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Enhancing Seamless Walking in Virtual Reality: Application of Bone-Conduction Vibration in Redirected Walking

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Figure 1: Conceptual illustration of the study: Utilizing bone conduction vibrations to enable users to seamlessly navigate without colliding into obstacles, thereby supporting uninterrupted walking.

Abstract

This study explored bone-conduction vibration (BCV) in redirected walking (RDW), a technology for seamless walking in large virtual spaces within confined physical areas, enhancing obstacle avoidance performance using nonelectrical vestibular stimulation without the side effects caused by electrical stimulation. We proposed four different BCV stimulation methods and evaluated their detection threshold (DT) extension performance and user experience in virtual reality (VR) conditions. The DT was successfully expanded from at least 23% to 45% under all BCV conditions while preserving the immersion and presence. Notably, user comfort increased when content sound was used for vestibular stimulation. Under the extended DT condition, a simulation study demonstrated that all BCV stimulation methods facilitated uninterrupted walking over extended distances when applying RDW to users with random movements. Thus, this research established the viability of using BCV in RDW applications and the potential for incorporating content sound into BCV stimulation techniques.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality;

1 Introduction

Walking is a fundamental human action in interaction with spaces. In virtual reality (VR), the experience of walking freely in an infinitely sized virtual space is important for immersive and seamless user experiences [35]. However, technical difficulties arise when users attempt to move in a boundless virtual space within confined, finite real spaces. Redirected walking (RDW) manipulates real-world walking paths, enabling movement in larger virtual spaces [37]. RDW adjusts a user's virtual path, allowing smooth, free movement while avoiding collisions. This is achieved via visual manipulation of the VR environment in response to user movements. For example, when a user walks straight in a virtual environment, RDW can manipulate the real-world path into an arc through visual manipulation that continuously rotates the virtual map. However, when the visual manipulation increases, the RDW reaches its limit of visual-vestibular inconsistency [47]. The modified visual information is inconsistent with other proprioceptive and vestibular senses of the user, which results in increased detection by the user and a reduction in the presence of the simulation, leading to simulation sickness [1, 4]. Thus, RDW has a detection threshold (DT), limiting manipulatable paths and expandable space [2, 19, 21, 22]. In this study, we aim to enhance the obstacle avoidance performance in RDW by extending the DT through the utilization of vestibular noise.

Vestibular noise helps mitigate visual-vestibular inconsistency due to human multisensory integration traits [12, 55]. During inconsistency, vestibular stimulation creates vestibular noise, which reduces vestibular information's relative reliability. This promotes a higher reliance on more reliable visual information, thereby alleviating inconsistency. The alleviation of visual-vestibular inconsistency through vestibular noise has mainly been studied to alleviate simulator sickness [12, 55]. It has been employed successfully in vehicle simulations [39], walking [55], and 360-degree video viewing [27, 36]. Fewer studies exist on using vestibular stimulation to expand the DT range [14, 28]. Matsumoto et al. expanded the DT effectively using noisy galvanic vestibular stimulation (GVS) [28]. However, electrical stimulation carries potential side effects [24, 52] and has safety concerns, particularly for certain groups like pregnant women or those with pacemakers [24]. Also, safety guidelines limit usage time, and user discomfort may arise [52].

Therefore, we propose a bone-conduction vibration (BCV) RDW system employing vestibular noise with BCV to extend users' DT, enhance RDW efficiency and improve obstacle avoidance, without the side effects of electrical stimulation (Fig. 1). Unlike air-conduction vibration (ACV), BCV directly stimulates the cochlear duct and auditory nerve with vibrations, generating sound signals [5, 6, 38]. BCV also stimulates the vestibular labyrinth when applied to the mastoid bone [7]. Prior studies used 200–500 Hz BCV vibrations, which effectively produce vestibular noise but can create constant auditory

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noise leading to perceived annoyance and discomfort [15,17,33,34], especially at constant vibration frequencies above 150 Hz [17,33,34]. Thus, we designed a BCV method using content sounds to replace discomforting noise and extend users' DT. We developed a comfortable and uninterrupted walking-supportive BCV RDW system, and compared the DT extension performance and user experience under each condition. Besides the control **ACV condition** and the **Noise BCV** condition generating continuous 200–500 Hz noise, we designed three additional BCV conditions applying content sounds as vibration stimulation to the mastoid (**Content BCV**, **Content BCV+ACV**, and **4Pole BCV** conditions). The details of each condition are presented in Section 3.1.

We measured the DT for each condition using the DT measurement experiment of Steinicke et al [47]. To understand how each condition affected the virtual environment experience of the user, we measured the discomfort, motion sickness, and presence through surveys. We also analyzed the potential problem of gait instability in vestibular stimulation RDW systems. The decrease in walking stability for VR users is attributed to the visual stimulation of VR thereby increasing their risk of falls and safety threats [13,16,32]. Moreover, vestibular noise impairs gait stability by interfering with vestibular sensation, further emphasizing the significant influence of vestibular stimulation on gait stability [53]. Therefore, we used pressure sensors in the form of insoles to measure the gait instability under each condition and to analyze the effect of our system on gait instability and the risk of falling. Moreover, we performed a comprehensive comparison of the five conditions and conducted a simulation study to investigate how effectively the DT expansion of each condition supports seamless walking in RDW situations. We designed an agent to walk along randomized paths and measured the average distance between each collision to demonstrate the effectiveness of each vestibular stimulation system in supporting seamless VR walking. The research questions for this study are as follows:

- Can each BCV stimulation method successfully expand DT to create a vestibular stimulation RDW system that is free from the side effects of electrical stimulation?
- How does each BCV stimulation method affect the VR user experience and gait stability?
- To what extent can BCV vestibular stimulation support the seamless gait of randomly moving users?

