

Electrical, Vibrational, and Cooling Stimuli-Based Redirected Walking: Comparison of Various Vestibular Stimulation-Based Redirected Walking Systems

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Figure 1: Concept image of a user experiencing vestibular stimulation redirected walking (RDW) in a game environment. The user walks in a wide virtual space while avoiding physical obstacles in the real space through the RDW system using different types of vestibular stimuli: galvanic vestibular stimulation (electrical), bone-conduction vibration (vibrational), and caloric vestibular stimulation (cooling).

ABSTRACT

Redirected walking (RDW) is a technology that enables users to walk seamlessly in an enormous virtual space within a narrow real space while avoiding collisions with physical elements. Although

RDW provides accurate proprioceptive sensations, redirection performance is limited by visual–vestibular inconsistencies. This study aims to support seamless walking in a VR environment by alleviating inconsistencies using four vestibular stimulations: noisy and directional galvanic vestibular stimulation, bone-conduction vibration, and caloric vestibular stimulation. The user study demonstrated that the stimulations successfully enable spatial expansion without impairing immersion and presence. Non-electrical stimulations (bone-conduction vibration and caloric vestibular stimulation) expanded the detection threshold, making them alternatives to electrical stimulations, and direction-based stimulation (directional galvanic vestibular stimulation) improved the user’s gait stability in RDW. Finally, the findings suggested improving the user experience for vestibular stimulation RDW either by lowering audio

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interference or increasing the synchronization between the RDW gain and the stimulation intensity.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; *Interaction devices*.

KEYWORDS

Virtual Reality; Locomotion; Redirected Walking; Vestibular Stimulation; Gait Stability; Haptic Device

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1 INTRODUCTION

Walking is one of the most basic and essential actions for immersive experiences in virtual reality (VR). However, the real environment where one walks in VR is limited compared with the virtual environment of an enormous space. Therefore, studying techniques of moving freely in an immense-sized virtual space in a finite-size real space is important. Omnidirectional treadmills [62] and walking-in-place [50] have been studied for this purpose. However, providing accurate kinesthetic, proprioceptive, and vestibular sensations using these techniques is challenging because they do not follow the natural human walking motions [49]. In this context, redirected walking (RDW) is designed to support moving in a larger virtual space in a narrow physical space using natural human gait motions [54].

RDW is a technology that changes the user's path by mismatching the user's movement in real space with that in virtual space [54]. It assists users to walk seamlessly in a virtual space by changing their path to prevent collisions with obstacles and walls with visual manipulations. For example, RDW technology can create an arc shape of the user's path in the real world through visual manipulation that continuously rotates the map to avoid obstacles when a user enters a virtual environment. The user can freely navigate the infinite virtual space because these RDW processes are provided in such a manner that the user is oblivious to them. However, when the user's direction must be changed to a broader angle to efficiently avoid obstacles, visual manipulations must be increased to a level so that the user might perceive these manipulations; thus, RDW reaches the limit of visual-vestibular inconsistency [71]. Modulated visual information is inconsistent with the user's self-acceptance and vestibular senses. If this inconsistency increases, the user notices the manipulation; the immersion and presence decrease, and simulation sickness increases [1, 9]. Therefore, a limitation in the RDW technique's ability for manipulation is called the detection threshold (DT) [71]. The limitations are manipulating the user's path and the range of the expandable space [4, 33–35].

This study introduces a method to expand DT by alleviating visual-vestibular inconsistency, a significant cause of DT, through various vestibular stimuli that have minimally been studied. We

expanded the DT using electrical (i.e., noisy galvanic vestibular stimulation (noisy GVS) and directional galvanic vestibular stimulation (directional GVS)) and non-electrical stimulations (i.e., bone-conduction vibration (BCV) and caloric vestibular stimulation (CVS)) (Figure 1). Furthermore, we verified the vestibular stimulation RDW in a game environment that is similar to the user's actual VR experience. Most RDW studies used only a simple DT measurement environment [5, 40, 71]; however, this environment differs from the content that users can experience. We implemented a game in which users played using their visual and auditory senses to locate objects. We investigated whether the user is affected by vestibular stimulation RDW in the following aspects: immersion and presence, task performance, simulator sickness, and discomfort.

In previous studies, noise was added to the vestibular organ using galvanic current [40] or inducing vestibular stimulation in a specific direction using a directional current [28, 64] to expand DT using vestibular stimulation. These studies expanded DT using a simple device. In addition, vestibular stimulation has the advantage that it can be used independently of the content compared to auditory or haptic manipulation [23, 41, 43] methods [40]. Among the various vestibular stimulation methods, those using galvanic currents have been mostly used although vestibular stimulation has been proven to be a promising technique to expand DT. Previous studies were limited in that they did not suggest an alternative or solution to the side effects of electrical stimulation of the skin (e.g., skin stimulation, retina stimulation, and eye muscle stimulation) [37, 76]. Research on non-electrical alternatives for people prone to these side effects is required for application to a broader range of users. To the best of our knowledge, this is the first study to explore the possibility of using non-electrical stimulations: BCV and caloric stimulation in RDW as an alternative to the side effects of these electrical stimulations. GVS, BCV, and caloric stimulation stimulate vestibular organs in different ways to modulate vestibular information. We confirmed that this stimulation method significantly affects DT expansion performance and user usability. This study shows that providing a non-electrical vestibular stimulation RDW technique for people suffering from side effects of electrical stimulation is possible.

We also investigated gait stability to confirm the safety of RDW using vestibular stimulation. The phenomenon in which the user's gait stability is lowered in the RDW situation has been proven through experiments [27, 29, 46], which can be a significant risk for the safety of users blindfolded with a head mounted display (HMD). We measured gait instability using foot pressure data to determine the effects of various vestibular stimulations on gait stability in the RDW. The first extensive comparison of GVS, BCV, and CVS in this study is expected to contribute to the non-electrical use of RDW with vestibular stimulation.

We fabricated a wearable device that provides a set of vestibular stimulations, including noisy GVS, directional GVS, BCV, and CVS. We conducted experiments in two environments to compare the modalities using the manufactured device. The first environment investigated quantitative factors to determine whether each vestibular stimulus can be used with the RDW technique, such as the DT expansion performance of each vestibular stimulus, degree of simulator sickness induced, gait stability, and stimulus discomfort. In the second environment, each vestibular stimulus was applied to

a simple game environment to investigate user experience using the vestibular stimulus RDW in an actual game. We investigated immersion and presence, task performance, simulator sickness, and stimulus discomfort over time in a simple ball game environment. The research questions of this study are as follows:

- How far can BCV and CVS extend the DT through vestibular stimulation instead of electrical stimulation?
- How do different vestibular systems affect gait stability and user experience?
- Which stimulation method guarantees immersion in-game environment?

2 BACKGROUND

2.1 Redirected walking

The experience of being able to move freely in the VR space is one of the most basic and essential interactions that a user can have with a virtual space. In particular, when moving using natural gait motion, the user can feel a higher sense of immersion in proprioception and kinesthetics [49]. However, the technology of walking in a virtual environment using natural human gait motion is often limited in terms of its usability because of the physical limitations of real space, such as furniture, pillars, and walls, which may pose a safety threat to users who are blindfolded with an HMD.

RDW, a technology that changes a user's direction by mapping the movement of the real and virtual environments by modulating the user movement or structure of the virtual environment without the user noticing it, was proposed to overcome this limitation of real space [54]. In particular, a technique for changing the user's direction by providing a gain, called the redirection gain, to the user's movement in a virtual environment is widely known. Steinicke et al. first divided redirection gain into three types depending on the user's movement gain: rotation, translation, and curvature gains [71] (Figure 2). Rotation gain (g_R) provides gain to the degree of rotation of the user in reality such that the rotation in the virtual environment does not match the rotation in reality. Rotation gain is defined as the ratio of the virtual rotation ($R_{virtual}$) to the real rotation (R_{real}) (i.e., $g_R = \frac{R_{virtual}}{R_{real}}$). Translation gain (g_T) allows users in a virtual environment to move a longer or shorter distance compared to that in reality by providing a gain to the straight distance covered by the user. The translation gain is the ratio of virtual translation ($T_{virtual}$) to the real translation (T_{real}) (i.e., $g_T = \frac{T_{virtual}}{T_{real}}$). Lastly, curvature gain (g_C) transforms the user's real path into a curved arc shape by rotating the map left or right for a user that goes straight in the virtual environment. By utilizing the curvature gain, users who think they are going straight in the virtual environment can move in the real world to avoid obstacles and walls such that collisions can be avoided. The curvature gain is expressed as the reciprocal of the arc curvature (r) created by the user (i.e., $g_C = \frac{1}{r}$). Because curvature gain is one of the most efficient manipulations for spatial expansion of RDW [40], we preferentially applied our vestibular stimulation RDW system to curvature gain. After the system is verified for curvature gain, we plan to study its application to other redirection gains.

2.2 Detection Threshold (DT) and Point of Subjective Equality (PSE)

RDW technology creates inconsistencies between the movement of the real environment and that of the virtual environment to overcome the physical limitations of real space. However, these manipulations inevitably lead to visual–vestibular inconsistencies, that is, the greater the manipulation of visual information for more directional change, the greater is the visual–vestibular inconsistency. This increased inconsistency causes simulator sickness, thereby making the user aware of the RDW manipulation, which causes a decrease in presence [71]. Therefore, all RDW techniques have a DT, which limits manipulation. Furthermore, DT limits the size of the direction change of RDW technology and determines the limit of avoidance performance for obstacles such as walls and furniture. Therefore, many studies have been conducted to measure and expand DT.

Steinicke et al. first presented the concept of DT and measured it using a two-alternative forced-choice (2 AFC) questionnaire, such as "Was the virtual movement smaller or greater than the physical movement?" and "Is the physical path bent left, or right?", to the participants by changing the rotation, translation, and curvature gains [71]. Participants were asked to choose one of two answers such as smaller/greater or left/right. Then, the gain value was defined as the point of subjective equality (PSE), which perceived physical and virtual movements equally based on the average participant responses. On both sides of the PSE, the points where the participant could distinguish between physical and virtual movements within a range of 75% were set as the upper DT (UDT) and lower DT (LDT).

