. 4) for each direction in the proposed four bimanual haptic feedback patterns, it can also be observed that the left and right directions, which have higher discrimination, were the fastest to distinguish across all modes. Vibration patterns were also comparatively simpler to differentiate in the front and back directions compared to the other directions, resulting in relatively quicker discernment periods. This discernment was corroborated by participants' subjective comments given in subsequent interviews.

Among the four bimanual haptic modes, Pattern 2 exhibited the best performance in almost all aspects, which we attribute to the fact that Pattern 2 was set up in a way that the vibration patterns of each direction had the least effect on each other, resulting in the highest discrimination. First, we consider the types of vibration, such as continuous and pulse vibrations, that are the easiest to differentiate, followed by the variation in the duration of the vibrations, which is very easy to distinguish, especially in the case of two-handed comparisons. As for the magnitude of the vibration intensity, we believe that the changes in pulse vibration are more noticeable than changes in vibration amplitude. However, the overall slower performance of Pattern 4 compared to Pattern 3 can be attributed to the longer intervals between weak pulses, which may require more time to make a judgment. Jones [28] also pointed out significant individual differences in perceiving changes in frequency. These observations are supported by subjective feedback from participants.

Based on the results and discussion, we select Pattern 2 with the best performance of spatial perception compared with the other three patterns for the follow-up experiment.

5 Experiment Two: Effects of Bimanual Haptic Feedback on Spatial Search

The goal of this experiment is to verify the effectiveness of bimanual haptic feedback on spatial search tasks in VR.

5.1 Participants and Apparatus

We recruited 16 participants (4 female) from the local campus, aged from 22 to 27 (M: 23, SD: 2.6). All of them had experience using VR devices. However, none of them had experience with bimanual haptic feedback in VR. All participants had a normal or corrected-to-normal vision and no hearing or touch-related impairments. Each participant was paid with 5 dollars for this experiment. In addition, the device used for this experiment was consistent with Experiment One.

5.2 Feedback Conditions

This experiment included the following feedback conditions: no feedback, visual arrow, unimanual haptic feedback, and bimanual haptic feedback.

No Feedback There were no additional cues available for spatial search in VR, which was regarded as the baseline.

Visual Arrow We adopted the 3D Arrow AG method proposed by Schmitz et al. [57] as a visual feedback for comparison. This involves a white arrow pointing to the target object that can rotate around all three axes in space and move with the user's head movement, synchronizing with the user's field of view. While many technologies for visual feedback have been proposed, such as Hivefive [33] that uses swarm motion for guidance; methods using attention-diverting objects (like fireflies) for guidance [10, 72]; and techniques using peripheral flickering for guidance [45, 57], the arrow remains the fastest and most widely applied method [33, 53]. Wallgrün 's experiment also showed that the arrow is generally accepted and popular [72]. The focus of this study is on the perception of spatial direction and object search, so for each trial, the arrow does not point to the precise location of the corresponding object, but to the direction of the object, i.e., the shelf where the object is located.

Unimanual Haptic Feedback We implemented the vibration feedback method proposed by Prouzeau et al. [52] as a unimanual haptic condition, which performed excellently in perceiving 3D scatter plot data. In this experiment, we specifically use the haptic vibrators of the VR controller to provide participants with information about the location of the target object. Only the haptic actuator closest to the target object provides vibration feedback, so the user determines the direction of the target by moving the controller. Additionally, the vibration amplitude is linearly modulated according to the angle between the user's viewpoint and the target object. Specifically, the vibration amplitude range is 0.2-1. Therefore, if participants turn towards the direction of the target, the vibration intensity would increase.

Bimanual Haptic Feedback The best scheme (Pattern 2) was selected from the first experiment.

5.3 Task Design

In this study, we followed the existing work to design the spatial search task in VR [17], where we constructed a VR scene containing eight virtual shelves with items on them. The eight shelves were consistent with eight directions predefined as in Experiment One, simulating the real-world scenario of searching for items on cluttered markets or store shelves. The virtual camera was located at the centre of the eight virtual shelves, and a virtual cylinder was used to display the target to be searched. The participants were asked to search for randomly displayed targets with the aid of the assigned feedback condition.

We used a within-subjects experiment design for two reasons. First, the four feedback conditions generally have different forms. Therefore, the difference in learning effect between the feedback conditions should not be as significant as in Experiment One. In addition, the within-subject experiment design enables better subjective feedback from users and eliminates differences between user groups.

5.4 Task Procedure

This task includes a practice phase and a formal experiment. The practice phase was set up in the same way as in Experiment One, participants needed to learn what directions the different bimanual haptic feedback information represented until they felt familiar with all directions. Participants also practiced tasks for the visual feedback and the unimanual haptic feedback so that they could become familiar with the feedback conditions and the experimental task.

During the formal experiment, participants were asked to click the start button in the virtual scene. Then a target object was randomly generated and displayed on the virtual table, and the corresponding feedback information was provided to the participant, indicating the direction and target object they needed to search for. Once the participants located the target object from virtual shelves, they were required to select using ray-casting by pressing the trigger of the controller and confirming it with the button of the controller. Each participant was also instructed to select the target as quickly as possible during the experiment. As participants needed to click the start button to generate the target object, they always started the search task from the same position, providing consistent initial conditions for each trial. In addition, participants could pause between each trial and were forced to pause when the feedback condition changed.

The order of feedback conditions was counterbalanced using a Latin square. Each participant conducted a total of 192 trials: 4 (four types of feedback conditions (no feedback, visual, unimanual haptic, bimanual haptic)) $\times$ 3 (blocks) $\times$ 16 (each block has eight directions $\times$ two repeats), and the positions of the objects in the scene were different in each trial to avoid any learning effects. The entire experiment took an average of 30 minutes.

5.5 Metrics

As dependent variables, we adopted the metrics from existing work [17, 30], to measure the head motion trajectory and task completion time, with user head data collected at a frequency of 50 times per second. Each participant needed to complete the NASA-TLX questionnaire four times with each conducted after finishing each of the four feedback conditions [26].