2 Background

2.1 RDW and DT

The exploration of space using natural gait motion in a virtual environment can provide greater immersion than other locomotion techniques [35]. This immersion is a result of the accurate proprioceptive and vestibular sensations that are provided [35]. Nonetheless, employing natural walking movements is restricted by real-world physical limitations, including furniture, columns, and walls, which present safety hazards to VR users. Researchers have proposed the use of RDW to overcome these limitations. RDW is a promising technology for immersive virtual environments that enables users to walk on paths in the real world that differ from those that are perceived in the virtual environment [37]. RDW provides a nonequivalent mapping of the movement in real and virtual environments, which modulates the movement of the user or structure of the virtual environment without the user noticing the modulation.

Redirection gain is a common technique that is used to change the direction of a user. Steinicke et al. [47] divided redirection gain into three types: rotation, translation, and curvature gain. Rotation gain creates a difference between physical and virtual rotations, translation gain modifies virtual movement distances, and curvature gain changes the user's path to a curved trajectory. Curvature gain is an effective manipulation technique for spatial expansion in RDW, particularly in the context of a vestibular stimulation RDW system [28]. In this study, we aimed to verify the efficiency of this system in terms of curvature gain and to explore its application.

RDW technique, using redirection gain, enables seamless navigation in virtual environments, adjusting user movement to avoid obstacles based on the virtual-real environment mismatch. However, this mismatch induces visual-vestibular inconsistency, a discrepancy between distorted visual information in the virtual environment and vestibular information from the real one, causing discomfort, motion sickness, and decreased presence [47]. This inconsistency escalates as the redirection degree increases for broader steering and obstacle avoidance, thus all RDW gains have a limit, the DT. The DT limits user direction change, restricting RDW's obstacle-avoidance ability, leading to ongoing studies measuring and expanding the DT.

The most widely used method for measuring the DT is the two-alternative forced-choice (2AFC) questionnaire proposed by Steinicke et al [47]. Steinicke et al. conducted experiments using this questionnaire, in which random RDW gains were repeatedly applied to participants in an experimental environment to determine whether they could detect the RDW gains. The participants were asked questions such as "Is the physical path bent left or right?" The participants answered by selecting one of two answers. If the participants did not fully detect the change in the applied gain; that is, if the gain was within the DT range, the correct rate would be around 50% on average. Thus, Steinicke et al. established the DT as the threshold where the participants were able to discern between physical and virtual motions within a 75% accuracy range. Additionally, they defined the point at which the participants perceived physical and virtual movements equally (i.e., the point at which the correct rate was 50%) as the point of subjective equality (PSE). In this study, we measured the DT of each BCV RDW system using the DT measurement experiment of Steinicke et al.

2.2 Multisensory Integration

The aim of this study was to extend the DT by reducing the inconsistency between the visual and vestibular information through BCV stimulation. Multisensory integration is a theoretical concept that integrates sensory information in the brain when decisions are made based on multiple senses [46]. The maximum likelihood estimation (MLE) model explains decision-making in multisensory integration by assigning independent weights to each sense [10]. According to the MLE model, the final decision is made based on the relative reliability of each sense. For example, Ernst and Banks provided participants with inconsistent visual and auditory information, and found that the reliability of the tactile information increased as that of the visual information decreased owing to visual noise, as predicted by the MLE model [10].

Several attempts have been made to reduce visual-vestibular inconsistency by decreasing the relative reliability of the vestibular information through vestibular noise based on the MLE model [12,55]. Certain studies based on the MLE model have attempted to resolve these inconsistencies and to extend DT in RDW situations. For example, Matsumoto et al. artificially created vestibular noise by applying 2 mA of bioelectric noise to the vestibular system of a user using noisy GVS [28]. They expected that vestibular noise would reduce visual-vestibular inconsistency and increase the DT, and their results confirmed an expansion effect of approximately 12%–16% on the DT. Therefore, we proposes the use of BCV, which has been demonstrated to produce vestibular noise and reduce visual-vestibular inconsistency effectively, through the MLE model principle of decreasing the relative reliability of the vestibular system to contribute to DT expansion.

2.3 Bone-Conduction Vibration

BCV, along with ACV, is used to stimulate the vestibular system. Research by Colebatch et al. showed that both BCV and ACV can activate vestibular-evoked myogenic potentials (VEMPs), triggering otolithic function [5, 6]. VEMPs show otolithic neural activation due to sound and vibration, with BCV requiring less intensity than ACV for stimulation. Vibration and sound lead to fluid displacement in the vestibular labyrinth, influencing vestibular information [8]. Vibration frequency significantly impacts vestibular stimulation and vestibular receptor hair bias cycle [7]. BCV in the 200–500 Hz range generates the highest potentials [42, 43, 50]. However, individual skull and vestibular labyrinth variations call for BCV stimulation intensity adjustment [9, 38].

Numerous studies affirm BCV's efficacy in disrupting the vestibular system and altering vestibular information [39, 55]. As a safer alternative to GVS, BCV has fewer side effects [48]. While GVS uses electrical stimulation on the mastoid, impacting vestibular information [51], it can cause side effects in some healthy individuals. These side effects include skin discomfort, vertigo, eyestrain, blurred vision, and concentration difficulties. Additionally, it is not recommended for certain groups, such as those with pacemakers or pregnant women [24, 52]. BCV can lower the vestibular system's relative reliability in the MLE model of multisensory integration, thus reducing motion sickness by mitigating visual-vestibular inconsistency. Extensive research shows BCV's potential to reduce motion sickness in VR and vehicles [39, 55], often combined with unique haptic stimulation [27, 36]. Based on these principles, BCV can be used as a safe and efficient method for expanding the DT.