2.3 Multisensory Integration

This study used direction-based and noise-based methods to alleviate visual–vestibular inconsistencies using vestibular stimulations. Direction-based methods (directional GVS) relieve inconsistencies by providing vestibular stimulation consistent with visual information, whereas noise-based methods (noisy GVS, BCV, and CVS) alleviate inconsistencies by utilizing multisensory integration characteristics. In this section, we describe how noise-based methods can alleviate visual–vestibular inconsistencies.

Multisensory integration evaluates how information obtained from different sensory modalities is combined to influence decision-making and judgment [69]. Among the several multisensory integration studies, we focused on those based on the maximum likelihood estimation (MLE) model. In multisensory integration based on the MLE model, each modality independently influences the user's judgment, and the weight of each modality is based on its relative reliability. The integration model to which the MLE was applied was first presented by experiments that applied visual and tactile senses [17]. In this study, the authors simultaneously provided conflicting visual and tactile information to the participants and found that the more noise there was in the visual information, the higher was the weight of the tactile information. We confirmed that this multisensory integration feature could be used to alleviate visual–vestibular inconsistency using vestibular stimulation, which applied noise to vestibular information [25, 80]. Each vestibular stimulus creates noise in the vestibular information, and vestibular

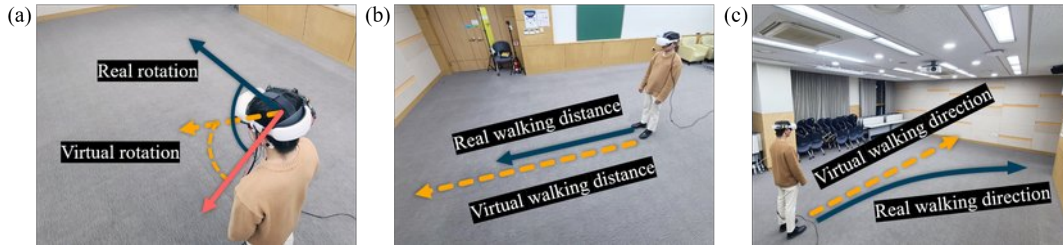


Figure 2: Three types of redirected walking gains presented by Steinicke et al. The figure shows the actual and virtual paths in (a) rotation gain, (b) translation gain, and (c) curvature gain.

information has relatively low reliability in multisensory integration compared to visual information. Therefore, vestibular information has a small weight compared to visual information, which can alleviate the inconsistencies by creating a higher dependence on visual information in visual-vestibular inconsistencies. A previous related study attempted to expand the DT by creating noise in the vestibular information using the noisy GVS [40]. A DT expansion performance of approximately 12%–16% was confirmed.

2.4 Galvanic vestibular stimulations & Bone-conduction vibration & Caloric vestibular stimulation

2.4.1 Noisy galvanic vestibular stimulation & Directional galvanic vestibular stimulation. The GVS technique is a modification of transcranial direct current stimulation that modulates vestibular information by applying an electric current to the participant's skin [75]. GVS applies electrical stimulation to the mastoid process where the vestibular nerve is located. The vestibular nerve passes through the vestibular brainstem nuclei and ventroposterolateral nucleus in the inner ear. Furthermore, it connects to the cortical vestibular areas such as the central sulcus, somatosensory cortex, and parieto-insular-vestibular cortex [75]. Electrical stimulation of the GVS modulates vestibular information by inducing polarization effects on the vestibular nerve.

HCI researchers use GVS to provide new stimuli, such as roller-coaster simulations and balancing games [8], as an interaction tool between users [66] or a methodology to reduce motion sickness [25, 80]. Several studies have been conducted on the use of vestibular stimulation in RDW [28, 40, 64]. A study expanded DT by adding electrical noise to the vestibular organ to lower the reliability of the vestibular information for proprioception [40] or providing vestibular information that was consistent with the visual information to users using directional current [28, 64].

The noisy GVS provided white-noise current stimulation by attaching electrodes to both mastoids, thereby creating noise in vestibular information, which can alleviate visual-vestibular inconsistencies by reducing the effect of vestibular information on proprioception. However, if the electrical stimulation of the noisy GVS has a current density less than 0.8 A/m^2 [3], stochastic resonance may occur [21, 47, 51, 83], a phenomenon where a weak input is amplified because of the noise in a nonlinear system [22]. If vestibular information is amplified, its effect on proprioception

increases, which can intensify visual-vestibular inconsistencies [40].

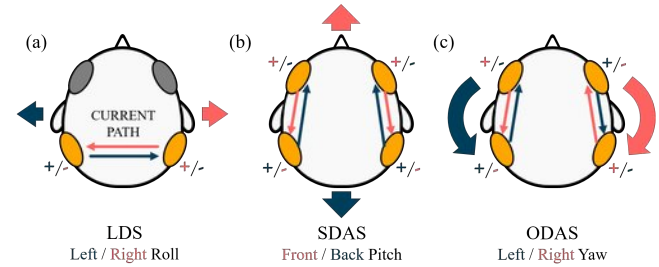


Figure 3: Conceptual diagram of the three types of vestibular stimulation that four-pole GVS can provide. The current direction (thin arrow) and head movement (large arrow) are shown under (a) lateral directional stimulation, (b) same directional anteroposterior stimulation, and (c) opposite directional anteroposterior stimulation. The electrode attachment location is the yellow ellipse, and the plus-minus sign beside the electrode indicates the electrode polarity.

Unlike noisy GVS, four-pole GVS alleviates visual-vestibular inconsistency by providing directional vestibular information that matches the visual information to the user. The four-pole GVS was proposed by Aoyama et al., and the vestibular information can be modulated in the roll, pitch, and yaw three-axis directions by attaching a total of four electrodes to both mastoids and temples [2]. Different directional current stimulations of lateral directional stimulation (LDS), same-directional anteroposterior stimulation (SDAS), and opposite-directional anteroposterior stimulation (ODAS) produce triaxial modulation of vestibular information, as shown in Figure 3.

All RDW studies using the above devices positively affected the DT expansion. However, these studies did not include alternatives or solutions for the side effects of GVS that directly apply electric current to the skin (e.g., skin irritation, retinal stimulation, and eye muscle stimulation) [37, 76]. Although GVS is generally safe [31], the potential risks of long-term exposure to GVS have not been studied. Furthermore, it can cause side effects in some healthy people [76]; for specific people, such as pacemaker users, applying direct-current stimulation to body surfaces can be a significant

threat [37]. Therefore, we limited the intensity of electrical stimulation to induce polarization effects to biphasic 15 V, ± 2 mA, based on the medical safety limits of previous studies [65].

2.4.2 Bone-conduction vibration. BCV has been studied as a method for stimulating the vestibular system using air-conducted sound (ACS). Colebatch et al. demonstrated that BCV and ACS stimulate otolithic function by activating vestibular-evoked myogenic potentials (VEMPs), which is evidence of otolithic neural activation by sound and vibration [10, 11, 55]. Considering that the intensity of BCV is significantly lower than that of ACS required for activation, even a small intensity can induce vestibular stimulation [14]. Sound and vibration create a displacement of the fluid in the vestibular labyrinth, which can modulate vestibular information by inducing deflection of type-I vestibular receptor hair [13]. The frequency of vibration affects the deflection period of vestibular receptor hair and acts as a significant variable in vestibular stimulation. In previous studies, BCV of 200–500 Hz produced the largest VEMPs [58, 59, 74]. The intensity of BCV stimulation that induces vestibular stimulation varies depending on the shape and size of the skull, as well as the structure of the vestibular labyrinth [15, 55]. Therefore, the strength of the stimulation was adjusted for each participant. Many studies have shown that BCV can effectively disturb vestibular organs by modulating vestibular information [15, 55, 58, 59, 73] and is a safe vestibular stimulation method with few reported side effects [12].

BCV has been extensively studied as a method for reducing motion sickness in vehicles [56] or in VR walking [80]. The above study reduced motion sickness by using the noise BCV imposed on the vestibular organs and alleviated visual–vestibular inconsistency. The characteristics of BCV that apply noise to the vestibular organ by displacing the fluid in the vestibular labyrinth, which is discussed in this section, can expand DT by alleviating visual–vestibular inconsistency due to the characteristics of multisensory integration described in Section 2.3. Noise introduced by BCV reduces the reliability of vestibular stimulation in multisensory integration. This makes people more dependent on stable visual signals with relatively less noise in sensory conflict situations, and the asymmetry of these weights results in a relatively reduced inconsistency. The alleviation of inconsistency by such noise will lead to the extension of curvature DT, as in previous studies on noisy GVS [40]. To the best of our knowledge, this is the first attempt to use the BCV for RDW.

2.4.3 Caloric vestibular stimulation. CVS stimulates the adjacent vestibular labyrinth by stimulating the external auditory meatus at warm or cold temperatures. Temperature stimulation applied to the CVS regulates the fluid density in the vestibular organ, which induces vestibular receptor hair movement and vestibular stimulation [19, 61, 68]. Presently, CVS is being studied for the treatment of aphasia [82], depression [52], and chronic pain [63] because of its characteristic of increasing blood flow across various cortical regions [20], including the language domain [44].

Using cold or warm water is the most popular method for vestibular stimulation of the CVS [20, 38, 42]. However, because of the characteristics of the VR walking system, it is difficult to continuously make the water flow into the external auditory meatus at a constant temperature. Previous studies show that the vestibular

response to air stimuli at 24 °C and 50 °C is similar to that produced by water at 30 °C and 44 °C [16, 24]. Based on the results of previous studies, we fabricated a wearable device that cools the external auditory meatus using cold air at 24 °C. Similar to noisy GVS and BCV, CVS creates noise in the vestibular information through temperature. This study intends to expand the curvature DT by reducing visual–vestibular inconsistency using the characteristics of the vestibular signal of CVS. The vestibular receptor hair movement generated by CVS and the resulting vestibular signal is a noise that differ from the actual human-balance information. This noise can lower the relative reliability of vestibular information compared to visual information owing to the characteristics of multisensory integration described in Section 2.3. Because visual information has a relative advantage in sensory conflict situations due to CVS, alleviation of inconsistency can be expected. CVS, such as noisy GVS and BCV presented in the previous section, can extend DT owing to this theoretical background. To the best of our knowledge, this is the first attempt to use CVS for RDW.