5.6 Results and Analysis

In Experiment Two, we measured the time of the user's selection and the range of head rotation. According to [30] we defined the movement overhead as the ratio of the actual head rotation angle to the optimal

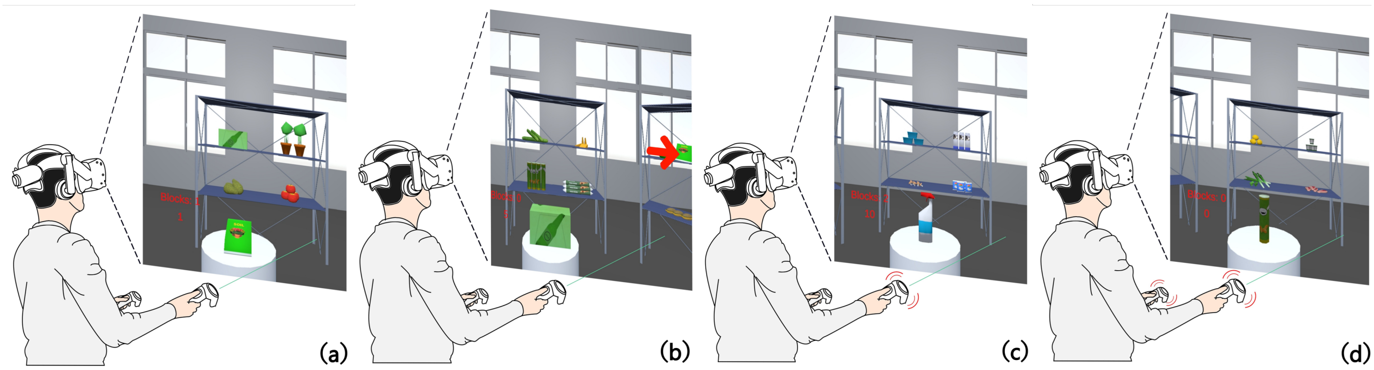


Fig. 6: Feedback conditions in Experiment Two: (a). no additional feedback. (b). visual arrow. (c). unimanual haptic. (d). bimanual haptic. User's viewpoint during the experimental task.

Fig. 7: The overall virtual scene from the viewpoint of the outside of the shelves. It is important to note that the virtual camera is located at the centre during the experiment (see Fig. 6).

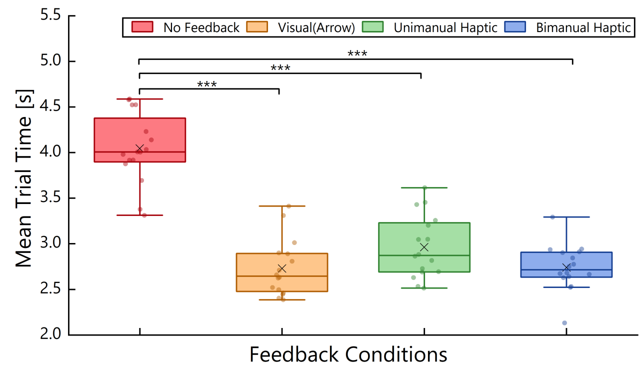


Fig. 8: Boxplots of completion times for all feedback conditions.

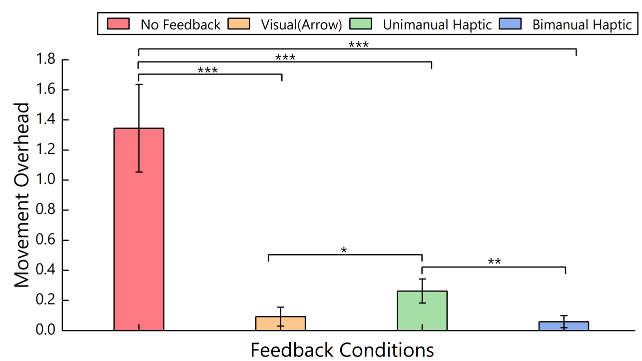


Fig. 9: Bar chart of movement overhead for all feedback conditions. Error bars represent standard deviation.

Table 3: Task completion times and movement overhead for different feedback conditions

Feedback Conditions	Median Trial Time	Mean Trial Time (SD)	Movement Overhead (SD)
No Feedback	3.73	4.04(1.79)	134.46(29.15)
Visual(Arrow)	2.57	2.72(1.00)	9.22(6.27)
Unimanual Haptic	2.82	2.95(0.98)	26.26(8.01)
Bimanual Haptic	2.60	2.73(0.73)	5.90(3.99)

rotation angle minus one. A value of 0% means that the user follows the optimal path exactly, and a value of 100% means that the user's rotation angle is twice as long as the optimal path. Thus, the movement overhead measures how straightforward it is for the user to locate the target. Table 3 and Fig. 8 show the descriptive results.

For selection time and movement overhead, the Shapiro-Wilk method was used to test the normality of the experimental data, and approximately 1% outliers were removed. We performed repeated measures ANOVA on the experimental data with directions and feedback conditions as independent factors and post-hoc tests using the Bonferroni correction. A Mauchly's sphericity test was performed for each condition's tests.

Task Completion Time There was a main effect on selection time for feedback conditions in terms of task completion time ($F_{3,60} = 58.492, p < 0.05, \eta^2 = 0.745$). Post-hoc two-by-two comparisons showed no significant difference between bimanual haptic feedback and visual arrow($p = 1.000$) and unimanual vibration ($p = 0.351$) in terms of overall task completion time, and no significant difference between unimanual vibration and visual arrow ($p = 0.290$).

For each direction, the results showed that there was a correlation between the repeated measures data ($p = 0.001$) and there was a correlation between the directions and the conditions ($F_{21,420} = 11.24, p = 0.000$). The descriptive results for each direction are shown in Table 4 and Fig. 10. In the front, left and right rear directions, bimanual haptic was not significantly different from the visual arrow and unimanual haptic (both $p > 0.05$). In the back direction, unimanual haptic was not significantly different from the visual arrow ($p = 1.000$), and bimanual haptic was significantly different from both the visual arrow ($p = 0.016$) and unimanual haptic ($p = 0.011$). In directions left and right, bimanual haptic was not significantly different from the visual arrow (both $p = 1.000$) and was significantly different from unimanual haptic (Left: $p = 0.006$, Right:$p = 0.027$). In directions Left Front and Right Front, there was no significant difference between bimanual

Table 4: Task completion times for different feedback conditions in eight directions.