Furthermore, BCV can convey sound to users through skull vibration. The vibrations produced by BCV impact all skull bones and travel through the jaw, cartilage, and connective tissue, generating sound in the external auditory canal [49, 54]. The sound characteristics of BCV vary based on the attachment location [29–31, 45]. Previous studies show that users can distinguish even faint sounds when a vibrator is attached to the condyle [29–31, 45]. Despite being a lightweight and unobtrusive sound device, BCV has drawbacks compared to ACV, like a lower perceived volume, about 40 dB less [30]. Given the limitations of BCV in discerning subtle auditory variations, we have designed two additional stimulation conditions. Firstly, we introduced the **Content BCV+ACV** condition, which incorporates ACV to enhance the delivery of more distinct content sound. Secondly, we proposed the **4Pole BCV** condition, designed to provide an identical auditory signal at the condyle, the point of lowest auditory threshold.

2.4 Gait Stability

Gait stability refers to the ability of an individual to walk without falling when subjected to disturbances during movement [3]. Previous studies demonstrated that the use of VR and RDW can decrease the gait stability, which may be particularly hazardous for users who wear an HMD and cannot perceive their surroundings [13, 16, 32]. Moreover, the BCV device applies vestibular noise stimulation to the vestibular organ, which can further affect the gait stability [53]. Therefore, we evaluated the safety of the system by measuring the gait stability in our experiment, as the BCV RDW system potentially increases the gait instability of the user.

We measured the changes in gait stability using an insole sensor to measure the plantar pressure. Insole sensors are commonly used in gait studies because they do not interfere with the gait of the participant [44]. We used the anterior/posterior (A/P) gait stability method, which measures the gait instability by assessing the center of pressure (CoP) movement based on the plantar pressure [23]. If the gait of a walker is stable, the CoP moves from heel to toe; that is, posterior to anterior. However, if the gait is unstable, CoP movement in the opposite direction is observed. Therefore, the gait instability can be calculated by dividing the number of CoP frames that move anterior to posterior during a stride by the total number of stride frames [23]. Thus, this study aimed to evaluate the stability of the BCV RDW system by recording the CoP points in real time using an insole pressure sensor, and assessing the gait instability of each condition based on the CoP movement.

3 Implementation

3.1 BCV Stimulus Condition Design

For this experiment, we designed five conditions and compared them with respect to the DT and user experience. In this section, we describe the design of each condition in detail.

- **ACV** condition: We standardized the volume of ACV to 60 dB in this experiment as a control for differences in the user experience depending on the volume. We used the speaker module of the Oculus Quest 2, which we assumed is a common situation for users.

- **Noise BCV** condition (abbreviated as **Noise**): This method, commonly used in previous BCV vestibular stimulation studies [39, 55], applies a constant 500 Hz vibration to the user's mastoid to induce vestibular noise. The mastoid receives vibrations at a specific frequency of 500Hz, while the Oculus internal speaker plays content sounds. We selected a vibration intensity that was the most substantial level possible without causing discomfort to the user, which is consistent with previous studies [39, 55]. We standardized the volume of the content sound from the speaker of the Oculus Quest 2 to 60 dB.

- **Content BCV** condition (abbreviated as **Content**): In this condition, content sounds are played through vibration on the mastoid. A personalization was conducted before the experiment to ensure that the user perceived the sound volume that was played through the mastoid bone as 60 dB.

- **Content BCV+ACV** condition (abbreviated as **Con+ACV**): In this condition, content sounds are played through vibration on the mastoid of the user while ACV is simultaneously used to play content sounds. The relative volume of the sound through the mastoid and air conduction is matched through personalization. Subsequently, the user-perceived volume was set to 60 dB when playing on both devices simultaneously.

- **4Pole BCV** condition (abbreviated as **4Pole**): The condyle of the user, which is often used to clarify sound in a playback device that uses BCV, vibrates along with the sound of the content, while the mastoid is concurrently vibrated for vestibular stimulation in this condition. This design was based on previous studies that have shown that sound that is transmitted through BCV on the condyle is the clearest [29–31, 45]. The relative volume of the sound that was played through the condyle and mastoid was matched, following which the perceived volume of the users was personalized to 60 dB when playing on both devices simultaneously.

3.2 BCV Device

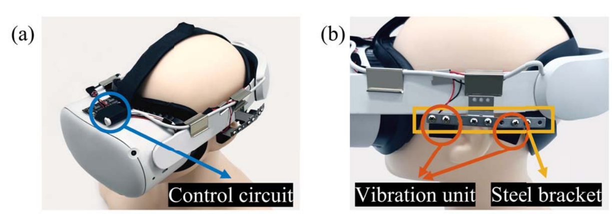


Figure 2: Appearance of the custom device created for this experiment, showcasing the (a) control circuit, (b) vibrator, and an adjustable elastic steel bracket designed to fit the participant's head comfortably.

Our study designed a device for applying five distinct conditions to users (Fig. 2). We employed the Oculus Quest 2 as the HMD, which by default, provided ACV playback through its speakers. We used Adafruit's bone conductor transducer module for the BCV modules, weighing 9.6 g, with a 1 W output and 8 Ω impedance. The module's frequency range was 300 Hz–19 kHz, covering most audible frequencies and allowing for 500 Hz vestibular stimulation vibration and content sound. The four transducers were designed to fix onto each user's mastoid and condyle for vibration delivery. To account for variations in mastoid and condyle positions, we made transducers adjustable to fit each participant. Our device secured each transducer on an adjustable elastic steel bracket that accommodated different head shapes.

The four transducers were linked to a Bluetooth audio amplifier module atop the Oculus Quest 2. This module independently supplied each transducer with a maximum output of 5 W, powered by the Oculus Quest 2's Lipo battery. The circuit connected to the mastoid and condyle could independently power and control each position's vibration stimulation as per the conditions. This allowed for the adjustment of individual stimulation intensities. Consequently, our device could independently regulate the volume of the ACV speaker, mastoid transducer, and condyle transducer, which was essential for personalizing the volume size for each participant [9, 38].