2.5 Gait stability

Stable gait refers to a gait where the user does not fall when a perturbation occurs [7]. If the gait stability is low, the user falls easily, increasing the risk of injury. In particular, when wearing an HMD, the user cannot observe the external environment; therefore, low gait stability is fatal to the user. According to previous studies, both VR and RDW applications induce a decrease in gait stability [27, 29, 46]. As described above, gait stability, an essential factor in RDW, was checked to verify the safety of the RDW system.

Gait stability varies depending on the intensity of the noise applied to the vestibular system. In the case of a weak noise stimulus, stochastic resonance in the vestibular organs increases the gait stability; however, with an intense stimulus, noise disturbs vestibular sensation, thereby decreasing the gait stability [77]. Noisy GVS, BCV, and CVS used in the present experiment expand the DT by perturbing the user's vestibular organs through intense stimulation. Therefore, because stimulation may worsen a participant's gait stability, its stability must be experimentally confirmed.

The sensor measures the user's stability by measuring the pressure applied to the sole of the foot. There are two methods for measuring plantar pressure: the platform method, where a pressure sensor is installed on the floor, and an in-shoe method, where a sensor is installed in a shoe [53]. In this experiment, we measured plantar pressure using the in-shoe method to adapt the participant's walks on different paths depending on the curvature gain. In the case of the in-shoe method, the stability can be measured without affecting walking [60], considering that a fabric pressure sensor is placed in the shoe without connecting cables or wearing additional equipment. In this study, anterior/posterior (A/P) and medial/lateral (M/L) gait stability was measured using plantar pressure measurements [36]. According to previous studies, a stable gait center of pressure (CoP) moves from posterior to anterior. As gait becomes unstable, the time taken to move from the anterior to the posterior increases. Therefore, we measured the A/P gait instability by dividing the number of frames with A/P CoP motion toward the heel during stride by the total number of frames in the stride length. Additionally, during stable walking, the CoP starts from the middle

area, moves in the lateral direction, and returns to the middle-area direction. At this time, the more unstable the gait is, the more the CoP moves to the left and right. Therefore, we measured the M/L instability when the velocity–time curves exceed ± 0.5 mm/s per step after zero-crossing the M/L CoP velocity–time curve.

3 IMPLEMENTATION

3.1 Device 1: Noisy galvanic vestibular stimulation & Directional galvanic vestibular stimulation

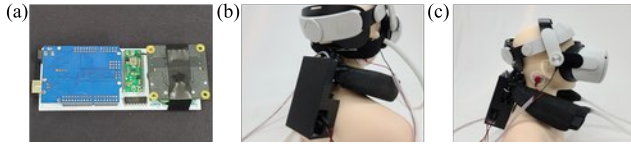


Figure 4: (a) GVS-stimulator circuit, (b) appearance of the GVS device, and (c) system attached to the participant.

The GVS device used in this study was designed to provide both directional and noisy GVS stimulation of four-pole GVS (Figure 4). Four electrodes were attached to the left and right temple and mastoid. Electrical stimulation was applied at 15 V and 2 mA. The GVS device was divided into control and stimulus sections, and each part was galvanically isolated for safety. The microcontroller unit (MCU) communicates information through BLE communication with an experimental environment created using Unity. The built-in IMU sensor sends information regarding the user's head orientation to Unity. Then, based on information received and the experimental environment, Unity calculates the type of stimulus to be applied to the user and transmits it to the GVS device. The direction and intensity of current stimulation was controlled using the H-bridge of the L293D motor driver and pulse-width modulation, respectively. All electrical stimulations were applied using a ramp function to prevent unintentional tingling, and a first-order low-pass filter with a cutoff frequency of 33 Hz was installed. This stimulus was delivered to the user via a conductive bioelectrode through a 3.5 mm connector. All devices were powered by an 8000 mAh LiPo battery and controlled by a single power switch, thereby allowing the participant to shut down quickly at any time for safety. Signals corresponding to the left and right temples can be turned on and off using the SSR relay, which is controlled to ensure that electrical signals are not sent to the temples in LDS and noisy GVS situations. All devices were designed using open-source hardware, and various sensors, such as heart-rate, electrocardiogram, and skin-conduction sensors, can be used for further research.

The noisy GVS signal uses white Gaussian noise, based on research by Matsumoto et al [40]. To prevent stochastic resonance of the noisy GVS, as described in Section 2.4.1, we provided stimulation with a current density of 0.8 A/m^2 or higher and below the safety standard. The average current stimulation and standard deviation were set to 0 mA and 1 mA, respectively. All noises were designed to be within the range of 2σ . The electrode used was a circular electrode with a radius of 2.5 cm; therefore, the applied current density was 1.02 A/m^2 . The four-pole GVS can modulate

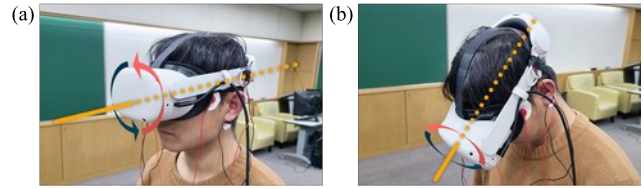


Figure 5: An example of coordinate transformation according to the direction of the user's head. (a) The situation where the LDS stimulus creates the roll-direction vestibular information in the global coordinate when the user faces the front and (b) the situation where the LDS stimulation applies the yaw-direction vestibular stimulation in the global coordinate when the user looks at the floor.

the user's vestibular information in the three directions of roll, pitch, and yaw in the user's head coordinate system using three current-stimulation directions: LDS, SDAS, and ODAS. However, the head coordinate system of the user does not always coincide with the global coordinate system. For example, as shown in Figure 5, if LDS stimulation is applied when the user is facing the front, vestibular stimulation in the roll direction can be applied in the global coordinate system. However, when a user looks at the floor or ceiling, the same stimulus creates a yaw-direction vestibular stimulus in the global coordinate system. Therefore, we developed a system that can stimulate the user in the desired direction in the global coordinate system by receiving the user's head-direction information using IMU data built into the device.

All GVS stimulations used in this experiment were conducted to alleviate visual–vestibular inconsistency. Noisy GVS is triggered when visual information is manipulated to alleviate inconsistency based on the characteristics of multisensory integration. The triggered device provides continuous electrical noise to the vestibular system. Then, directional stimulation of the four-pole GVS was provided to match the user's visual and vestibular information. For example, consider a situation where the user experiences a curvature gain while moving straight in the virtual environment while looking straight ahead. At this time, the visual system transmits information to the brain that the user is going straight without curvature in the left and right directions. Simultaneously, the vestibular sense transmits information to the brain, where the body rotates toward the yaw-directed curvature gain, thereby resulting in visual–vestibular inconsistencies. In this situation, we provided the user with a vestibular stimulus in the same direction in the global coordinate system to alleviate the visual–vestibular inconsistency.

3.2 Device 2: Bone-conduction vibration

We manufactured the BCV device (Figure 6) using the bone-conduction module of a human-bone conduction speaker (Duramobi, Hong Kong), which communicates with the experimental environment in real time using Bluetooth 5.0. It can produce sound of up to 115 dB and has a sound frequency range of 200 Hz–20 kHz. We used two units, one for each mastoid; each unit was 40 mm in diameter and weighed 35 g. Each BCV unit has an impedance of 4Ω and an output of 3 W, and is driven by a Bluetooth audio signal amplified



Figure 6: (a) BCV device used in this experiment, (b) inside of the BCV stimulator, and (c) device attached to the participant.

by the HAA2018 5W audio amplifier chip (Figure 6.(b)). An elastic band was attached to the vibration unit of the participant's mastoid process, and the position of the module was adjusted based on the participant. In attaching the vibrator, we were careful not to place the vibrator on the electrode of the GVS attached to the same mastoid or on the hair of the participant such that the vibration was not transmitted properly. If the participant's mastoid area was narrow and the electrode positions of the BCV and GVS interfered, the position of each stimulation device was modified according to the experimental conditions. This process corrected the position such that the stimulation under each experimental condition could be clearly felt. Moreover, before every experiment, we asked participants whether the stimuli were well delivered.

In this experiment, we triggered BCV upon visual manipulation using RDW to alleviate visual-vestibular inconsistencies. The frequency of the BCV used in this experiment was 500 Hz, which is the range that generated the largest VEMPS in previous studies. Considering that the intensity of the BCV for vestibular stimulation is significantly different based on the participant's characteristics, the intensity of the stimulus depending on the participant [81] must be controlled. We used the following calibration method for the participant's comfort while applying vestibular stimulation: The vibration intensity was divided into 15 stages by setting the minimum and maximum outputs to 1 and 15, respectively. After applying the minimum-vibration-intensity stimulation to each participant, they were asked if they could tolerate the strength of the stimulation. If not, the intensity was decreased by one step, and, if possible, the intensity was increased by one step. Then, the same process was repeated. Thus, we obtained the maximum vibration intensity within the comfortable range for each participant.

