Adding Proprioceptive Feedback to Virtual Reality Experiences Using Galvanic Vestibular Stimulation*

Extended Abstract†

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ABSTRACT

We present a small and lightweight wearable device that enhances virtual reality experiences and reduces cybersickness by means of galvanic vestibular stimulation (GVS). GVS is a specific way to elicit vestibular reflexes that has been used for over a century to study the function of the vestibular system. In addition to GVS, we support physiological sensing by connecting heart rate, electrodermal activity and other sensors to our wearable device using a plug and play mechanism. An accompanying Android app communicates with the device over Bluetooth (BLE) for transmitting the GVS stimulus to the user through electrodes attached behind the ears. Our system supports multiple categories of virtual reality applications with different types of virtual motion such as driving, navigating by flying, teleporting, or riding. We present a user study in which participants ($N = 20$) experienced significantly lower cybersickness when using our device and rated experiences with GVS-induced haptic feedback as significantly more immersive than a no-GVS baseline.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; **Virtual reality**; **User interface design**; *Haptic devices.*

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CHI 2019, May 4–9, 2019, Glasgow, Scotland UK

ACM ISBN 978-1-4503-5970-2/19/05…$15.00
https://doi.org/10.1145/3290605.3300905

KEYWORDS

Galvanic Vestibular Stimulation; Wearables; Interaction design; Haptic feedback; Virtual Reality; Cybersickness

ACM Reference Format:
Misha Sra, Abhinandan Jain, and Pattie Maes. 2019. Adding Proprioceptive Feedback to Virtual Reality Experiences Using Galvanic Vestibular Stimulation: Extended Abstract. In *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May 4–9, 2019, Glasgow, Scotland UK.* ACM, New York, NY, USA, Article 4, 14 pages. https://doi.org/10.1145/3290605.3300905

1 INTRODUCTION

The objective of virtual reality systems (VR) is to provide an immersive and realistic experience [63]. Most VR systems offer enough visual and auditory cues for the perceptual system to interpret the virtual environment as a place. The sense of being in this place is referred to as *presence* [53]. An important factor behind *presence* is perception through natural sensorimotor contingencies, i.e., the more the body is directly involved in the process of interaction, the more natural the virtual experience [52].

As the next step towards attaining a more natural and immersive virtual experience, researchers argue that VR systems should support the haptic sense [8, 56]. While the word *haptics* most commonly refers to the ability to sense a natural or synthetic environment through touch, it also includes proprioception or "muscle sense" [23]. Proprioception is defined as our ability to perceive position and posture, movement and velocity (kinesthesia), resistance or heaviness, and vestibular sensations [50]. In this work, our use of the term *haptics* refers to proprioception.

There has been a good amount of progress towards simulating the proprioceptive qualities of motion in VR, especially walking. The goal is often to create a more natural experience and to minimize cybersickness by reducing the visuo-vestibular conflict. Solutions include the use of omnidirectional treadmills [11] and walking-in-place systems that aim to mimic the limb motions of real walking. Unfortunately, people still got sick when they walked on a motion platform [34] and real walking was found to be more immersive than walking-in-place [65]. Other solutions include techniques like redirected walking [47], reorientation [46, 58], and $1:1$ mapping of physical and virtual spaces [56, 62]. A major limitation of these techniques is that physical dimensions of the tracking space constrain the size of the virtual worlds that can be explored on foot. While this limitation is overcome by design-based navigation methods like teleportation [7], magic carpets [45], or miniaturization [9], they introduce some new problems. The missing sensation of lower limb movement and corresponding proprioceptive feedback is inadequate [65] and the mismatch between the visual and vestibular system can cause cybersickness [48]. Additionally, *presence* in VR may break if the user does not get any kinesthetic sensation [51].