3.3 Gait Stability Analysis

We measured the A/P gait instability using the plantar pressure to investigate the effects of vestibular stimulation on the gait instability and fall risk. Real-time plantar pressure measurements were conducted using an OpenGo pressure sensor from Moticon. The OpenGo pressure sensor is widely used in various experiments related to gait stability measurement. It has 16 pressure sensors located on each foot, covering 65% of the total foot area, with a 50 Hz sampling rate, a 0-50 N/cm2 measurement range, and a 0.25 N/cm resolution. We recorded the real-time CoP points from both feet and saved the data in Unity. The position information was used to filter out walking data that were not related to the RDW gain and vestibular stimulation, such as when the user stopped to complete a survey or walked to move to the experimental site. Following the experiment, the recorded data were analyzed using MATLAB.

4 Evaluation of DT and User Experience of BCV RDW System

This study aimed to investigate the DT expansion performance of the RDW system through BCV stimulation and explore the user experience under each condition. This section presents the experimental setup and results for measuring the DT expansion performance and user experience. The research hypotheses are as follows:

- **H1**: All BCV conditions will expand the DT compared to **ACV**, and the degree of expansion will be proportional to the intensity of the vibration specifically targeted at the mastoid.
- **H2**: The gait instability of the user will increase when a relatively larger vibration amplitude is applied to the mastoid.
- **H3**: Users will feel greater comfort and immersion when content sounds are used to stimulate vibration than when 500 Hz noise is constantly applied.

Hypothesis **H1** was formulated based on the characteristics of multisensory integration, as detailed in Section 2.2. BCV stimulation reduces the relative reliability of the vestibular information compared with visual information by creating noise in the vestibular system, which makes it more reliant on visual information in situations of visual-vestibular inconsistency, thereby resolving inconsistencies [27, 36, 39, 55]. The intensity of the vibration specifically applied to the mastoid bone has a significant impact on BCV-induced vestibular noise. Although the volume perceived by each condition is the same (60 dB), the strength of the vibration on the mastoid, which mainly influences the DT expansion, differs for each system. Therefore, we formulated the hypothesis that conditions applying strong vibrations specifically to the mastoid bone will result in a higher level of DT extension. Hypothesis **H2** arises from the relationship between vestibular stimulation and gait instability, as discussed in Section 2.4. Previous studies have revealed that when vestibular noise is applied to participants, the gait becomes unstable [53]. Our hypothesis thus asserts that a condition which applies a higher degree of vibration to the mastoid would lead to an enhanced induction of vestibular noise, consequently provoking instability in the user's gait. Finally, Hypothesis **H3** is based on prior research, which has demonstrated that a constant vibration at a specific frequency above 150 Hz causes perceived annoyance and discomfort to the user [17, 33, 34]. A previous study applied vibrations of various frequencies to the head of the participant and found that a higher frequency resulted in greater discomfort for the participant. The condition of using content sounds also applies to vibrations of various frequencies, including those above 500 Hz. However, because the content sound does not continuously apply consistent vibrations and does not include auditory noise, it can be inferred that the use of content sounds will be more comfortable.

4.1 Experimental Setup

Figure 3: Experimental setting: Participants were instructed to walk in a straight line along the green path, commencing from the red block.

This section provides an overview of our experiment to validate our hypotheses, drawing on Steinicke et al.'s DT measurement environment [47], as outlined in Section 2.1. As shown in Fig. 3, the experimental environment was set up as a medieval street. We played a one-hour sound containing people's voices, horse neighs, and carriage wheel sounds to match the background. In addition to the DT measurement environment of Steinicke et al., we measured the simulator sickness, discomfort, immersion to investigate the user experience for each stimulus using the measurement methods described in the following questionnaire section. Moreover, as mentioned in Section 2.4, we analyzed the potential safety risks of our system by examining the stability of the walking of users in an environment containing the proposed stimuli, based on the research that suggest that VR and RDW can result in unstable walking [13, 16, 32], and that vestibular stimulation can affect walking stability [53].

The experiment comprised four vestibular stimulation conditions (**Noise**, **Content**, **Con+ACV**, **4Pole**) and a control condition (**ACV**), randomized via a Latin square. The same equipment was used across all conditions to minimize bias. Nine different RDW gains ($\pm\pi/180$, $\pm\pi/90$, $\pm\pi/60$, $\pm\pi/45$, and 0) were applied randomly to each condition. Each gain was applied five times, resulting in 45 walks per condition. Participants were healthy, stable walkers without any vestibular, neurological, cardiovascular conditions, sensitive skin, or brain diseases. Twenty participants were recruited (N = 20, age: 20–26, M = 22.15, SD = 1.98, 10 males, 10 females). The study was approved by the Institutional Review Board.

Questionnaire. We used the 2AFC questionnaire that was adopted by Steinicke et al. to evaluate the DT [47]. On a trial-by-trial basis, the participants selected either left or right in response to the query "Is the physical path bent to the left or the right?" We used the Simulator Sickness Questionnaire (SSQ) to assess the simulation sickness for each stimulus that was applied once per condition [18]. We used the discomfort score measurement questionnaire developed by Fernandes and Feiner to evaluate the user discomfort [11]. After each stimulus instance, the participants evaluated their level of discomfort on a scale from 0 to 10. In this scale, 0 represents the baseline discomfort level of the participant, while 10 signifies a level of discomfort so severe that it precludes further participation in the experiment. To evaluate immersion and presence, we employed the Igroup Presence Questionnaire (IPQ), which comprises three sub-scales: spatial presence, involvement, and realism [41].

Device wear and personalization. Prior to the experiment, we personalized the BCV devices for each participant. We first adjusted the positions of the vibrators to be located on the mastoid and temple areas and verified that the vibrators were firmly secured. Subsequently, each participant responded on whether the sound intensity that was experienced through the BCV device was louder or softer than that of a 60 dB ACV speaker, which had been meticulously pre-tuned to 60 dB. For the **Noise** condition, following previous research, we sought the maximum vibration tolerable without causing discomfort [39, 55]. Starting at a moderate device vibration, we gradually increased it to find each participant's tolerance. This customization ensured all participants experienced stronger vibrations in the **Noise** condition than the set 60 dB intensity.