3.3 Device 3: Caloric vestibular stimulation

The devices used in this experiment were a TES1-7102 thermoelectric module (Figure 7.(c)) to stably produce cold air at 24 °C. TES1-7102 is a 20 mm-sized thermoelectric module with a power consumption of 10.3 W, and the temperature difference between the high and low-temperature parts is up to 65 °C. To ensure stable performance of the thermoelectric module, a fan driven by a DC motor was attached to the heating part of the device to release heat to the back of the participant's neck (Figure 7.(c)). As shown in Figure 7.(a, d), the BLDC motor draws air from the vents and sends the air through the silicone tube to the thermoelectric module. The YWY-002F BLDC motor (Figure 7.(b)) was used to generate wind with low noise. The acoustic-noise level caused by cold air was approximately 65–70 dB. The cold air in contact with the cooling part of the thermoelectric module entered the participant's external auditory meatus via a silicone tube. An elastic band was used to

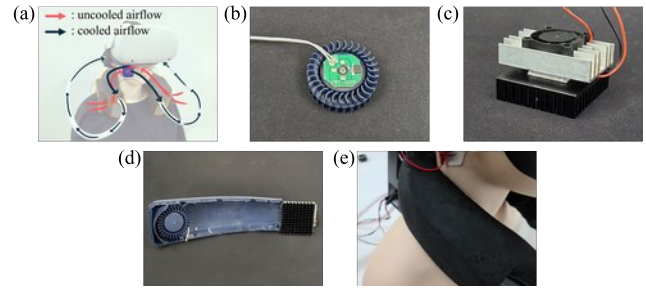


Figure 7: (a) Appearance of the CVS device and conceptual diagram of its working principle. (b) Appearance of the BLDC motor and (c) thermoelectric module used. This part is attached inside the device, as in (d), and all devices are insulated with polymer clay, as in (e).

secure the silicone tube to the ear, and a 3D printed plastic tip was used to apply cooled air stimulation to the participant's ear external auditory meatus. To insulate the device's cold air and ensure the participants' comfort, the device was coated on the outside with polymer clay (Figure 7.(e)). We conducted a preliminary test to confirm that our device can reliably produce cold air at 24 degrees. After mounting the CVS device on the head model, we attached a thermometer to the nozzle going into the participant's ear, and checked the temperature change of the air entering the participant's ear for 30 minutes. The preliminary test confirmed that at an external temperature of 26 °C, our device stably generates cooled air at 24 °C for 30 min, excluding the initial approximately 1 min required for cooling the thermoelectric module (All experiments in this study were conducted within 30 min). Therefore, first, the thermoelectric module was operated for 1–2 min prior to all CVS experiments to consistently create cool air.

The CVS used in this experiment was based on a previous study where cold air at 24 °C was blown into each ear through a nozzle into the external auditory meatus. The total airflow rate was set at 5 L/min. If the participant felt uncomfortable because the wind was too strong, the flow rate was reduced to 4 L/min. The outside temperature was always maintained at 26 °C during the experiment using an air conditioner. CVS is also triggered when visual information is modulated in the same manner as other noise-based vestibular stimulations.

3.4 Gait stability analysis

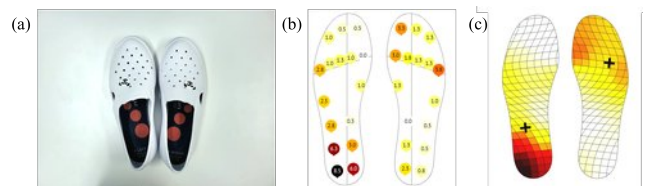


Figure 8: (a) Opengo plantar pressure sensor insole (Moticon, Germany) used and (b, c) an example of pressure measurement data.

In this study, we implemented a system that records plantar pressure in real time to measure A/P and M/L gait stability. Pressure was measured using an Opengo pressure sensor insole (Moticon, Germany) (Figure 8). We used three sensors of different sizes (approximately 240, 260, and 275 mm) depending on the participant's foot size. The sensor had 16 capacitive pressure sensors attached to each foot, with a measurement range of 0–50 N/cm² and a resolution of 0.25 N/cm. The area covered by the pressure sensors was 65% of the total area of the sensor insole. The sensor operates wirelessly and transmits the pressure data of each sensor via BLE communication. The transmitted data were stored at a sampling rate of 50 Hz, and the stored data were analyzed using MATLAB.

4 EXPERIMENT 1. QUANTITATIVE RDW PERFORMANCE VERIFICATION OF GVS, BCV, AND CVS (E1)

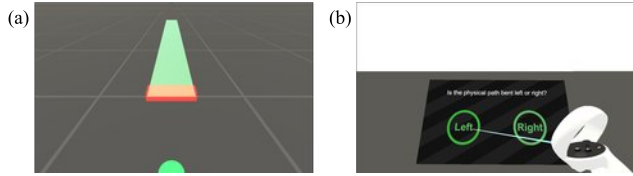


Figure 9: (a) The virtual environment used in E1. Participants had to walk straight along the green road, starting from the red block. (b) View of a user conducting a survey in the game.

This study investigated the possibility of using four vestibular stimuli in RDW: noisy GVS, directional GVS, BCV, and CVS. The following were hypothesized:

- **H1:** Non-electrical stimulations (BCV and CVS) can extend the curvature DT instead of electrical stimulation.
- **H2:** Direction-based stimulation (directional GVS) makes the user walking more stable than noise-based stimulations (noisy GVS, BCV and CVS).
- **H3:** Participants believe that non-electrical stimulations (BCV and CVS) are more uncomfortable than electrical stimulations (noisy GVS and directional GVS), and this interferes with the user's immersion and experience in the game environment.

H1 was set based on the MLE model of multisensory integration described in Section 2.3. When visual and vestibular information are conflicting, vestibular noise caused by BCV and CVS lowers the weight in the multisensory integration of vestibular information. Therefore, the visual–vestibular inconsistencies can be alleviated because the conflict is resolved owing to the relative predominance of visual information; thus, the curvature DT can be expanded. **H2** was set based on previous studies on gait stability presented in Section 2.5. Noise-based stimulations caused unstable gait because they restricted the use of vestibular information in gait in previous studies [77]. Because direction-based stimulation provides vestibular information modified to suit visual information, unlike noise-based stimulations, it will enable relatively more stable walking. **H3** was set based on the vestibular stimulation method of non-electrical stimulations. Non-electrical stimulations stimulate the vestibular

systems by using physical stimuli, such as vibrations or cold fluids. These physical stimuli can interfere with the user's immersion and experience. The experiment to verify the hypothesis was conducted in two stages. All experiments in this study were approved by the Institutional Review Board (IRB 20220628-HR-67-18-04).

In the first experiment (E1), quantitative factors, such as DT expansion performance, induced simulator sickness, gait stability, and stimulus discomfort, were tested when each vestibular stimulus was applied to the RDW. Each factor was measured by changing the curvature gain to 0, $\pm\pi/180$, $\pm\pi/90$, $\pm\pi/60$, and $\pm\pi/45$. The experimental environment was created based on the DT-measurement environment proposed by Steinicke et al [70] (Figure 9). In the second experiment (E2), a simple ball-search game environment with RDW was built. E2 was conducted on how users feel about RDW using vestibular stimulation in a realistic game environment, such as immersion and presence, task performance, simulator sickness, and stimulus discomfort over time. Based on the DT measured through E1, RDW was applied using the steer-to-center algorithm, which continuously redirected the user toward the center of the room [54].

Device wear and personalization. In all experiments and cases, participants wore the device in the same way so that the experimental results were not affected by the fit of the stimulation device. Before the experiment, all vestibular stimuli were applied once to each participant for personalization of stimulations. Two GVS stimuli were applied to the participant; if the participant felt extremely uncomfortable, the experiment was immediately terminated. In the case of BCV, the 15-step vibration personalization method introduced in Section 3.2 was used to determine the vibration intensity suitable for each participant. Finally, CVS stimulation was applied at a flow rate of 5 L/min. If the participant felt highly uncomfortable, stimulation was applied at a flow rate of 4 L/min. Before all experiments, the wearing condition of the participants was checked. If there was interference between devices (particularly in the electrodes of the GVS and the BCV vibrator), the position of the interfering stimulation part was modified such that the stimulation for the experimental case could be received well. The details of each experiment are as follows

4.1 Experiment Setup

In E1, we measured DT, gain stability, simulation sickness, and discomfort when vestibular stimulation was used for the RDW. The experimental environment was configured based on the DT-measurement environment proposed by Steinicke et al [71]. A detailed description of the experimental environment is presented in this section. In E1, each participant experienced four types of vestibular stimulation (noisy GVS, directional GVS, BCV, and CVS), and a control condition in which no stimulation was applied for a total of five cases. To exclude unexpected results from wearing the equipment, the equipment was worn under all conditions. We randomized the experimental sequence of all stimulation cases using Latin square. The participant experienced nine different curvature gains ($\pm\pi/180$, $\pm\pi/90$, $\pm\pi/60$, $\pm\pi/45$, and 0) in the experimental environment. Each curvature gain was randomly applied 45 times (five times per case). The total number of participants recruited in E1 was 20 ($N=20$, age range: 20–28, $M = 23.05$, $SD = 2.33$). No participant

had a history of epilepsy, vestibular system disorders, migraine, brain injury, cardiovascular disorders, central-nervous-system abnormalities, or sensitive skin. Pregnant women and people with pacemakers were excluded from this study. Moreover, no participant had motion-sickness symptoms for 3D games, and there were no problems with normal walking while wearing the HMD.

Questionnaire. We used the 2-AFC questionnaire used by Steinicke et al. to measure DT in this experiment [71]. Participants answered left or right to “Is the physical path bent left or right?” on the in-game VR per trial. We used the simulator sickness questionnaire (SSQ) to measure the simulation sickness once for each stimulus [30]. Furthermore, simulator sickness was measured once in the initial state before all the experiments. To measure the user’s discomfort in the game, we used Fernandes and Feiner’s discomfort score measurement questionnaire [18]. The participant answered, “On a scale of 0–10, zero being how you felt coming in, ten is that you want to stop, where are you now?” for discomfort with the VR controller.

Procedure. The participants changed shoes with pressure sensors to measure gait stability and answer the SSQ. After completing the questionnaire, the participants wore the stimulation device and calibrated the strength of the BCV. When the experiment started after taking sufficient rest after calibration, the participants started from the green disk shown in Figure 9 (a) and moved forward along the green path. All curvature gains were simultaneously applied after a straight path of 1.5 m to prevent the participants from noticing the gain. The participants walked along the path where a curvature gain of 5 m was applied (a total of 6.5 m walking) and stopped when the questionnaire screen appeared. The questionnaire comprised the 2-AFC questionnaire to measure DT, and Fernandes and Feiner’s discomfort score to measure discomfort. After the survey, the participants returned to the initial point indicated by the green disk shown in Figure 9 (a) and repeated the same task. When one case was completed, the participants removed the HMD, answered the SSQ for the case, and freely wrote about whether or not the stimulus was uncomfortable and the reason for discomfort. After the questionnaire, the participants were provided sufficient rest before conducting the experiment on the next stimulus case.

4.2 Result of E1

Table 1: Lower DT (LDT), upper DT (UDT), and PSE values measured for each vestibular-stimulation condition.