Direction	No Feedback	Arrow	Unimanual Haptic	Bimanual Haptic
Front	2.15(1.41)	**1.76(0.57)**	2.09(1.25)	2.05(0.62)
Back	4.70(1.41)	4.04(0.78)	4.03(0.67)	**3.42(0.57)**
Left	4.27(1.59)	2.60(0.58)	2.95(0.64)	**2.37(0.38)**
Right	4.43(1.72)	2.62(0.55)	2.89(0.54)	**2.43(0.50)**
Left Front	3.96(1.96)	**1.99(0.54)**	2.43(0.88)	2.53(0.57)
Right Front	3.99(1.97)	**1.93(0.47)**	2.30(0.51)	2.52(0.49)
Left Rear	4.31(1.36)	3.34(0.62)	3.50(0.67)	**3.31(0.60)**
Right Rear	4.52(1.46)	3.52(0.84)	3.48(0.67)	**3.22(0.64)**

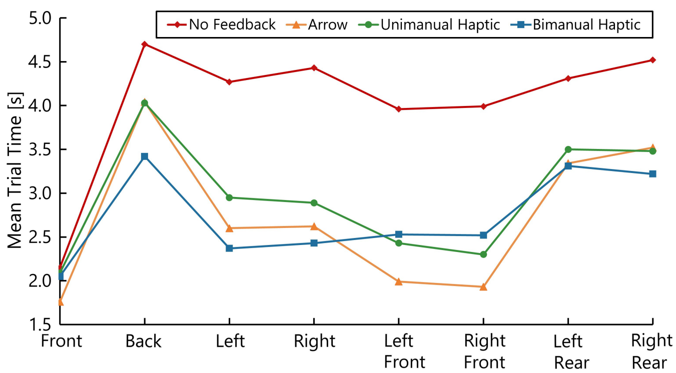


Fig. 10: Task completion times for different feedback conditions in eight directions.

haptic and unimanual haptic (both $p = 1.000$), and bimanual haptic was significantly different from visual arrow (Left Front: $p = 0.048$, Right Front: $p = 0.006$). It can also be seen from Fig. 10 that for selection times, the trends for the three guidance modalities other than no cue were essentially the same for selection times for each direction, and that the selection times were also related to the angle of the object to the initial head.

Movement Overhead A significant main effect was also found for feedback conditions on movement overhead ($F_{3,60} = 245.582, p < 0.05, \eta^2 = 0.925$). Post-hoc comparisons showed no significant difference in bimanual haptic feedback in terms of movement overhead with visual arrow ($p = 1.000$), and significant differences between unimanual haptic and bimanual haptic ($p = 0.003$) and visual arrow ($p = 0.018$).

For each direction, there was a correlation between repeated measures ($p < 0.001$), and there was no significant difference between the directions and the conditions ($F_{21,420} = 1.0540, p = 0.397$). No feedback was significantly different from the other three conditions of guidance in all directions ($p < 0.001$), and there was a significant difference between unimanual and bimanual haptic in the right rear direction ($p = 0.042$).

Subjective Feedback We checked the normality of subjective experimental data and analyzed the effects of feedback conditions on the six dimensions of the NASA-TLX (Table 5). The results showed that there were main effects for feedback conditions on the six dimensions of the NASA-TLX: Mental Demand ($F_{3,60} = 7.382, p < 0.001, \eta^2 = 0.270$), Physical Demand ($F_{3,60} = 5.726, p = 0.002, \eta^2 = 0.223$), Temporal Demand ($F_{3,60} = 6.382, p = 0.001, \eta^2 = 0.242$), Performance ($F_{3,60} = 6.238, p = 0.001, \eta^2 = 0.2338$), Effort ($F_{3,60} = 4.927, p = 0.004$, $eta^2 = 0.1198$), Frustration ($F_{3,60} = 6.352, p = 0.001, \eta^2 = 0.241$).

We further conducted post hoc comparisons. There was a significant difference ($p < 0.05$) on Mental Demand between all conditions except for no feedback vs. unimanual haptic ($p = 0.478$) and bimanual haptic vs. unimanual haptic ($p = 0.095$). A significant difference was found on Physical Demand between no feedback and all other conditions($p < 0.05$). There was no significant difference on Temporal Demand between bimanual haptic and visual arrow ($p = 0.816$) and unimanual haptic($p = 0.19$), and no significant differences ($p > 0.05$) between the other conditions. As expected, there was a significant difference on Performance between bimanual haptic and no feedback ($p = 0.026$), and between visual arrow and no feedback ($p < 0.01$) and unimanual haptic($p = 0.003$). In terms of Effort, no significant difference was found between bimanual haptic and visual arrow ($p = 0.002$), but significant differences existed between visual arrows and no feedback ($p < 0.01$) and unimanual haptic($p = 0.003$). There was a significant difference in Frustration between bimanual haptic and no feedback ($p = 0.002$), and between visual arrow and no feedback ($p < 0.001$) and unimanual haptic($p = 0.014$).

The vast majority of participants indicated that the visual arrow remained the most intuitive way to guide and locate the target and that the most striking advantage of the visual arrow was its simplicity, clarity, and intuition, which made it very easy to understand and use. However, participants also indicated that the use of bimanual haptic feedback would dramatically reduce searching and localisation time if used proficiently, especially for objects located at the back of them. This bimanual haptic feedback provided more direct and accurate information, allowing them to locate the target faster. However, for unimanual haptic feedback, participants indicated that they needed to go through the virtual space to perceive and distinguish the strongest vibration sensation.