Procedure. Participants initially wore an insole-type pressure sensor and completed its initialization process. They then put on an HMD and BCV device, calibrated according to the aforementioned procedure. Upon calibration, participants walked a 6.5 m straight line in the virtual environment, with curvature gains applied after the first 1.5 m to prevent participants from noticing them. After each 6.5 m walk, participants answered the 2AFC questionnaire and returned to the start for the next trial. This was repeated 45 times (nine gains × five trials per gain) per stimulus case. At the end of the experiment, the participants were asked to remove the device and answer a post-hoc survey for the stimulus case, including discomfort scores, SSQ, IPQ, and open-ended discomfort questions. Sufficient breaks were provided between experimental cases.

4.2 Results

4.2.1 Curvature DT of Each Vestibular Stimulus

Table 1: Lower DT (LDT), upper DT (UDT), and PSE values acquired for each vestibular stimulation scenario.

	Curvature DT results				
Stimuli type	LDT	PSE	UDT	DT area	**Increase**
ACV	-0.069	-0.005	0.059	0.129	**-**
Noise	-0.071	0.008	0.087	0.159	**23.3%**
Content	-0.087	-0.007	0.072	0.159	**23.3%**
Con+ACV	-0.080	-0.001	0.078	0.158	**23.0%**
4Pole	-0.096	-0.002	0.092	0.188	**45.8%**

The curvature measurements for every vestibular stimulation were examined utilizing the 2AFC method. The results are presented in Fig. 4, which depicts the measured probability of the left responses of the participants for nine different curvature gains (±π/180, ±π/90, ±π/60, ±π/45, and 0). The standard error is marked in each graph and the measured value was fitted with a sigmoid function.

The calculated DT values are presented in Table 1. The **4Pole** condition had the largest DT area, whereas the control condition had the smallest. The other three conditions resulted in similar DT areas. The DT areas of the **Noise** and **Content** conditions increased by 23.3%, that of the **Con+ACV** condition increased by 23.0%, and that of the **4Pole** condition increased by 45.8% compared to the DT area of the control condition. These findings imply that users were less aware of directional changes due to BCV, suggesting the potential to significantly alter users' direction in RDW and enhance obstacle avoidance performance.

4.2.2 A/P Gait Instability

The gait instability was measured using an in-shoe pressure sensor and the results are as follows (Fig. 5). In all five conditions, the skewness and kurtosis values did not exceed 3.0 and 10.0, so normality was satisfied. We conducted a one-way repeated-measures (RM) ANOVA to examine the effect of vestibular stimuli on the A/P gait stability. The violation of sphericity was detected using Mauchly's test ($\chi^2(9) = 247.545$, $p < .001$); thus, we applied a Greenhouse–Geisser correction for the degrees of freedom (ε = .691). There was a significant difference in the A/P instability for the five conditions: F(2.764,442.214) = 2.878, p = .040.

We performed a post-hoc test using Bonferroni correction for pairwise comparisons. No significant differences were observed except for the **4Pole** condition. All other conditions in which vestibular stimulation was applied exhibited similar or lower instabilities compared to the **ACV** condition, although the difference was not statistically significant. The **Con+ACV** condition had the lowest A/P instability compared to the other conditions, whereas the gait of **4Pole** was significantly unstable (p = .017). Consequently, the BCV stimulation methods in this study generally did not lead to unstable walking of the users; however, the **4Pole** condition slightly destabilized their walking.

4.2.3 Simulator Sickness

The severity scores measured using the SSQ were as follows (Fig. 6). The simulator sickness was measured once at the end of each session. In all instances, normality was achieved since the absolute values of skewness and kurtosis did not surpass 3.0 and 10.0. We conducted a one-way RM ANOVA to analyze the effects of the vestibular stimulations. The assumption of sphericity was tested using Mauchly's test and found to be violated ($\chi^2(9) = 29.932$, $p < .001$). Therefore, we used the Greenhouse–Geisser correction for the degrees of freedom (ε = .605). There was a significant difference in the simulator sickness among the five conditions: F(2.419,43.540) = 3.935, p = .020.

Subsequently, a post-hoc test was conducted using the Bonferroni correction to compare the significance of each condition. However, no statistically significant differences were observed under any of the conditions. The **ACV** condition exhibited the lowest score among all conditions, although it was not statistically significant, and the **Content**, **Con+ACV**, **Noise**, and **4Pole** conditions showed similar values. Hence, we confirmed that our BCV stimulation system did not increase the simulator sickness of users.

4.2.4 Discomfort

The discomfort results for each condition were collected using the questionnaire of Fernandes and Feiner (Fig. 7). The participants indicated their degree of discomfort on a scale of 0–10. The statistics followed normality because the absolute values of skewness and kurtosis did not exceed 3.0 and 10.0, respectively, for all conditions. One-way RM ANOVA was conducted to verify the discomfort level that was induced by the vestibular stimulations. The assumption of sphericity was tested using Mauchly's test and found to be satisfied ($\chi^2(9) = 13.113$, p = .160). There was a significant difference in the discomfort: F(4,64) = 7.152, $p < .001$.