Stimuli type	Curvature DT results				Increase
	LDT	PSE	UDT	DT area	
Control	-0.055	-0.001	0.054	0.109	-
Noisy GVS	-0.055	0.003	0.061	0.116	6.42%
Directional GVS	-0.068	0.001	0.07	0.138	26.61%
BCV	-0.061	0.005	0.07	0.131	20.18%
CVS	-0.061	0.003	0.068	0.129	18.35%

4.2.1 Curvature DT of each vestibular stimulus. The curvature DT-measurement results of each vestibular stimulus were analyzed using the 2-AFC questionnaire. The results are as follows: Figure 10

shows the measured probability of the participant’s left response at nine different curvature gains ($\pm\pi/180$, $\pm\pi/90$, $\pm\pi/60$, and $\pm\pi/45$, 0). Each graph is marked with a standard error. Each measured value was fitted using a sigmoid function [71], and the calculated DT values are listed in table 1. The pooled DT region was the largest in directional GVS and expanded in the order of BCV, CVS, and noisy GVS. Furthermore, the pooled DT area between the lower and upper DT was the smallest in the control condition and expanded by 6.42%, 26.61%, 20.18%, and 18.35% in the noisy GVS condition, directional GVS condition, BCV condition, and CVS condition, respectively.

The above results confirm that the user did not notice the direction change when the directional GVS stimulus was applied. Furthermore, the user’s movement could be significantly changed. Directional GVS stimulation was the most advantageous in terms of spatial expansion or obstacle avoidance among all the conditions. In contrast, the noisy GVS stimulus exhibited the most negligible DT expansion, which was slightly different from the experimental results of Matsumoto et al. (12%–16.4%) because of the difference in the magnitude of the voltage used. However, additional verification is required (Matsumoto et al. used 100 V, whereas this study used 15 V).

4.2.2 Gait stability - Anterior/Posterior (A/P) gait stability. The results of A/P gait instability measured using plantar pressure data are as follows (Figure 11). Under all conditions, the absolute values of skewness and kurtosis did not exceed 3.0 and 10.0, respectively; thus, normality is satisfied [32]. To analyze the change in A/P gait instability according to the type of vestibular stimulation, a one-way analysis of variance (ANOVA) was used. The analysis showed a significant difference in A/P gait instability for the five different vestibular stimuli. $F(4, 895) = 8.747$, and $p < 0.001$.

Post-hoc comparisons were performed using Bonferroni correction for five different vestibular stimuli. The A/P gait in the control condition was significantly stable than that in the noisy GVS and BCV conditions. Furthermore, the A/P gait of the directional GVS was significantly stable compared to that of the noisy GVS and BCV, similar to the control condition. Although CVS was not statistically significant, A/P gait instability was higher than that in the control and directional GVS, and gait instability was lower than that of noisy GVS and BCV.

4.2.3 Gait stability - Medio/Lateral (M/L) gait stability. The results of the M/L gait instability measured using plantar pressure data are as follows (Figure 12). Normality was satisfied because the absolute values of skewness and kurtosis of all conditions did not exceed 3.0 and 10.0, respectively. One-way ANOVA was used to examine the effect of vestibular stimulation type on the M/L instability. The M/L instability for the five different vestibular stimuli showed a significant change ($F(4, 895) = 12.139$, $p < 0.001$).

The Bonferroni correction was used for post-hoc comparison of vestibular stimulation. The results for M/L gait instability were similar to those for A/P gait instability. In the control and directional GVS conditions, the M/L gait was significantly stable compared to those of the noisy GVS, BCV, and CVS conditions. Although not statistically significant, BCV had the most unstable M/L gait among GVS, BCV, and CVS. Additionally, although insignificant, directional GVS was the most stable during M/L walking. Thus, the noisy GVS, BCV, and CVS, which add noise to the vestibular

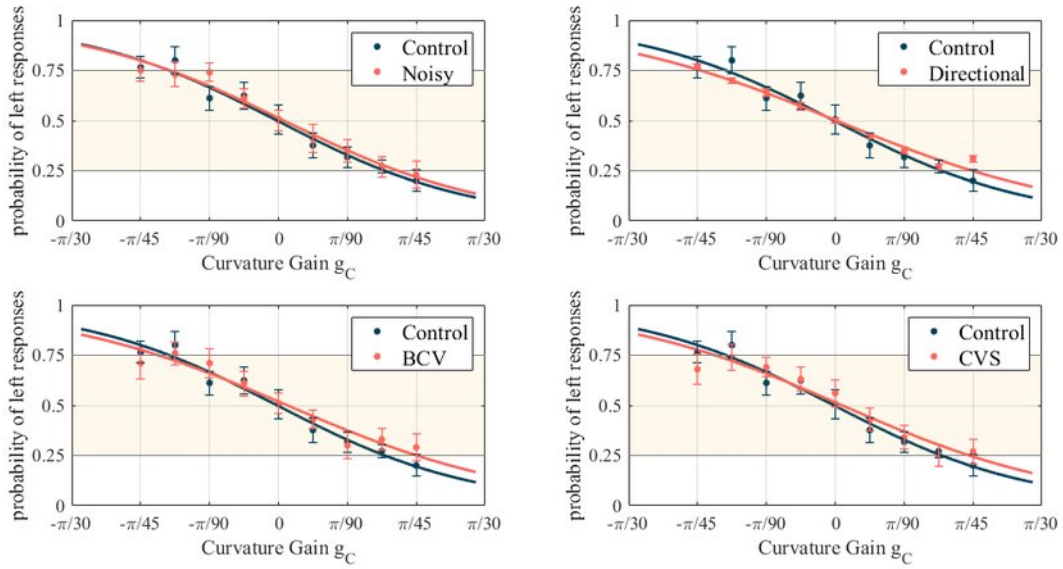


Figure 10: Pooled results according to each vestibular stimulation type of E1. The x-axis represents the curvature gain, and the y-axis is the probability that the participant answered that the physical path was curved to the left. Each result was fitted as a psychometric function. The 25% and 75% lines are marked, and the inner area is shaded in yellow.

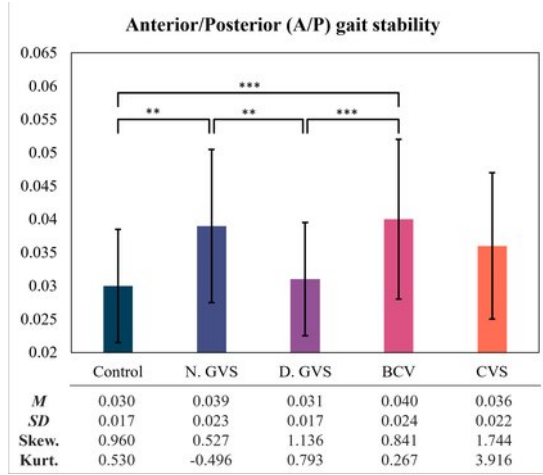


Figure 11: Anterior/Posterior (A/P) gait stability according to each condition. Error bars indicate standard deviation. ** $p < .01$, *** $p < .001$

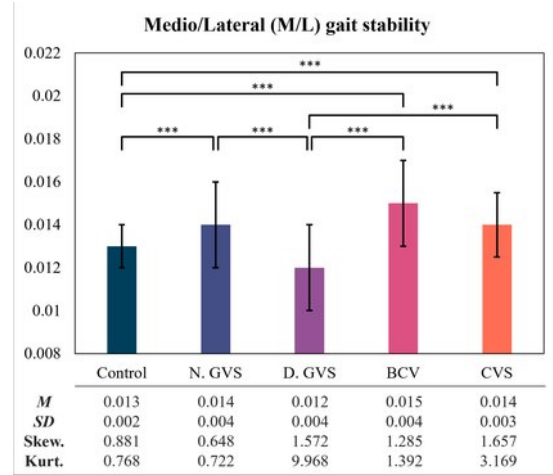


Figure 12: Media/Lateral (M/L) gait stability according to each condition. Error bars indicate standard deviation. *** $p < .001$

information, had higher gait instability in the M/L direction than that of the directional GVS, which provides vestibular information suitable for visual information.

4.2.4 Simulator sickness. The total severity scores measured using the SSQ are as follows (Figure 13). The simulator sickness was measured once in the initial state before the experiment and once for each of the five conditions. For all the conditions, the absolute values of skewness and kurtosis did not exceed 3.0 and 10.0, respectively;

therefore, normality was satisfied. We performed one-way ANOVA to determine the effect of each vestibular stimulus on simulator sickness. However, the simulator sickness for the five experimental conditions and one pre-question was not statistically significant, $F(5, 114) = 3.371$, $p = 0.007$, but $\eta_p^2 = 0.129$, indicating moderate significance.

Post-hoc comparisons of each condition were analyzed using the Bonferroni correction. The analysis confirmed that the simulator sickness significantly increased in the CVS condition compared to

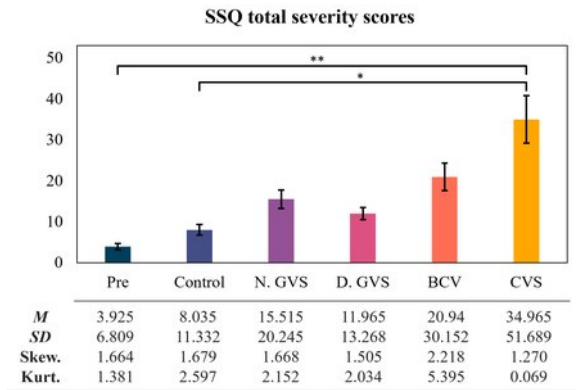


Figure 13: SSQ total severity scores for each condition in E1. Error bars indicate the standard error. * $p < .05$, ** $p < .01$

the pre-question and control conditions. While no significant difference was found in other conditions, directional GVS showed the least simulator sickness among the vestibular stimulations. Thus, the simulator sickness felt by the participant under the vestibular stimulation condition, except for CVS, showed a statistically insignificant change compared to the pre-condition and control conditions.