5.7 Discussion

Our experimental findings demonstrate that the bimanual haptic feedback achieved comparable performance to that of the visual arrow and outperforms it in terms of movement overhead. This is due to the fact that participants were able to directly determine the corresponding direction, rather than having to follow the arrow to turn in the corresponding direction.

In addition, we compared the visual arrow method and the bimanual haptic method from the following two aspects. First, the visual arrow requires the user to follow them to update the view [33, 53, 72]. For the targets located in the field of view (the three front locations), the visual arrow can provide direct guides to participants. This may lead to a faster performance than the bimanual haptic feedback, which requires participants to recognize and process the pattern to identify the spatial direction. Second, as the bimanual haptic feedback can provide the initial direction for turning, it could be faster to search the targets located at the back than the visual arrow, which requires participants to follow it to rotate to the back. This result is supported by subjective feedback.

Regarding the unimanual haptic feedback, its mechanism dictates that it requires the user to keep rotating. The vibration intensity gradually decreases after surpassing the direction with the strongest vibration, which enables the participant to distinguish the direction of the strongest vibration. This was the reason for the relatively high movement overhead under the unimanual haptic feedback condition, and this is also supported by the results of subjective evaluation.

As expected, no feedback condition performed the worst in task completion time and movement overhead. This result was anticipated as the participant lacks knowledge of the precise direction of the target object and can only rely on visual search. Consequently, the participants tended to rotate around for a considerable time before successfully locating the target during visual search, which is also the reason for the high value of movement overhead in this condition.

6 General Discussion

Based on the results of Experiments One and Two, we summarize the following conclusions. First, results revealed the cognitive mechanism and preference characteristics of people's vibration feedback, which was consistent with the study of [28], and provided a basis and guidance for the design of vibration feedback that better meets people's needs, as well as a valuable reference for designing bimanual haptic feedback.

Table 5: NASA-TLX ratings for all techniques (values range from 0 (very low) to 10 (very high)).

Feedback Conditions	**Mental Demand Mean (SD)**	**Physical Demand Mean (SD)**	**Temporal Demand Mean (SD)**	**Performance Mean (SD)**	**Effort Mean (SD)**	**Frustration Mean (SD)**
No Feedback	3.13(2.53)	6.69(2.85)	6.69(2.94)	6.75(1.88)	6.38(2.68)	4.56(2.37)
Visual(Arrow)	1.56(0.72)	3.31(1.49)	3.56(1.50)	9.00(0.97)	3.44(1.86)	2.00(0.97)
Unimanual Haptic	3.63(1.78)	5.13(2.31)	4.81(2.07)	7.31(1.62)	5.38(2.34)	3.63(1.89)
Bimanual Haptic	4.81(2.38)	4.50(2.16)	3.75(2.32)	8.00(1.59)	6.25(2.79)	2.50(1.79)

Second, compared with previous work such as HapticHead [30], Tactileglove [25] and GuideBand [66], the biggest advantage of using bimanual haptic feedback for orientation is that it does not require users to purchase or build complex external devices, but only requires the use of on-shelf VR controllers. The overall performance of the proposed technique is roughly as good as that of visual arrow [33, 45, 57, 72], indicating the general usefulness of the proposed scheme. Note that for visual feedback, due to lighting conditions, visual overload or visual obstacles, visual feedback may not be ideal or usable in many applications [30]. In addition, since the data in each direction shows that we have better performance for the direction behind us than for visual feedback, we also believe that the bimanual haptic feedback can be used in combination with other types of feedback to form a multimodal feedback approach to further enhance the user's spatial perception and navigation efficiency in VR.

In addition, visual search is essential for spatial search tasks and has two main ways to perform [72]. One is to follow a guide (i.e., visual, auditory, haptic) to locate a target [12, 30, 53] and the other is to decode a guide pattern to identify the target location [59]. For example, researchers compared the performance of a visual arrow and a radar for spatial search [72]. Some participants applied the first way to search for a target with the visual arrow, while others adopted the second way by using the radar to directly indicate the exact target position. Based on previous studies, in Experiment Two, we also adopted the two ways: visual arrow and unimanual haptic methods were designed based on the first way, and bimanual haptic feedback followed the second way.

Our method also carries the drawback of requiring learning efforts and mental loads, as indicated by user feedback and NASA-TLX scores 5. However, the participants also reported that bimanual haptic feedback does reduce time if they become proficient in using it, particularly regarding the directions behind them. Despite the learning curve associated with our technique, once users have adapted and mastered it, they can perform tasks more efficiently. This indicates that bimanual haptic feedback can serve as an effective tool for fast and precise spatial search.

6.1 Design Implication

Based on the results of two experiments, we derive some design implications as follows. First, the results in Experiment One show that Pattern 2 outperformed the other vibration patterns. To design effective and user-friendly vibration feedback for spatial navigation in VR, we should primarily consider Pattern 2 and use it as the first option for bimanual haptic design for VR controllers.

Second, the results of Experiment Two indicate that bimanual haptic feedback performed comparably to the visual arrow. Additionally, the use of bimanual haptic feedback for searching targets located at the back side yielded better performance than that with the visual arrow. The result can guide the design of VR game applications. For example, for first-person shooter VR games, spatial guidance can be offered through bimanual haptic feedback, thus providing more information to improve user experience. In addition, the bimanual haptic feedback could also be applied to VR assembly tasks, which may further reduce the time required to locate necessary parts surrounding the user.

6.2 Limitation and Future Work

We list the following limitations and future work. First, we used Unity's included spatial audio system, which uses g-HRTF, in line with the existing studies [12, 30]. However, the use of the p-HRTF system can be personalised to the characteristics of an individual's ear and thus more accurately mimic the real hearing effect [24, 39, 77], potentially improving the performance considerably. In future, we will compare the bimanual haptic feedback proposed in this study to that spatial audio using the p-HRTF.

Second, although male participants were the majority in this work, gender did not have a significant effect on the experiment results. Both groups showed an average selection time of 2.72s (SD = 0.73) for males and 2.78s (SD = 0.72) for females. There was no significant difference in selection time for bimanual haptic feedback between male and female participants (p = 0.234). However, we acknowledge the importance of gender balance in ensuring the fairness and reliability of the study and will balance the participants in future related studies.