A post-hoc test using Bonferroni correction was performed to compare the significance of each condition pair. The **ACV** control condition exhibited the lowest value among all conditions at only

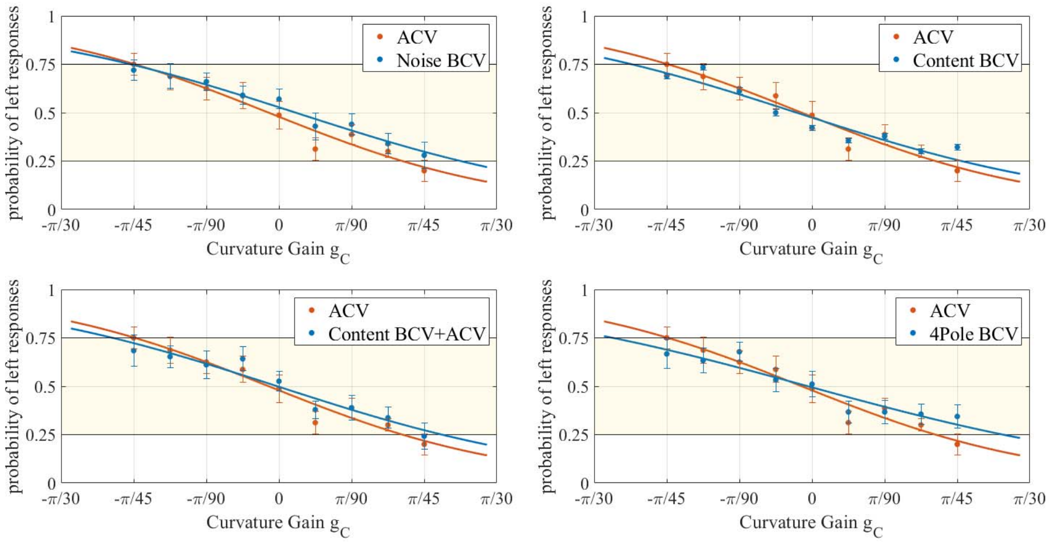
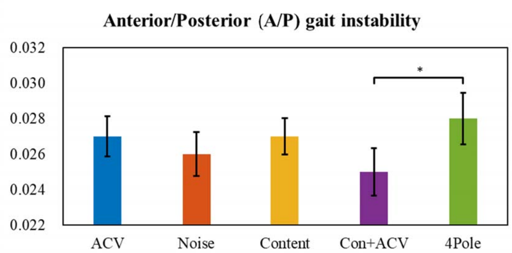
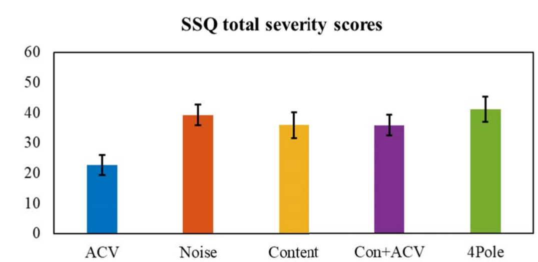


Figure 4: DT outcomes for each type of vestibular stimulus. The x-axis denotes the curvature gain, while the y-axis signifies the likelihood of participants perceiving the physical path as curving leftward. Each outcome is fitted to a psychometric function. The 25% and 75% lines are demarcated, with the inner region shaded yellow.



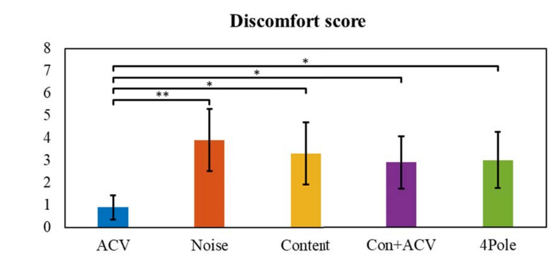
	ACV	Noise	Content	Con+ACV	4Pole
M	0.027	0.026	0.027	0.025	0.028
SE	0.002	0.002	0.002	0.003	0.003
Skew.	-0.447	0.395	-0.360	0.269	1.089
Kurt.	-0.098	-0.265	-0.629	-0.376	4.793

Figure 5: A/P gait instability corresponding to each condition. The error bars represent the standard deviation. *$p < .05$



	ACV	Noise	Content	Con+ACV	4Pole
M	22.625	39.270	35.905	35.827	41.130
SE	6.571	6.579	8.521	6.712	8.373
Skew.	1.784	0.660	0.991	0.391	0.610
Kurt.	3.411	-0.374	-0.306	-1.304	-1.071

Figure 6: Total SSQ severity ratings for every condition. The error bars display the standard error.



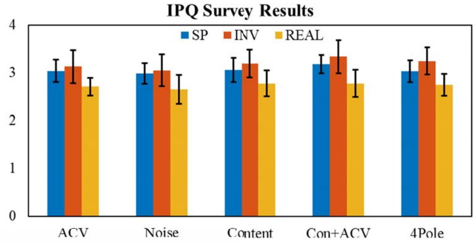
	ACV	Noise	Content	Con+ACV	4Pole
M	0.889	3.895	3.300	2.895	3.000
SD	1.079	2.767	2.755	2.331	2.513
Skew.	0.876	0.474	0.340	0.848	0.398
Kurt.	-0.521	-0.897	-1.094	-0.175	-0.844

Figure 7: Discomfort evaluations for each condition. The error bars demonstrate the standard deviation. *$p < .05$, **$p < .01$

30% of the other conditions. All other conditions had significantly higher values than **ACV**. In particular, the **Noise** condition exhibited the most significant difference, at $p = .007$. This validated that the users found the noise stimulation to be the most uncomfortable. As per Hypothesis **H3**, we have confirmed that providing users with vibrotactile vestibular stimulation using natural content sounds is more comfortable on average than the traditional approach of applying constant vibration noise stimulation. However, we have found that the stimulation using content sounds did not produce a statistically significant increase in comfort.

4.2.5 Immersion and Presence

Presence and immersion can be divided into three subcategories: spatial presence (SP), involvement (INV), and realism (REAL). The measurement results for the three subcategories are presented in Fig. 8. The absolute values of skewness and kurtosis of the three subscales did not exceed 3.0 and 10.0, respectively, for all stimulus conditions. Therefore, all statistics satisfied normality. We conducted one-way RM ANOVA to test the effect of each stimu-



		ACV	Noise	Content	Con+ACV	4Pole
(■ SP)	*M*	3.04	2.98	3.06	3.18	3.03
	SD	0.46	0.43	0.51	0.39	0.46
(■ INV)	*M*	3.13	3.05	3.19	3.34	3.25
	SD	0.69	0.66	0.58	0.69	0.56
(■ REAL)	*M*	2.17	2.65	2.78	2.78	2.75
	SD	0.37	0.61	0.54	0.56	0.45

Figure 8: IPQ score components for each vestibular stimulus: spatial presence (SP), involvement (INV), and realism (REAL).

lation condition on the immersion and presence in the same group of participants. In addition to realism, the results of Mauchly's test revealed that sphericity was not violated ($\chi^2_{SP}(9) = 6.371$, p_{SP} = .704, $\chi^2_{INV}(9) = 13.823$, p_{INV} = .130). In the case of realism ($\chi^2_{REAL}(9) = 19.899$, p_{REAL} = .019), we performed the Greenhouse–Geisser correction (ε = .627).