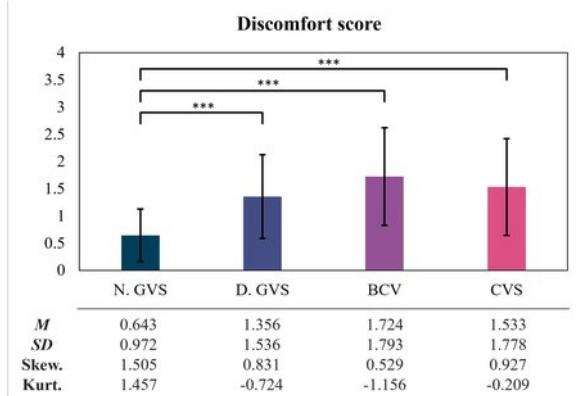


Figure 14: Discomfort scores for each condition in E1. Error bars indicate standard deviation. * $p < .001$**

4.2.5 Discomfort. The results of the discomfort of each stimulus collected during the game are as follows (Figure 14). The questionnaire was designed to assess current discomfort on a scale of 0–10. The skewness and kurtosis of the data collected from all stimuli satisfied normality considering their absolute values did not exceed 3.0 and 10.0, respectively. We performed a one-way ANOVA to analyze whether each type of vestibular stimulation affected discomfort. The discomfort results according to the four types of stimuli showed significant differences: ($F(3, 716) = 16.564, p < 0.001$).

The effect of each vestibular stimulus on discomfort was evaluated by post-hoc comparison using the Bonferroni correction. The analysis showed that the noisy GVS was the most comfortable, and

the discomfort was 50% lower than for all other vestibular stimuli. Although directional GVS, BCV, and CVS did not show a statistically significant difference, on average, users were most uncomfortable with BCV and least uncomfortable with directional GVS. Therefore, among the four vestibular stimuli, users felt uncomfortable with noisy GVS and other vestibular stimuli, except for noisy GVS.

4.3 Summary of E1

Through the E1 experiment, we confirmed the DT expansion performance, gait stability, simulator sickness, and discomfort felt by the users for each stimulus when each vestibular stimulus was used in the RDW. First, noisy GVS had the lowest user discomfort. However, the DT-expansion performance of noisy GVS was the worst; therefore, expecting a significant effect in space expansion or obstacle avoidance using RDW is difficult. In addition, noisy GVS has high gait instability, which may cause safety problems for the users. In contrast, directional GVS has higher user discomfort than noisy GVS. However, the DT-expansion performance was the best; therefore, using RDW to perform well in space expansion and obstacle avoidance can be expected. Furthermore, directional GVS has the lowest gait instability; hence, it can support a user in stably and safely walking in a virtual environment. Next, BCV has the advantage that it can be used as a non-electrical alternative for people who cannot use GVS, which is an electrical stimulus. A promising RDW performance can be expected because the DT-expansion performance of BCV is also high. However, similar to other methods of providing noise to the vestibular system, there is a high gait instability, which may cause safety problems for the user and has a disadvantage of high discomfort felt by the user. Finally, similar to BCV, CVS can be used as a non-electrical alternative to GVS, an electrical stimulation, but it induces significantly higher simulator sickness compared to other conditions. In addition, good usability and safety cannot be assured using CVS because of high discomfort and gait instability. We analyzed these shortcomings of CVS based on a survey of participants, which will be dealt with in the Discussion section. Based on the E1 results, the answers to **H1** and **H2** were obtained. For **H1**, we confirmed our hypothesis as BCV and CVS extended the curvature DT by 20.18% and 18.35%, respectively. Moreover, for **H2**, our hypothesis was confirmed because direction-based stimulation produced a more stable gait than noisy GVS, BCV in A/P gait stability, and all noise-based stimulations in M/L gait stability.

5 EXPERIMENT 2. USABILITY EVALUATION IN REALISTIC GAME SCENARIO OF RDW SYSTEM USING GVS, BCV, AND CVS (E2)

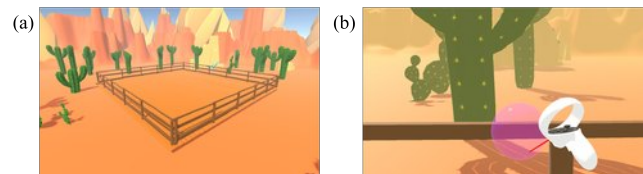


Figure 15: (a) A desert-style game environment used in E2. (b) Participants find a pink ball within the fence for safety.

Immersion and presence, task performance, simulator sickness, and discomfort were investigated over time when a user played a game to which RDW was applied using each vestibular stimulus. Based on the results of E1, the range of RDW curvature gain in a ball search game (Figure 15) environment of E2 was set. In E2, an experiment was designed to test the user's game experience according to the characteristics of each stimulus by unifying the range-of-curvature gains for all cases. The range-of-curvature gain used in this experiment is the average value of the DT obtained through E1, $[-\pi/52.360, \pi/62.086]$.

5.1 Experimental Setup

In this experiment, the experimental environment was constructed based on the environment used in the live-user experiment of RDW by Sun et al. and Hodgson et al [26, 72]. Each study used a game of finding a stick or a ball. Thus, the user could freely move around as much as possible in an environment where RDW was applied. Previous studies used fog or adjusted the transparency of the ball to encourage the user's free movement. In the present study, the same method as that of Sun et al. was used to control the transparency of the ball [72]. The transparency of the ball decreases in proportion to the distance between the user and the ball. Therefore, in a place far away from the ball, the ball is transparent, and the user has to randomly search the map to find the ball, moving around the map in various ways. In addition, we made the ball make a sound so that the user could enjoy the game using various modalities. The ball provides a stereo sound according to the location, and the user can search the ball by inferring the location where the sound is heard. The user walked freely in a virtual space of 5 m X 5 m in total and searched for a ball for three minutes per trial. The remaining time and the number of balls found are displayed on the UI at the bottom of the participant, encouraging participants to actively participate in the game. The total number of balls found in each condition was recorded as task performance and was used to indicate how well the participant performed the task required in the game. Participants experimented with each of the four vestibular stimuli and one non-stimulus control condition, and all trials were randomized to a Latin square. A total of 27 participants were recruited in E2 ($N = 20$, age range 20–36, $M = 23.89$, $SD = 3.17$). As in E1, no participant had history of epilepsy, vestibular system-related migraine, brain injury, cardiovascular disorder, central nervous system abnormality, or sensitive skin. Pregnant women and pacemaker wearers were excluded from recruitment. No participant had motion-sickness symptoms related to 3D games and VR, and there was no problem with walking for a long time while wearing an HMD.

Questionnaire. In this experiment, the following questionnaire was used to measure the immersion and presence, simulator sickness, and discomfort over time. For immersion and presence, the Igroup Presence Questionnaire (IPQ) was used, and three sub-scales (spatial presence, involvement, realism) were used [57]. Spatial presence measures the sense of being physically in the virtual environment. Involvement indicates the attention devoted to the VE and the involvement experienced. Experienced realism indicates how much the participant's experience in the virtual environment appear like the real one. Simulator sickness was measured using SSQ. IPQ and SSQ were measured once after the experiment for

each condition. Moreover, SSQ was measured once before all experiments to measure the initial state. We used Fernandes and Feiner's discomfort score measurement questionnaire every 30 seconds in-game to measure discomfort over time. The participant submitted an answer to "On a scale of 0–10, zero being how you felt coming in, ten is that you want to stop, where are you now?" about their discomfort while finding the ball. The timer for the remaining time during the questionnaire was stopped so the participant could think enough about the questionnaire.

Procedure. Participants first answered the simulator sickness in the initial state through the SSQ questionnaire. After the participant wore the vestibular stimulation device, the BCV strength was calibrated. After providing sufficient rest time after calibration, the participant stood in the middle of the room and waited for the experimental environment to start. After the experiment started, the participant explored the virtual environment using sight and sound to find as many balls as possible within the 3 min time limit. When a discomfort questionnaire appeared every 30 s during navigation, the participant stopped, answered the questionnaire, and then immediately resumed the game. After the time limit, the participant took off the HMD, answered questions, such as IPQ and SSQ, and had sufficient rest time. After sufficient rest, the participants proceeded with the experiment under the following conditions.

5.2 Result of E2

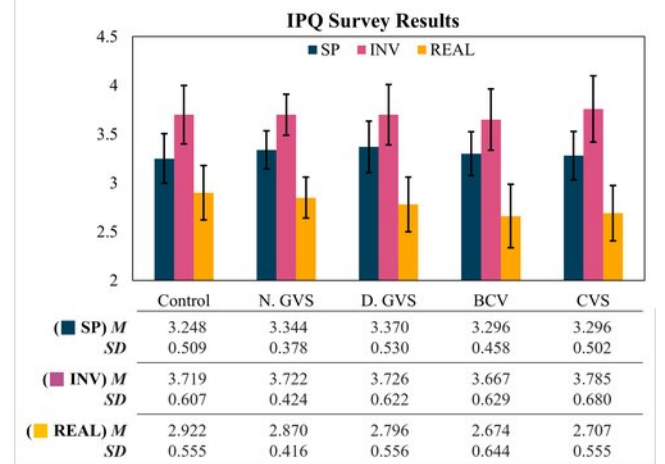


Figure 16: Three sub-scales of IPQ scores for each vestibular stimulus (spatial presence, involvement, and realism).

5.2.1 Immersion and Presence. Immersion and presence were measured on three subscales (spatial presence, involvement, and realism). The measurement results are shown in Figure 16. All the conditions satisfied normality because absolute skewness and kurtosis values did not exceed 3.0, and 10.0, respectively. A one-way ANOVA was performed to determine whether each vestibular stimulus affected immersion and presence. The resulting spatial presence ($F(4, 130) = 0.266$, $p = 0.899$), involvement ($F(4, 130) = 0.133$, $p = 0.970$), realism ($F(4, 130) = 0.985$, $p = 0.418$), and the total score ($F(4, 130) = 0.278$, $p = 0.892$) were not significantly different. These

results indicated that the imposition of vestibular stimulation on users does not impair immersion or presence. Therefore, in terms of immersion and presence, vestibular stimulation RDW is a system that does not harm the user's experience.