Third, we will aim to distinguish more precisely between the two phases by improving experimental tasks in future. This could allow for a better assessment of the performance of bimanual haptic feedback. In our experiment, it was difficult to distinguish the time for searching a specific sector and finding the target in the sector. Nonetheless, the time for the latter phase would be similar across feedback types given that the target location was identical in the sector for a trial. So the total time should be able to reflect the time for the visual search phase. In future work, we will investigate a better assessment of the search phase of bimanual haptic feedback.

Last, to evaluate the performance of feedback types, the primary task participants needed to perform was spatial search. This is a common experiment setting and has been employed in previous studies [12, 30, 53]. We did not include other tasks during the spatial search procedure, as using other tasks could complicate our experiment design and may contaminate experiment results given that another task-related factor is involved in the experiment. However, it is still of interest to explore the performance of bimanual haptic feedback with both spatial search and other applied tasks. For example, the use of bimanual haptic feedback could enable users to control or move their hands in a primary task such as grabbing or manipulating an object to a location. Users need to learn and memorize the patterns for spatial directions and rely on the bimanual haptic feedback to assist the primary task.

7 Conclusion

We proposed and studied four types of bimanual haptic feedback with different combinations of vibration properties for spatial orientations in VR. We carried out two experiments to evaluate their effectiveness on a spatial search task in VR. The results of the first experiment indicated that bimanual haptic feedback achieves significant improvements in accuracy and speed compared to spatial auditory feedback. The second experiment explored the effectiveness of the optimal bimanual haptic feedback selected from experiment One on spatial search tasks in VR. The findings of the second experiment showed that bimanual haptic feedback performed comparably as the visual arrow, and even performed better in directions behind the user. The results suggest that the proposed bimanual haptic feedback can be used as a supplementary or alternative to visual feedback, providing a more reliable and intuitive spatial search in VR applications, such as VR games and VR education.

Acknowledgments

We thank the participants who volunteered their time, and the reviewers whose insightful comments and suggestions helped improve our paper. This work was supported in part by National Key R&D Program of China (2022YFC3303604) and in part by NSFC (62372212).

REFERENCES

[1] M. Azadi and L. A. Jones. Evaluating vibrotactile dimensions for the design of tactons. *IEEE Transactions on Haptics*, 7(1):14–23, 2014.

[2] P. Bala, R. Masu, V. Nisi, and N. Nunes. " when the elephant trumps" a comparative study on spatial audio for orientation in 360º videos. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–13, 2019.

[3] K. Bark, J. W. Wheeler, S. Premakumar, and M. R. Cutkosky. Comparison of skin stretch and vibrotactile stimulation for feedback of proprioceptive information. In *2008 Symposium on haptic interfaces for virtual environment and teleoperator systems*, pp. 71–78. IEEE, 2008.

[4] D. Beattie, L. Baillie, M. Halvey, and R. McCall. What's around the corner? enhancing driver awareness in autonomous vehicles via in-vehicle spatial auditory displays. In *Proceedings of the 8th nordic conference on human-computer interaction: fun, fast, foundational*, pp. 189–198, 2014.

[5] D. Bial, D. Kern, F. Alt, and A. Schmidt. Enhancing outdoor navigation systems through vibrotactile feedback. In *CHI'11 Extended Abstracts on Human Factors in Computing Systems*, pp. 1273–1278. 2011.

[6] N. Binetti, L. Wu, S. Chen, E. Kruijff, S. Julier, and D. P. Brumby. Using visual and auditory cues to locate out-of-view objects in head-mounted augmented reality. *Displays*, 69:102032, 2021.

[7] S. Boll, A. Asif, and W. Heuten. Feel your route: A tactile display for car navigation. *IEEE Pervasive Computing*, 10(3):35–42, 2011.

[8] F. Bork, C. Schnelzer, U. Eck, and N. Navab. Towards efficient visual guidance in limited field-of-view head-mounted displays. *IEEE Transactions on Visualization and Computer Graphics*, 24(11):2983–2992, 2018.

[9] S. Boukhris and B.-A. J. Menelas. Towards the use of a serious game to learn to identify the location of a 3d sound in the virtual environment. In *Human-Computer Interaction. Interaction Contexts: 19th International Conference, HCI International 2017, Vancouver, BC, Canada, July 9-14, 2017, Proceedings, Part II 19*, pp. 35–44. Springer, 2017.

[10] C. Brown, G. Bhutra, M. Suhail, Q. Xu, and E. D. Ragan. Coordinating attention and cooperation in multi-user virtual reality narratives. In *2017 IEEE Virtual Reality (VR)*, pp. 377–378. IEEE, 2017.

[11] H.-Y. Chang, W.-J. Tseng, C.-E. Tsai, H.-Y. Chen, R. L. Peiris, and L. Chan. Facepush: Introducing normal force on face with head-mounted displays. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, pp. 927–935, 2018.

[12] T. Chen, Y.-S. Wu, and K. Zhu. Investigating different modalities of directional cues for multi-task visual-searching scenario in virtual reality. In *Proceedings of the 24th ACM symposium on virtual reality software and technology*, pp. 1–5, 2018.

[13] S. Choi and K. J. Kuchenbecker. Vibrotactile display: Perception, technology, and applications. *Proceedings of the IEEE*, 101(9):2093–2104, 2012.

[14] A. Cosgun, E. A. Sisbot, and H. I. Christensen. Guidance for human navigation using a vibro-tactile belt interface and robot-like motion planning. In *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 6350–6355. IEEE, 2014.

[15] V. A. de J. Oliveira and A. Maciel. Assessment of tactile languages as navigation aid in 3d environments. In *Haptics: Neuroscience, Devices, Modeling, and Applications: 9th International Conference, EuroHaptics 2014, Versailles, France, June 24-26, 2014, Proceedings, Part II 9*, pp. 104–111. Springer, 2014.