In this paper, we propose adding proprioceptive feedback to virtual motion by means of galvanic vestibular stimulation (GVS) using a custom built wearable device (Figures 3, 4). Traditionally used in physiology [18] and psychology [66], GVS is a specific way to elicit vestibular reflexes that has been used for over a century as a means to discover and probe the function of the vestibular system [19]. HCI researchers have considered possible applications of GVS, for example, Maeda et al. [37] affected another person's balance via remote control, Aoyama et al. [3] synchronized a video of a roller coaster with GVS feedback, and Nagaya et al. [44] investigated altering a person's visual perception based on music tuned to GVS stimulation. Although the effect of GVS in modulating the vestibular system is recognized, its use for enhancing *presence* and reducing cybersickness in VR remains quite limited. Maeda et al. [38] studied the relationship between vection produced by optical flow and vection created by GVS. They used randomly scattered dots under constant downward velocity as the visual stimulation to measure lateral body sway in a setup that did not employ a VR head-mounted display (HMD). In contrast, our device and study use an immersive 3D roller coaster experience to demonstrate how GVS can enhance *presence* and reduce cybersickness using the HTC Vive HMD.

While computing technology has a tendency of getting smaller, requiring less power, and becoming wearable over time, VR haptic feedback systems have not followed this trend. For example, haptic technologies like the Haptx exosuit[1], the Stewart platform[2] or the Infinadeck[3] are large, bulky, expensive and require considerable amounts of power. They resist miniaturization because they require physical motors, platforms, actuators and mechanics. In this work, we present a haptic feedback device in a lightweight wearable form factor that can be easily integrated with different types of existing VR devices and applications. GVS provides the advantage that it can be digitally controlled, and therefore lends itself to being connected with other sensing and game devices [10].

Using GVS for haptic feedback requires extensive background knowledge. This includes knowledge about circuit design to generate or modify GVS stimulus to achieve a specific vestibular response, the number and placement of electrodes, as well as the sensitivity and response behavior of different individuals. A lot of initial effort could thus be typically spent in building the hardware prototype before being able to explore the intended research questions [35, 64]. We present a plug and play system (Figure 4,6) that can help reduce the initial time and effort and enable researchers to quickly focus on the design of novel applications and interaction techniques. Our system comprises of a hardware module, a smartphone app, and a sample VR application. It offers a modular design that supports connecting different types of physiological sensors to the GVS device and provides a robust communication protocol using BLE. We hope our system serves as a starting point to explore GVS induced proprioceptive feedback for HCI research.

Our wearable device supports three different types of vestibular stimulation, namely: electrical, caloric and bone conduction. Electrical stimulation is known to activate the otoliths which provide a sense of linear acceleration, and the semicircular canals which provide a sense of angular acceleration [32]. This is useful in scenarios where the user is on a boat, driving, experiencing VR, or watching a 3D or IMAX movie. Caloric vestibular stimulation creates convection currents that stimulate the semicircular canals [6]. Both cold and hot air are used to elicit different types of sensations like body rotation or vertigo and can be used to induce nausea. Bone conduction activates the otolith neurons and provides an alternate pathway to inducing linear acceleration and a sense of gravity [15] and can be used during driving, flying or VR.

We chose electrical stimulation for our user study as it elicits vestibular reflexes faster than the other two techniques and speed was critical for the roller coaster experience. Among the previously explored responses to GVS are body sway, imbalance and tilt, changes in walking trajectory, vection, and eye movements. These reflexes are observed when a small current (below 2mA) is passed between the mastoid processes [19] (see Figure 5). Our study explores the impact of induced vection on *presence* and cybersickness in a VR application (see Section 5).

Our user study ($N = 20$) shows that participants enjoy the proprioceptive feedback; that presence is higher in GVS versus non-GVS conditions; that users predominantly felt lower cybersickness using GVS than without; that incorporating

[1]Haptx: https://haptx.com/
[2]Stewart platform: https://en.wikipedia.org/wiki/Stewart_platform
[3]Infinadeck: http://www.infinadeck.com/

GVS can be done even for existing applications; and that GVS based vection can be easily and effectively integrated into the design of new VR applications. With this work we aim to encourage designers to consider adding vestibular feedback for enhancing immersion in VR experiences and reducing cybersickness. The contributions of our work are:

- The concept of providing proprioceptive feedback corresponding to different types of virtual motion by means of galvanic vestibular stimulation.
- A lightweight wearable device that can be easily integrated with existing virtual reality devices.
- A mechanism to reduce cybersickness and enhance presence in virtual reality.