None of the three cases exhibited any significant differences in the results ($F_{SP}(4,76)$ = .831, p_{SP} = .510, $F_{INV}(4,76)$ = 1.223, p_{INV} = .308, $F_{REAL}(2.507,47.635)$ = .258, p_{REAL} = .821). These results indicate that although the vestibular organ of the user was stimulated through our device, there was no significant loss in immersion or presence. Therefore, it can be concluded that stimulation using our approach did not degrade the immersion and presence.

5 Discussion

5.1 Hypothesis Validation and Analysis

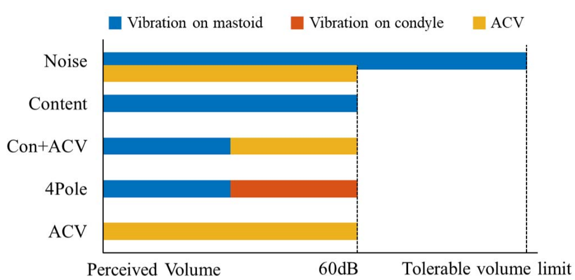


Figure 9: Conceptual diagram showing the vibration stimulation intensity for each experimental condition. The horizontal axis is not drawn to scale and is intended to provide a general representation, rather than exact units.

In this section, we validate our hypotheses based on the experimental results for each BCV condition. Our first hypothesis, **H1**, has been confirmed valid. It illustrates that all BCV scenarios extend the DT compared to **ACV**. Moreover, the expansion degree correlates with the vibration intensity particularly administered to the mastoid across all conditions, with the exception of the **4Pole** scenario. The vibration intensities that were used for each condition were as follows (Fig. 9). **Noise** condition: maximum vibration at a level where participants did not feel discomfort; **Content** condition: vibration at a level perceived as 60 dB; **Con+ACV** condition: vibration at a level perceived as 60 dB when ACV and BCV sounds were played simultaneously; and **4Pole** condition: vibration at a level perceived as 60 dB when simultaneous vibrational stimuli were applied to the condyle and mastoid. All participants experienced higher vibrations in the **Noise** condition as they used the maximum tolerable vibration compared to the other conditions. Furthermore, it can be inferred that the participants experienced stronger vibrations in the **Content** condition, in which only mastoid vibration was used to achieve 60 dB, compared to the **4Pole** and **Con+ACV** conditions, in which additional sounds were delivered through other devices. Finally, although the perceived sound intensity was the same at 60 dB in both the **Con+ACV** and **4Pole** conditions, stronger vibrational stimuli were provided in the **4Pole** condition, as the participants experienced vibration using four vibrators. Therefore, it can be concluded that the sequence of vibrations that were provided to the mastoid was **Noise**, **Content**, **4Pole**, and **Con+ACV**.

Measured DT expansions were: **Noise**: 23.3%, **Content**: 23.3%, **Con+ACV**: 23.0%, and **4Pole**: 45.8%. Surprisingly, despite third-ranking vibration, **4Pole**'s DT expansion surpassed others. It is difficult to explain this phenomenon conclusively based solely on the experimental results; however, we can infer that higher vestibular stimulation was induced when attaching additional vibrators to the head of the participant. According to previous research, vestibular noise reduces pedestrian stability [53], and in this experiment, the walking instability in the **4Pole** condition was higher than that in the other conditions. Thus, we inferred that the additional vibrators in the **4Pole** condition heightened vestibular stimulation. Yet, to substantiate this, further rigorous analysis and direct measures, such as VEMP indicators of otolithic neural activation, are required.

Hypothesis **H2** was disproven in this study, demonstrating that the user's gait instability would not increase when a relatively larger vibration amplitude is applied to the mastoid. As mentioned previously, the sequence of vibrations that were applied to the mastoid was **Noise**, **Content**, **4Pole**, and **Con+ACV**; however, the walking of the participants was most unstable in the **4Pole** condition. Therefore, we could infer that the **4Pole** condition induced greater vestibular noise even though the intensity of the vibration that was directly applied to the mastoid was relatively low. However, additional experiments are required to provide direct evidence.

Finally, Hypothesis **H3**, suggesting that users would experience greater comfort and immersion when content sounds are used to stimulate vibration than when 500 Hz noise is constantly applied, was partially validated based on the results. The discomfort of the participants was higher in the **Noise** condition than in the conditions using content sounds (**Content**, **Con+ACV**, and **4Pole**); however, the use of sound effects did not result in statistically enough improvements. We analyzed this cause through a frequency analysis of the content sound. Although the sounds used did not have persistent low-frequency vibrations, which could cause discomfort [17,33,34], they still contained sporadic vibrations in low frequency. Therefore, we concluded that a careful selection of content sounds with suppressed low-frequency vibrations is crucial for making more definitive improvements in comfort. Moreover, contrary to Hypothesis 3, there was no significant difference in immersion across all conditions. Thus, the use of content sounds for vibration provided more comfort to users but did not affect their immersion. Previous research has demonstrated that the presence or absence of sound in a gaming environment influences user immersion, whereas sound quality does not have a significant effect [40]. Based on this previous research, it can be inferred that the immersion was not significant compared to the control condition in this experiment, as content sounds were played under all conditions.