[16] V. A. de J. Oliveira and A. Maciel. Introducing the modifier tactile pattern for vibrotactile communication. In *Haptics: Neuroscience, Devices, Modeling, and Applications: 9th International Conference, EuroHaptics 2014, Versailles, France, June 24-26, 2014, Proceedings, Part I 9*, pp. 309–316. Springer, 2014.

[17] V. A. de Jesus Oliveira, L. Brayda, L. Nedel, and A. Maciel. Designing a vibrotactile head-mounted display for spatial awareness in 3d spaces. *IEEE Transactions on Visualization and Computer Graphics*, 23(4):1409–1417, 2017.

[18] H. Elsayed, M. Weigel, J. Semsch, M. Mühlhäuser, and M. Schmitz. Tactile vectors for omnidirectional arm guidance. In *Proceedings of the Augmented Humans International Conference 2023*, pp. 35–45, 2023.

[19] J. B. V. Erp, H. A. V. Veen, C. Jansen, and T. Dobbins. Waypoint navigation with a vibrotactile waist belt. *ACM Transactions on Applied Perception (TAP)*, 2(2):106–117, 2005.

[20] B. Gao, Z. Chen, X. Chen, H. Tu, and F. Huang. The effects of audiovisual landmarks on spatial learning and recalling for image browsing interface in virtual environments. *Journal of Systems Architecture*, 117:102096, 2021.

[21] B. Gao, B. Kim, J.-I. Kim, and H. Kim. Amphitheater layout with egocentric distance-based item sizing and landmarks for browsing in virtual reality. *International Journal of Human–Computer Interaction*, 35(10):831–845, 2019.

[22] B. Gao, H. Kim, B. Kim, and J.-I. Kim. Artificial landmarks to facilitate spatial learning and recalling for curved visual wall layout in virtual reality. In *2018 IEEE International Conference on Big Data and Smart Computing (BigComp)*, pp. 475–482. IEEE, 2018.

[23] G. García-Valle, M. Ferre, J. Breñosa, R. Aracil, J. M. Sebastian, and C. Giachritsis. Design and development of a multimodal vest for virtual immersion and guidance. In *Haptics: Perception, Devices, Control, and Applications: 10th International Conference, EuroHaptics 2016, London, UK, July 4-7, 2016, Proceedings, Part II 10*, pp. 251–262. Springer, 2016.

[24] M. Geronazzo, A. Bedin, L. Brayda, C. Campus, and F. Avanzini. Interactive spatial sonification for non-visual exploration of virtual maps. *International Journal of Human-Computer Studies*, 85:4–15, 2016.

[25] S. Günther, F. Müller, M. Funk, J. Kirchner, N. Dezfuli, and M. Mühlhäuser. Tactileglove: Assistive spatial guidance in 3d space through vibrotactile navigation. In *Proceedings of the 11th pervasive technologies related to assistive environments conference*, pp. 273–280, 2018.

[26] S. G. Hart and L. E. Staveland. Development of nasa-tlx (task load index): Results of empirical and theoretical research. In *Advances in psychology*, vol. 52, pp. 139–183. Elsevier, 1988.

[27] T. Hulin, K. Hertkorn, P. Kremer, S. Schätzle, J. Artigas, M. Sagardia, F. Zacharias, and C. Preusche. The dlr bimanual haptic device with optimized workspace. In *2011 IEEE International Conference on Robotics and Automation*, pp. 3441–3442. IEEE, 2011.

[28] L. A. Jones and N. B. Sarter. Tactile displays: Guidance for their design and application. *Human factors*, 50(1):90–111, 2008.

[29] O. B. Kaul, K. Meier, and M. Rohs. Increasing presence in virtual reality with a vibrotactile grid around the head. In *Human-Computer Interaction–INTERACT 2017: 16th IFIP TC 13 International Conference, Mumbai, India, September 25-29, 2017, Proceedings, Part IV 16*, pp. 289–298. Springer, 2017.

[30] O. B. Kaul and M. Rohs. Haptichead: A spherical vibrotactile grid around the head for 3d guidance in virtual and augmented reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 3729–3740, 2017.

[31] F. Kiss, R. Boldt, B. Pfleging, and S. Schneegass. Navigation systems for motorcyclists: exploring wearable tactile feedback for route guidance in the real world. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pp. 1–7, 2018.

[32] A. Kron, G. Schmidt, B. Petzold, M. I. Zah, P. Hinterseer, and E. Steinbach. Disposal of explosive ordnances by use of a bimanual haptic telepresence system. In *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA'04. 2004*, vol. 2, pp. 1968–1973. IEEE, 2004.

[33] D. Lange, T. C. Stratmann, U. Gruenefeld, and S. Boll. Hivefive: Immersion preserving attention guidance in virtual reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–13, 2020.

[34] R. W. Lindeman, J. L. Sibert, E. Mendez-Mendez, S. Patil, and D. Phifer. Effectiveness of directional vibrotactile cuing on a building-clearing task. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pp. 271–280, 2005.

[35] R. W. Lindeman, Y. Yanagida, H. Noma, and K. Hosaka. Wearable vibrotactile systems for virtual contact and information display. *Virtual Reality*, 9:203–213, 2006.

[36] A. Marquardt, C. Trepkowski, T. D. Eibich, J. Maiero, E. Kruijff, and J. Schöning. Comparing non-visual and visual guidance methods for narrow field of view augmented reality displays. *IEEE Transactions on Visualization and Computer Graphics*, 26(12):3389–3401, 2020.

[37] A. Meier, D. J. Matthies, B. Urban, and R. Wettach. Exploring vibrotactile feedback on the body and foot for the purpose of pedestrian navigation. In *Proceedings of the 2nd international Workshop on Sensor-based Activity Recognition and Interaction*, pp. 1–11, 2015.

[38] L. Meli, C. Pacchierotti, and D. Prattichizzo. Sensory subtraction in robot-assisted surgery: fingertip skin deformation feedback to ensure safety and improve transparency in bimanual haptic interaction. *IEEE Transactions on Biomedical Engineering*, 61(4):1318–1327, 2014.