2 RELATED WORK

The work presented in this paper builds on research related to proprioceptive feedback for VR, in particular related to virtual locomotion, electrical stimulation, and cybersickness.

Proprioception

Haptics is subdivided into cutaneous feedback (e.g., tactile) and proprioceptive feedback (e.g., body position and motion) [22]. A large body of research in VR has focused on proprioceptive feedback received through natural body movement. Since natural walking leads to the highest sense of *presence* [65], it is a desirable feature in many VR applications though it remains a challenge because of space and tracking requirements. Redirected walking makes natural walking in VR possible by tracking and manipulating the user's real world trajectory [47] though it may cause cybersickness due to noticeable scene rotation. Change blindness is a perceptual phenomenon that occurs when a person fails to detect a visual change to an object or scene over time. It was used to allow a user to walk through a virtual environment that was one order of magnitude larger than the tracking space [61]. Inattentional blindness, another cognitive illusion, was used to allow users to walk through a virtual environment 4 times larger than the available tracking space [58]. Proprioception has also been used as an input and output mechanism where the system manipulates a user's limbs into specific poses through electrical muscle stimulation (EMS) and the resulting pose provides information to the user through proprioception [36]. The design is, however, limited to input and output for a single body part like the wrist. Our system provides proprioceptive feedback related to virtual motion by directly stimulating the user's vestibular system. It induces a full body sensation of motion and works for different VR scenarios such as walking, flying, or driving.

Electrical Stimulation

Electrical muscle stimulation (EMS) and galvanic vestibular stimulation (GVS), both originated in the field of medicine and continue to be used there. For example, noisy GVS has recently been shown to improve static postural stability in healthy subjects [20, 27] as well as improve dynamic stability during walking [69]. Both techniques have also been explored in HCI research. Tamaki et al.[64] guided users with EMS in learning a new instrument in possessed hand while Sra et al. [57] used GVS to remotely change a user's walking trajectory in an asymmetrical VR experience. In both these examples, electrical stimulation is used to move a limb through muscle stimulation or the body through inner ear stimulation. In our work, we use GVS as a feedback mechanism to add the sensation of motion without explicitly moving any body parts. Farbiz et al. [17] used EMS on the wrist muscles to render the sensation of a ball hitting a racket in an AR tennis game. Conceptually, our system is similar to theirs as it uses electrical stimulation to provide haptic feedback though we differ in our use of GVS. Moore et al. [42] used GVS as a training tool for astronauts to simulate post-flight effects. We use GVS to simulate lateral g-forces in a roller coaster experience. Byrne et al. [10] designed a non-digital balance game where two players stand on a wooden board resting on a wooden beam and use GVS to throw each other off balance. While Byrne et al. use GVS as an interaction mechanic between two co-located users, we use GVS as a feedback mechanic in a single user immersive VR experience. The similarity between both GVS devices ends at using the same century old technology of electrically stimulating the vestibular system. Our device supports caloric and bone conducted sound as additional stimulation techniques in a small wearable form factor. It provides a plug and play mechanism to add physiological sensors. It includes an accompanying Android app to provide a simple way for other researchers to use GVS + physiological sensing in their research. To the best of our knowledge, our work is the first to formally test the impact of GVS on *presence* and cybersickness (not simulator sickness) in an immersive VR experience, even though GVS has been used with screen-based or non-3D virtual experiences before [2, 3, 37, 38].