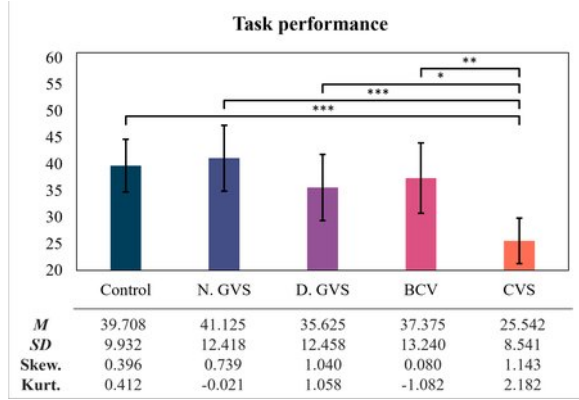


Figure 17: Task performance for each condition. Error bars indicate standard error. * $p < .05$, ** $p < .01$, * $p < .001$**

5.2.2 Task performance. The following are the results of task performance depending on the type of vestibular stimulation. Participants in this experiment had to find as many balls as possible within the 3 min time limit, and task performance was measured using the total number of balls found in each trial. The results are shown in Figure 17. In all cases, normality was confirmed by the absolute values of skewness and kurtosis. The ANOVA of the task-performance results for the five stimulus conditions was $F(4, 115) = 6.918$, $p < 0.001$, confirming statistical significance. As a result of post-hoc analysis using the Bonferroni correction, no statistical significance was found in any condition except CVS. However, the CVS had a significantly poorer task performance than the other stimulation conditions. Thus, we confirmed that vestibular stimulation, except for CVS, did not affect the user's ability to achieve the game goal using sight and hearing. However, CVS significantly hindered users from achieving the goal of the game, and the reason for this could be confirmed through the survey. Over 90 % of the users answered that the CVS wind noise interfered with the auditory experience of the game. Additionally, other opinions included difficulty concentrating and dizziness. Although BCV had auditory noise, there was no significant effect on the task performance compared to CVS noise. It is presumed that the noise of the CVS is wind noise and is distributed over the entire frequency range; however, the noise of the BCV is a single frequency of 500 Hz. Therefore, it was assumed that the auditory noise of the BCV did not interfere with the sound of the ball.

5.2.3 Simulator sickness. The following are the total severity scores felt by users in the actual game to which the RDW using each vestibular stimulus measured by the SSQ was applied. The simulator sickness was measured under six conditions. The absolute values of skewness and kurtosis did not exceed 3.0 and 10.0, respectively, in all conditions, thereby satisfying normality. The results are shown in Figure 18. The effect of each vestibular stimulus on simulator

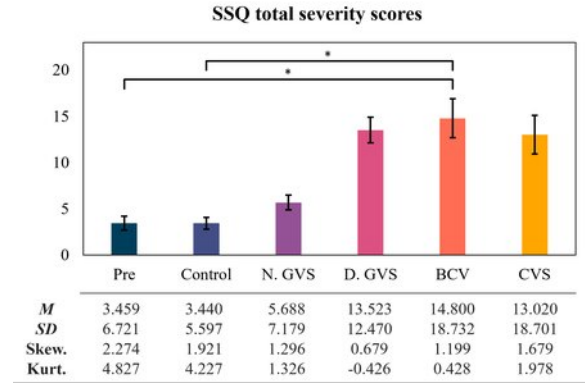


Figure 18: SSQ total severity scores for each condition in E2. Error bars indicate standard error. * $p < .05$

sickness was investigated using one-way ANOVA. As a result of the analysis, simulator sickness for the six conditions was $F(5, 146) = 4.493$, $p < 0.001$, which was statistically significant.

The Bonferroni correction was used for post-hoc comparison of all conditions. The analysis confirmed that BCV caused significantly higher simulator sickness than the pre-question and control conditions. Although not statistically significant under other conditions, the noisy GVS showed an average low simulator sickness compared to other vestibular stimuli. Therefore, each vestibular stimulus, except BCV, showed a statistically insignificant increase in the simulator sickness in the virtual game environment compared to the pre-question and control conditions. Among them, the increase in noisy GVS was the smallest. Thus, we could confirm that noisy GVS and BCV caused the least and most simulator sickness, in the E2 environment, respectively.

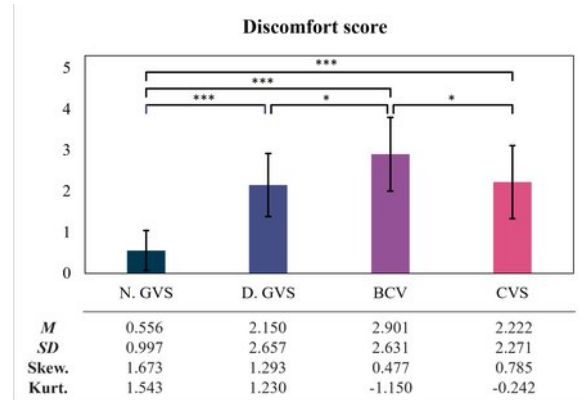


Figure 19: Mean discomfort score for each vestibular stimulus in E2. Error bars indicate standard deviations. * $p < .05$, * $p < .001$**

5.2.4 Discomfort. For Fernandes and Feiner's discomfort score measurement questionnaire, the participants responded in-game with a score of 0–10 for their discomfort every 30 s. We performed a

one-way ANOVA on six measurements for each vestibular stimulus to investigate whether there was a difference in the discomfort score with time for each vestibular stimulus. In all vestibular-stimulation conditions, no significant change in discomfort was observed with time, and the results were as follows: discomfort score over time with noisy GVS, $F(5, 156) = 0.131$, $p = 0.985$; directional GVS: $F(5, 154) = 0.241$, $p = 0.944$; BCV: $F(5, 156) = 0.026$, $p = 1.000$; CVS: $F(5, 156) = 0.067$, $p = 0.997$;

Therefore, we conducted a one-way ANOVA of the mean discomfort to investigate the differences in discomfort for each vestibular stimulus. The results are shown in Figure 19. For all conditions, normality was confirmed using skewness and kurtosis. The mean discomfort score for the four vestibular stimuli was $F(3, 642) = 31.831$, $p < 0.001$, which indicated a significant difference. We used the Bonferroni correction for post-hoc analysis. BCV showed significantly higher discomfort than all other stimuli. The directional GVS and CVS were lower than the BCV but induced higher discomfort than the noisy GVS. Finally, the noisy GVS significantly induced the lowest discomfort. Therefore, we confirmed that the noisy GVS and BCV were most comfortable and uncomfortable in the E2 environment, respectively. Most participants answered that the reason for the discomfort of BCV was vibration and the accompanying sound. They reported that the vibration of the BCV was itchy or painful and that a constant sound of 500 Hz was highly uncomfortable.

5.3 Summary of E2

We used RDW with vestibular stimulation in a game scenario similar to the environment experienced by real VR users in the E2 experiment, distinct from the E1 experiment. We implemented a game in which users find objects using their visual and auditory senses to assume a situation in which users experience actual VR content. We investigated users' immersion and presence, task performance, simulator sickness, and discomfort with vestibular stimulation RDW in an actual game environment. We confirmed that vestibular stimulation did not impair users' sense of immersion.

First, the noisy GVS showed excellent task performance and reduced simulator sickness and discomfort. Next, the directional GVS showed a statistically similar value to the noisy GVS in terms of task performance and simulator sickness; however, user discomfort was significantly higher than in the noisy GVS. Next, BCV induced the most simulator sickness and discomfort in the game environment. We confirmed that the vibration and sound of the BCV caused significant discomfort to the users. However, BCV did not interfere with the user's achievement of the game's goal, nor did it interfere with the sense of immersion. Therefore, improving the vibration and noise of the BCV is expected to reduce BCV discomfort. Finally, although CVS performed poorly on the task, it was comparable to directional GVS in terms of simulator sickness and discomfort. However, characteristic wind noise of the CVS prevents the user from achieving the game's goal using hearing. It will be possible to use the CVS as an immersive RDW system if the wind noise of the CVS can be effectively reduced.

H3 was concluded from the results of E2. Non-electrical stimulations indicated relatively high discomfort and motion sickness. However, the vibration stimulation of BCV did not cause low task

performance, and BCV and CVS did not diminish users' sense of immersion. Directional GVS induced a relatively high sense of motion sickness and discomfort among the electrical stimulations; therefore, our hypothesis H3 was false. This is analyzed in detail in the Discussion section.

6 DISCUSSION

In this section, we divide the vestibular stimuli into groups and analyze new aspects based on the characteristics of each group, unlike the above sections, which compared various aspects of all vestibular stimuli. The vestibular stimuli were classified according to two criteria. First, we divided vestibular stimulation into electrical stimulation (noisy GVS, directional GVS) and non-electrical stimulation (BCV, CVS). Second, we divided vestibular stimulation into direction-based (directional GVS) and noise-based stimulation (noisy GVS, BCV, and CVS). The following are the conclusions that we arrived at for each group.

6.1 Electrical versus non-electrical stimulations

We first compared electrical stimulation (noisy GVS, directional GVS) with non-electrical stimulation (BCV, CVS), and the most significant difference between the two groups was the side effects of electrical stimulation of the skin (e.g., skin, retina stimulation, eye muscle stimulation) [37, 76]. Non-electrical stimulation is a technique that can be considered for multiple users who are prone to side effects when electrical stimulation is applied to their skin [12]. Non-electrical stimulation uses vibration and cold air instead of electrical stimulation, which the participants primarily perceive as auditory noise. The BCV applies a vibration of 500 Hz within the human audible frequency. The CVS blows wind into the external auditory meatus, causing the vibration of the eardrum. Therefore, the participant experienced noise from all non-electrical stimulations, which significantly affected discomfort.

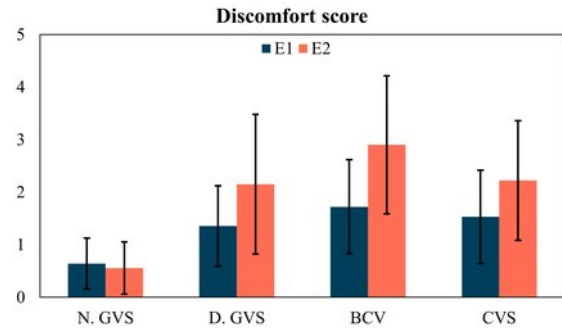


Figure 20: Discomfort score for each condition in E1 and E2. Error bars indicate standard error.