[39] A. Meshram, R. Mehra, H. Yang, E. Dunn, J.-M. Franm, and D. Manocha. P-hrtf: Efficient personalized hrtf computation for high-fidelity spatial

sound. In *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 53–61. IEEE, 2014.

[40] V. V. Meshram, K. Patil, V. A. Meshram, and F. C. Shu. An astute assistive device for mobility and object recognition for visually impaired people. *IEEE Transactions on Human-Machine Systems*, 49(5):449–460, 2019.

[41] K. Minamizawa, S. Kamuro, N. Kawakami, and S. Tachi. A palm-worn haptic display for bimanual operations in virtual environments. In *Haptics: Perception, Devices and Scenarios: 6th International Conference, EuroHaptics 2008 Madrid, Spain, June 10-13, 2008 Proceedings 6*, pp. 458–463. Springer, 2008.

[42] M. Mirzaei, P. Kán, and H. Kaufmann. Effects of using vibrotactile feedback on sound localization by deaf and hard-of-hearing people in virtual environments. *Electronics*, 10(22):2794, 2021.

[43] M. Morioka and M. J. Griffin. Magnitude-dependence of equivalent comfort contours for fore-and-aft, lateral and vertical hand-transmitted vibration. *Journal of sound and vibration*, 295(3-5):633–648, 2006.

[44] J. Murayama, L. Bougrila, Y. Luo, K. Akahane, S. Hasegawa, B. Hirsbrunner, and M. Sato. Spidar g&g: a two-handed haptic interface for bimanual vr interaction. In *Proceedings of EuroHaptics*, vol. 2004, pp. 138–146, 2004.

[45] E. Nonino, J. Gisler, V. Holzwarth, C. Hirt, and A. Kunz. Subtle attention guidance for real walking in virtual environments. In *2021 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pp. 310–315. IEEE, 2021.

[46] T. Nukarinen, J. Rantala, A. Farooq, and R. Raisamo. Delivering directional haptic cues through eyeglasses and a seat. In *2015 IEEE World Haptics Conference (WHC)*, pp. 345–350. IEEE, 2015.

[47] S. Paneels, M. Anastassova, S. Strachan, S. P. Van, S. Sivacoumarane, and C. Bolzmacher. What's around me? multi-actuator haptic feedback on the wrist. In *2013 World Haptics Conference (WHC)*, pp. 407–412. IEEE, 2013.

[48] A. Peer and M. Buss. A new admittance-type haptic interface for bimanual manipulations. *IEEE/ASME Transactions on Mechatronics*, 13(4):416–428, 2008.

[49] R. L. Peiris, Y.-L. Feng, L. Chan, and K. Minamizawa. Thermalbracelet: Exploring thermal haptic feedback around the wrist. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–11, 2019.

[50] J. S. Pierce, A. S. Forsberg, M. J. Conway, S. Hong, R. C. Zeleznik, and M. R. Mine. Image plane interaction techniques in 3d immersive environments. In *Proceedings of the 1997 symposium on Interactive 3D graphics*, pp. 39–ff, 1997.

[51] M. A. Plaisier and M. O. Ernst. Two hands perceive better than one. In *Haptics: Perception, Devices, Mobility, and Communication: International Conference, EuroHaptics 2012, Tampere, Finland, June 13-15, 2012 Proceedings, Part II*, pp. 127–132. Springer, 2012.

[52] A. Prouzeau, M. Cordeil, C. Robin, B. Ens, B. H. Thomas, and T. Dwyer. Scaptics and highlight-planes: Immersive interaction techniques for finding occluded features in 3d scatterplots. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–12, 2019.

[53] P. Renner and T. Pfeiffer. Attention guiding techniques using peripheral vision and eye tracking for feedback in augmented-reality-based assistance systems. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 186–194. IEEE, 2017.

[54] H. Ro, S. Chae, I. Kim, J. Byun, Y. Yang, Y. Park, and T. Han. A dynamic depth-variable ray-casting interface for object manipulation in ar environments. In *2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pp. 2873–2878. IEEE, 2017.

[55] S. Rothe, H. Hußmann, and M. Allary. Diegetic cues for guiding the viewer in cinematic virtual reality. In *Proceedings of the 23rd ACM symposium on virtual reality software and technology*, pp. 1–2, 2017.

[56] N. Ryu, H.-Y. Jo, M. Pahud, M. Sinclair, and A. Bianchi. Gamesbond: Bimanual haptic illusion of physically connected objects for immersive vr using grip deformation. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–10, 2021.

[57] A. Schmitz, A. MacQuarrie, S. Julier, N. Binetti, and A. Steed. Directing versus attracting attention: Exploring the effectiveness of central and peripheral cues in panoramic videos. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 63–72. IEEE, 2020.

[58] C. Sherrick. Vibrotactile pattern perception: Some findings and applications. *The psychology of touch*, pp. 189–218, 1991.

[59] A. L. Simeone. The vr motion tracker: visualising movement of non-participants in desktop virtual reality experiences. In *2016 IEEE 2nd Workshop on Everyday Virtual Reality (WEVR)*, pp. 1–4. IEEE, 2016.

[60] Q. Song, N. Yao, Z. Feng, H. Chen, and H. Wang. Combining spatial and non-spatial sonification for sound localization in virtual environment: a subjective study. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts*, pp. 1–7, 2022.

[61] E. Strasnick, C. Holz, E. Ofek, M. Sinclair, and H. Benko. Haptic links: Bimanual haptics for virtual reality using variable stiffness actuation. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pp. 1–12, 2018.

[62] A. Talvas, M. Marchal, and A. Lecuyer. A survey on bimanual haptic interaction. *IEEE Transactions on Haptics*, 7(3):285–300, 2014.

[63] H. Tan, R. Gray, J. J. Young, and R. Taylor. A haptic back display for attentional and directional cueing. 2003.

[64] H. Z. Tan, C. M. Reed, and N. I. Durlach. Optimum information transfer rates for communication through haptic and other sensory modalities. *IEEE Transactions on Haptics*, 3(2):98–108, 2009.