To summarize, all the BCV stimulations successfully extended the DT in comparison to the control condition of **ACV**, contributing to the spatial expandability and obstacle avoidance performance in RDW. Interestingly, the extent of DT was nearly proportional to the intensity of the vibrations applied to the mastoid. However, the

4Pole condition, which had smaller vibrations applied to the mastoid, demonstrated the widest DT extension. Therefore, we found that the contribution of BCV to the obstacle avoidance performance in RDW through DT expansion is proportional to the magnitude of the vibration applied to the mastoid but, exceptionally, when additional vibrations were applied to the condyle, the DT extension range increased significantly (**H1**). All BCV RDW systems were found to not render the users' gait unstable, except for the **4Pole** condition, confirming that the systems do not pose a threat to the safety of the users (**H2**). Lastly, BCV stimulation utilizing sound generated from the content maintained user comfort compared to traditional BCV stimulation that continuously played noise. Although noise-playing BCV induced relatively higher discomfort, the sense of immersion remained consistent across all BCV stimulation conditions (**H3**).

5.2 Confirmation of User Path Manipulation in the BCV RDW System

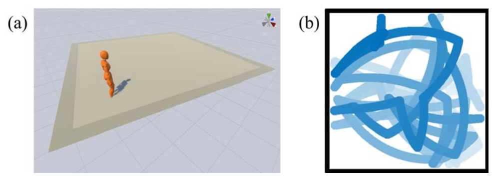


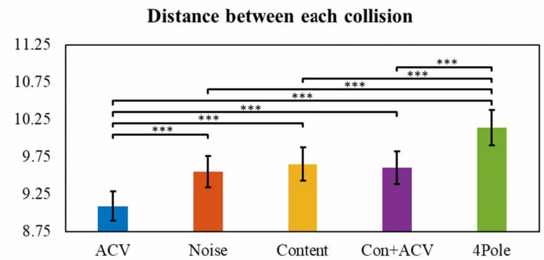
Figure 10: (a) Environment used in simulation analysis and (b) examples of walking path results in simulation environment.

In this section, we simulate the obstacle avoidance performance when the DT area from each stimulation condition, as measured in the experiment, was applied to actual RDW situations. The purpose of the simulation is to verify how users manipulate their path within the expanded DT range and illustrate simulated scenarios that users may experience with our BCV system. We measured the average distance between resets under each DT condition. This value represented the mean distance that was walked by the simulation agent between hitting a wall and the subsequent collision.

We simulated a single-user room-scale VR scenario (Fig. 10) using the openRDW library's benchmark [26]. The agent navigates the 10 m square room through randomly chosen straight-line lengths (2-8 m) and 90-degree turns, completing a trial after traversing 200 m. We recorded the average distance between resets for each trial. The steer-to-center algorithm directs the agent towards the center of the room, preventing collisions with the walls. The algorithm uses the maximum curvature gain corresponding to the DT determined during the experiment. We conducted 1000 trials per method and excluded 49 data points (0.1%) due to the agent getting lodged in a room corner, resulting in abnormally high collisions.

5.2.1 Results

The average distribution of the distance traveled from one reset to the next in the simulation is presented in Fig. 11. The skewness and kurtosis did not exceed 3.0 and 10.0, for all DT conditions, indicating that all distributions satisfied normality. One-way ANOVA was performed to confirm the difference in distance between the different stimulation cases based on the degree of DT expansion. The results revealed a significant difference according to the stimulus case: $F(4,4946) = 36.4$, $p < .001$. Subsequently, a post-hoc test using Bonferroni correction was performed to confirm the significance between each condition. In all cases, the agent could move significantly longer distances ($p < .001$) compared to the **ACV** condition. Furthermore, the **4Pole** condition supported the longest distance for free walking without collision compared to all other conditions. This simulation demonstrated that all BCV stimulations significantly supported uninterrupted walking compared to the control condition.



	ACV	Noise	Content	Con+ACV	4Pole
M	9.088	9.551	9.652	9.600	10.137
SE	0.397	0.421	0.442	0.437	0.470
Skew.	-0.048	0.075	0.093	0.402	0.803
Kurt.	1.236	1.122	0.692	1.555	3.869

Figure 11: Distance between collisions for each condition. The error bars present the standard deviation. ***$p < .001$

Notably, in the **4Pole** condition, we observed a significant increase in the average distance that was walked without collisions compared with all other conditions. Based on the results, we were able to demonstrate the practical effects on users' paths of using DT extended by BCV in RDW, indicating that users can walk longer distances without interruptions.

6 Conclusions and Future Work

We proposed four RDW systems that use BCV vestibular stimulation to avoid potential side effects of electrical stimulation. The results showed all four methods successfully extended DT, enabling continuous walking in RDW scenarios while maintaining user immersion, and simulator sickness similar to control condition. In all cases, BCV-induced DT expansion outperformed the 12-16% expansion found in prior studies using Noisy GVS [28]. Yet, to make a robust comparison, future research should compare BCV and GVS in identical environments. Additionally, the DT measurement range in this study spans approximately 30% to 70% of the maximum response. 100 data points were collected at each location for each of the 9-point sampling methods, resulting in a total of 900 data points per case. According to Lam et al. [20], our DT estimate has an error margin of less than 5%. For a more precise DT estimation, experiments should be conducted in the range of 10–90% of the maximum response [25]. Along with the noise BCV, we compared conditions that use the content sound as a vibrational stimulation to improve the user comfort. The results confirmed that using content sound for vibration stimulation led to improved comfort compared to constant noisy vibration. Therefore, we propose a stimulation method that can alleviate discomfort while enabling enhanced obstacle avoidance by providing content sound as a vibrational stimulation.

In future research, we plan to optimize stimulation methods to improve DT expansion and user experience by refining BCV. We observed significant differences in DT expansion using multiple vibrators. By adjusting vibrator placement or adding more, we plan to find the optimal BCV stimulation for safer and more immersive continuous walking experiences. We hope this study provides new insights and applications for RDW research using BCV vestibular stimulation.

Acknowledgments

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