Figure 20 shows the discomfort scores for each vestibular stimulus in E1 and E2. The graphs demonstrate the difference in discomfort between E1 and E2. We observed that discomfort in the E2 condition was higher than that in the E1 condition for all non-electrical stimulations. While additional analysis is required to determine whether this is significantly attributable to the sample

difference in the two conditions, the data collected in each condition represent the entire population because statistically they satisfy normality [45], and the results still have informative implications in terms of showing the difference in user experience according to the environment. We analyzed this cause as auditory noise produced by the BCV and CVS. E2 was designed to use both sight and hearing to set up a more general VR gaming environment compared with E1. Therefore, users must continuously use what they hear to enjoy the game in E2. In this situation, non-electrical stimulations continuously provide noise to users, which induces audio interferences. Humans exhibit a high cognitive load when auditory elements with multiple pieces of information are simultaneously reproduced [78], and they experience a decrease in concentration and comfort [39, 79]. These audio interferences in the E2 environment of this experiment increased the cognitive load and caused discomfort. This can be verified by the user's answer to the reason for discomfort. The users felt "tingling" as discomfort caused by electrical stimulation, which was mostly the same for E1 and E2. However, the answers regarding the discomfort due to non-electrical stimulations were different in E1 and E2. Constant sound in E1 and other non-electrical stimulations, such as the vibration of BCV, were the primary contributors to discomfort. However, in E2, most participants answered that the sound was aurally uncomfortable while enjoying the game. This indicates interference between the auditory elements of the game and the noise induced by non-electrical stimulations, and the cognitive load induced by this interference caused the discomfort.

Audio interferences could be used to investigate why non-electrical stimulations cause relatively high discomfort at E2. However, we observed higher discomfort in the directional GVS in E2 although it was an electrical stimulation. This is because of the difference between direction- and noise-based stimulations, as described in the next section.

6.2 Direction-based versus noise-based stimulations

In this study, we alleviated the visual-vestibular inconsistencies in two ways: 1) Direction-based stimulations (directional GVS) provide vestibular information consistent with visual information, and 2) noise-based stimulations (noisy GVS, BCV, CVS) add noise to the vestibular information. The two methods exhibited a difference in gait stability, as discussed in Sections 4.2.2–4.2.3. Noise-based stimulations reduce the reliability of vestibular information, thereby alleviating inconsistency by reducing the weight of decision-making. This property restricts the use of vestibular information in gait, and, similar to previous studies, it was possible to confirm the result of inducing an unstable gait. In this section, we focus on how the presence or absence of directionality affects the discomfort and simulator sickness experienced by users in E1 and E2.

First, we analyzed discomfort. As can be observed in Figure 20, the discomfort to directional GVS, which is a direction-based stimulation, was higher in E2 than in E1. However, the reason for the discomfort answered by the user was the same, "tingling," in both E1 and E2. Therefore, we interpreted this increase in discomfort as an increase in the tingling frequency. The participant experienced a constant curvature gain during one trial in E1. Therefore, the

direction and amount of visual manipulation felt by the user during each trial were constant. By contrast, E2 constantly changed the amount and direction of the curvature gain to redirect the user to the center of the room. Therefore, the user experienced considerable changes in the direction and intensity of visual manipulation during one trial, and the change in the direction of current also occurred frequently following visual manipulation. Furthermore, the current direction changed more frequently because, in E2, the user had to turn their head in various directions to find the ball compared to the game in E1. Therefore, the current direction in E2 changed more frequently than in E1, and the user would experience more frequent tingling because of the frequently changing current direction.

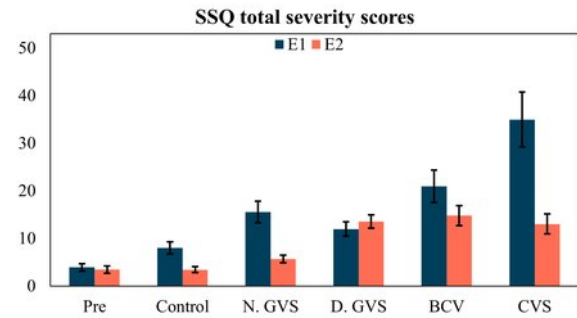


Figure 21: SSQ total severity scores for each condition in E1 and E2. Error bars indicate standard error.

Next, we analyzed the changes in simulator sickness at E1 and E2 with direction- and noise-based stimulations. As can be seen in the Figure 21, all noise-based stimulations decreased simulator sickness in E2 compared with E1, but the direction-based stimulations were almost the same. We believe that E2 had lower simulator sickness than E1 in most situations because of the difference in the time over which users experienced visual-vestibular inconsistency in RDW. The average time with RDW was 10–20 min for E1 and 3–4 min for E2. Therefore, the participants were less exposed to visual-vestibular inconsistency in E2 and showed relatively low simulator sickness compared to E1. However, direction-based stimulation induced relatively high simulator sickness at E2. We interpreted this to be because of frequent switching of the curvature gain at E2. There is a disadvantage in that it is challenging to determine how much current must be utilized to offer accurate vestibular information consistent with visual information [80]. A slight difference between the vestibular information modulated by directional GVS and visual information can significantly affect a participant's performance and comfort [37]. Although the direction of the curvature gain is the same as that of the vestibular information applied by the directional GVS, it may cause sensory inconsistency because the intensity changes continuously in E2. Therefore, direction-based stimulation is more susceptible to simulator sickness than noise-based stimulation. However, the alleviation of simulator sickness can be expected if the intensity of direction-based stimulations can be changed to match the curvature gain.

7 CONCLUSION & FUTURE WORKS

We implemented an RDW system using four vestibular stimuli: noisy GVS, directional GVS, BCV, and CVS, which successfully resolved visual–vestibular inconsistency. The RDW system was tested in two environments, and all the systems successfully verified the possibility of spatial expansion and obstacle avoidance performance without impairing immersion and presence. Furthermore, we could show the advantages and disadvantages of each type of stimulation (electrical versus non-electrical stimulation) and the modulation method of vestibular information (direction-based versus noise-based stimulation).

We succeeded in increasing the curvature DT by an average of 19.27% using non-electrical stimulations, demonstrating that non-electrical stimulations can be used as an alternative for people suffering from the side-effects of electrical stimulations. Although non-electrical stimulation can be used as an alternative for people experiencing side effects to electrical stimulation, it could destabilize gait; thus, it is not a completely safe alternative as it can increase the user's risk of falling. In contrast, electrical stimulations had significant advantages in the game environments; they did not generate acoustic noise; hence, they were free from the audio interference and induced relatively low discomfort. Moreover, the results indicated that the acoustic noise of non-electrical stimulations could cause an audio interference and induce discomfort in the gaming environment. In particular, the acoustic noise of CVS directly interferes with the auditory elements of the game.

Direction-based stimulations were found to enable stable gait compared to noise-based stimulation. Stable walking can protect a user from a dangerous situation where the user falls or loses the center of gravity. However, direction-based stimulations resulted in high discomfort and simulator sickness in a game environment where the curvature gain frequently changed. In contrast to direction-based stimulations, noise-based stimulation induced relatively low discomfort and simulator sickness in the game environment. We analyzed the cause of the frequent changes in the direction of stimulation and the difficulty in providing vestibular stimulation with the correct intensity.

The findings of this study provide a foundation for creating bespoke stimulation techniques tailored to the needs of both the user and the situational context. For instance, implementing BCV stimulation may be possible for individuals who experience adverse effects from electrical stimulation but can stably walk or to utilize simultaneous direction-based and noise-based stimulation to achieve a high DT without incurring user discomfort when visual manipulation is frequently changing. This study specifically focuses on examining the efficacy and user experience of various types of vestibular stimulations in RDW and does not delve into the combinations of such stimulation techniques. However, future research has the potential to address the limitations of certain stimulation methods, such as the risk of falls or discomfort, by combining different stimulation techniques.

In this study, we confirmed that the four vestibular stimulation RDW systems could successfully support users' seamless walking in VR by checking DT expansion, gait stability, induced simulator sickness, immersion and presence, discomfort, and task performance.

We preemptively verified the DT for the curvature gain of several vestibular stimuli. However, further studies could investigate vestibular stimulation in other RDW techniques, such as rotation and translation gain and using an attractor/distractor. In future studies, we intend to use our vestibular stimulation RDW system in more diverse environments. RDW technology can be used not only in games but also in numerous other VR scenarios. Inspired by this research, we intend to study users' experience of our RDW system in various VR environments. The environmental comparison in this work was between different participant groups; therefore, we will conduct research in various environments targeting the same participant groups in a follow-up study. A deeper understanding of vestibular stimulation RDW technology can be achieved by examining the effects of vestibular-stimulation RDW technology on users with more rigorous measurements and more diverse environments. In addition, we plan to conduct a follow-up study on our system's effect on users in various environments and interactions based on previous studies on the expansion of DT due to game elements and distraction in various environments [6, 48, 67]. In addition, to accurately measure the user's fall risk in various situations, we plan to develop an algorithm that can distinguish whether the user's gait instability is caused by each stimulation activated for RDW or is naturally induced by the user's interaction with the media in the application while walking. In addition, it is necessary to verify the performance of spatial expansion by quantifying how much each stimulation extends the perceived virtual space.

Finally, we will improve the way vestibular stimulation is applied. Noisy GVS could overcome the low DT scalability through voltage and current optimizations, whereas directional GVS could reduce user discomfort and simulated sickness by synchronizing stimulus intensity and curvature gain in RDW. BCV and CVS can make the RDW experience more comfortable and safer by reducing the acoustic noise (e.g., using cold metal for CVS). Reducing the discomfort of each vestibular stimulation would be an essential improvement and key step toward realizing the application of stimulation to various RDW techniques. Currently, our vestibular stimulation systems apply stimulation, which is sometimes uncomfortable, to the user following the modulation of visual information. Unlike RDW technology, where visual modulation occurs continuously (as in this study), vestibular stimulation can be a significant addition to overt redirection techniques (e.g., rotation gains with interventions and freeze-and-turn resetting).

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