[65] D. Ternes and K. E. MacLean. Designing large sets of haptic icons with rhythm. In *Haptics: Perception, Devices and Scenarios: 6th International Conference, EuroHaptics 2008 Madrid, Spain, June 10-13, 2008 Proceedings 6*, pp. 199–208. Springer, 2008.

[66] H.-R. Tsai, Y.-C. Chang, T.-Y. Wei, C.-A. Tsao, X. C.-y. Koo, H.-C. Wang, and B.-Y. Chen. Guideband: Intuitive 3d multilevel force guidance on a wristband in virtual reality. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–13, 2021.

[67] L. Turchet, P. Burelli, and S. Serafin. Haptic feedback for enhancing realism of walking simulations. *IEEE Transactions on Haptics*, 6(1):35–45, 2012.

[68] Unity. Xr interaction toolkit. docs.unity3d.com/2020.3/Documentation/Manual/com.unity.xr.interaction.toolkit.html.

[69] J. B. van Erp. *Tactile displays for navigation and orientation: perception and behaviour*. Utrecht University, 2007.

[70] R. Velázquez, E. Pissaloux, P. Rodrigo, M. Carrasco, N. I. Giannoccaro, and A. Lay-Ekuakille. An outdoor navigation system for blind pedestrians using gps and tactile-foot feedback. *Applied Sciences*, 8(4):578, 2018.

[71] U. Wagner, M. N. Lystbæk, P. Manakhov, J. E. S. Grønbæk, K. Pfeuffer, and H. Gellersen. A fitts' law study of gaze-hand alignment for selection in 3d user interfaces. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, pp. 1–15, 2023.

[72] J. O. Wallgrün, M. M. Bagher, P. Sajjadi, and A. Klippel. A comparison of visual attention guiding approaches for 360 image-based vr tours. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 83–91. IEEE, 2020.

[73] D. Wang and G. J. Brown. *Computational auditory scene analysis: Principles, algorithms, and applications*. Wiley-IEEE press, 2006.

[74] Y. Wang, Z. Chen, H. Li, Z. Cao, H. Luo, T. Zhang, K. Ou, J. Raiti, C. Yu, S. Patel, et al. Movevr: Enabling multiform force feedback in virtual reality using household cleaning robot. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–12, 2020.

[75] Y. Wang, B. Millet, and J. L. Smith. Designing wearable vibrotactile notifications for information communication. *International Journal of Human-Computer Studies*, 89:24–34, 2016.

[76] T. P. Way and K. E. Barner. Automatic visual to tactile translation. i. human factors, access methods and image manipulation. *IEEE Transactions on Rehabilitation Engineering*, 5(1):81–94, 1997.

[77] E. M. Wenzel, M. Arruda, D. J. Kistler, and F. L. Wightman. Localization using nonindividualized head-related transfer functions. *The Journal of the Acoustical Society of America*, 94(1):111–123, 1993.

[78] F. L. Wightman and D. J. Kistler. Factors affecting the relative salience of sound localization cues. *Binaural and spatial hearing in real and virtual environments*, 1:1–23, 1997.

[79] J. M. Wolfe and T. S. Horowitz. What attributes guide the deployment of visual attention and how do they do it? *Nature reviews neuroscience*, 5(6):495–501, 2004.

[80] W. Xue and C.-H. Lo. Sound-guided framing in cinematic virtual reality–an eye-tracking study. In *International Conference on Human-Computer Interaction*, pp. 520–535. Springer, 2022.

[81] Y. Yamazaki and S. Hasegawa. Providing 3d guidance and improving the music-listening experience in virtual reality shooting games using musical vibrotactile feedback. In *2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*, pp. 276–285. IEEE, 2023.

[82] A. Yoshimura, A. Khokhar, and C. W. Borst. Eye-gaze-triggered visual cues to restore attention in educational vr. In *2019 IEEE Conference on*

Virtual Reality and 3D User Interfaces (VR), pp. 1255–1256. IEEE, 2019.

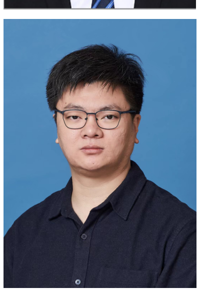
BoYu Gao is currently an associate professor with the College of Cyber Security, Guangdong Institute of Smart Education, at Jinan University, Guangzhou, China. He received his PhD degree and worked as a postdoc researcher both at Konkuk University in Seoul, S. Korea. His research interests include multimodal interaction and the believability in VR. His work has been published in top-tier conferences and journals (e.g., IEEE VR and IEEE TVCG).

Tong Shao is currently a master student at the College of Cyber Security/Information Science and Technology at Jinan University, Guangzhou, China. His research interest includes interaction design and implementation, particularly for the evaluation of haptic feedback interaction in VR.

Huawei Tu is a senior lecturer at La Trobe University in Australia. He received his PhD degree at Kochi University of Technology in Japan and has been a postdoc researcher in Ritsumeikan University of Japan and Swansea University of the U.K. His research focus includes gesture/pen interaction, VR, and UI design. His work has been published in top-tier conferences and journals (e.g., IEEE VR, IEEE TVCG, ACM TOCHI and ACM CHI).

Qizi Ma is currently a master student at the College of Cyber Security/Information Science and Technology at Jinan University, Guangzhou, China. Her research interest includes the human–computer collaboration interaction design and implementation.

Zitao Liu is the Dean of Guangdong Institute of Smart Education, Jinan University, Guangzhou, China. His research is in the area of machine learning and includes contributions in the areas of artificial intelligence in education and educational data mining. His work has been published in top tier conferences and journals (e.g., NeurIPS and CVPR, AAAI).



Teng Han is a researcher at the Institute of Software, University of Chinese Academy of Sciences. He received his PhD degree at the Human-Computer Interaction Laboratory, University of Manitoba, Canada. His research focus includes natural human-computer interaction, tactile perception and flexible tactile interfaces. His work has been published in top tier conferences and journals (e.g., ACM CHI and UIST).