Cybersickness

Visually induced motion sickness or cybersickness is a syndrome that occurs when physically stationary individuals view visual representations of self-motion [24]. Cybersickness is usually attributed to conflicting inputs from visual and vestibular afferents [1]. Despite sophisticated visual displays, improved computational capabilities and reduced latency, visuo-vestibular conflict remains the leading cause of cybersickness, with an incidence rate of 68% following flight simulator exposure [12]. Cobb et al. [13] found higher levels of cybersickness symptoms in passive viewing conditions compared to active control over movement in the virtual environment. Studies have also found a higher rate for cybersickness for females vs males [5, 43]. Motion sickness like symptoms can develop during or after the completion of a VR experience, either immediately afterward [40, 60] or up to 12 hours later [29]. A 2012 study by Cevette et al. [12] found that synchronizing virtual head signals to the speed and direction of a moving visual field [39], significantly reduced simulator sickness in a non-VR flight simulator application. They used a 5-electrode commercial GVS device with the visuals projected onto a screen in front of a seated user who controlled motion in the flight simulator with a joystick. In contrast, our device is a small wearable with two electrodes, custom designed for use with VR devices and aims to mitigate cybersickness (different from simulator sickness [59]). Our device offers a potential haptic feedback mechanism for different virtual motions like driving, flying, teleporting or riding while simultaneously enhancing the sense of presence felt in the VR experience. Users may be standing, seated or moving while using our device.

3 CYBERSICKNESS VS SIMULATOR SICKNESS VS MOTION SICKNESS?

While the terms motion sickness, cybersickness, and simulator sickness are often used interchangeably, they refer to different conditions. Stanney et al. [59] found that cybersickness and simulator sickness have significantly different symptoms. Cybersickness is characterized by disorientation, dizziness and nausea as the main symptoms while simulator sickness predominantly displays oculomotor distress. The total severity of cybersickness was found to be approximately three times greater than that of simulator sickness [59] making it an important problem to be solved. Cybersickness is also distinct from motion sickness in that the user is often stationary but has a compelling sense of self motion or vection through moving visual imagery [34]. Cybersickness can occur strictly with visual stimulation and no vestibular stimulation whereas, vestibular stimulation alone can be sufficient to induce real world motion sickness [41].

Cybersickness is a challenging problem that causes some users to exhibit symptoms similar to real world motion sickness both during and after a virtual experience. There is no agreed upon single cause for cybersickness which is often described as a polygenic sickness [30]. However, there are three main theories, namely the sensory conflict theory, the poison theory, and the postural instability theory [34] Published in 1975, the sensory conflict theory is the oldest and most widely accepted [48]. It states that because many VR experiences are designed around the illusion of motion, the conflict that exists between the visual experience and the inner ear experience [1] causes cybersickness. This conflict is commonly experienced in virtual environments that involve motion like flying, driving, riding or teleporting. The poison theory states that the physiological symptoms act as an early warning system which the body misreads as having ingested poison, leading to an emetic response. The postural instability theory, developed by Riccio and Stoffregen [49], is based on the idea that the body's primary goal is to maintain balance and stability which is constrained by the environment, for example, walking on ice vs on concrete. A sudden change in environment causes instability for a period of time. Therefore, it is prolonged postural instability in VR due to change in environment from the real world that results in cybersickness. In this work, we subscribe to the sensory conflict theory.

4 GVS FOR VR

Our main idea is to induce appropriate proprioceptive feedback by means of GVS to help reduce cybersickness and enhance the sense of *presence* in VR. In this work, we employ the terms immersion and presence as distinguished by Slater and Wilbur [55]. Immersion describes the extent to which VR systems are capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality. Presence is: the sense of being there, the extent to which VR takes precedence over reality, and the way users refer to their experience as having been to a place vs having seen a place [54]. Thus, a system that accommodates multiple sensory modalities will increase the user's presence. Our device works as an input system into the user's body, electrically stimulating their vestibular system by passing current through electrodes placed on the mastoids behind the user's ears. This allows us to induce the physical sensation of acceleration synchronized to the flow of virtual motion, minimizing the visuo-vestibular conflict. Figure 1 shows four example application scenarios for GVS induced feedback. GVS is considered safe when used within specified current and time limits [19] and repeated use of GVS has been shown to result in no deterioration to global function [68].

Vestibular System

The vestibular system provides sensory information about motion, equilibrium, and spatial orientation. The vestibular labyrinth, which is composed of three semicircular canals and two otolith organs in each ear, senses angular and linear movement of the head, thereby contributing to stabilization of body balance [19]. Receptors send impulses to the brain about gravity and linear movement as detected by the utricle and the saccule. Rotational movement is detected by the three semicircular canals. The brain integrates vestibular data with input received from the eyes and proprioceptive information received from the skin, muscles, and joints to create a holistic

Figure 1: Our GVS device induces proprioceptive feedback for VR motions: (a) riding a roller coaster, (b) driving a car, (c) leaping forward, and (d) navigating by flying.

view of the user's current body pose. A person can become dizzy or exhibit symptoms of motion sickness if conflicting sensory input is received from the eyes, muscles and joints, and vestibular organs which happens often in virtual reality.

Preliminary Prototype and Pilot

To get user feedback we designed an initial prototype of the GVS device (Figure 2) and tested it with six participants (5 females, average age 22.3, SD 3.2). Half the participants received GVS stimulus while the other half played the VR game without GVS. We tested our system with a game called InCell VR which took participants on a journey inside the micro world of human cells. We conducted the experiment in a quite room and calibrated the HTC Vive for standing experiences. The game automatically moved the participants along a cylindrical path and required them to lean their head left or right in order to rotate their body to avoid obstacles. We chose the game due to its high speed virtual motion and the resulting visuo-vestibular conflict.

The study was approved by our Committee on the Use of Humans as Experimental Subjects and all participants signed a consent form. All participants signed a consent form before the experiment. They filled out a biographical questionnaire and the Kennedy Simulator Sickness (SSQ) questionnaire [29] before the trial. They also filled out the SSQ after the trial and provided open ended feedback at the end of the session. Experimenters introduced the game mechanics and goal before the trial started. All participants wore the GVS equipment but it was only turned on for half of them. Participants played two levels of the game including the tutorial level or played for 10 minutes, whichever came first. On average, the trial plus questionnaires took approximately 30 minutes. We used two-pole noisy GVS to stabilize the participants when they leaned left or right during the experience. Noisy GVS is GVS delivered through electrodes placed over the mastoids (Figure 5) as zero-mean current noise of an imperceptible magnitude.

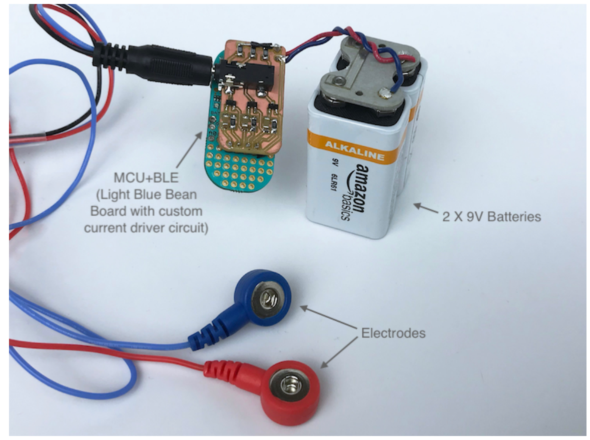

Figure 2: The first GVS prototype built using a Light Blue Bean Board with a custom current driver circuit board.

In general, participant reactions were positive. Suggestions from participants and our observations during the experiment helped inform the design of the second GVS device and user study. One with-GVS participant said they have had cybersickness in multiple VR experiences and they also get motion sick while playing video games. They were surprised and excited to report that they did not feel any dizziness or nausea during our experiment. Another participant said GVS made them feel stable and grounded even though the game did not allow them to control their forward motion. One of the without-GVS participants reported feeling queasy and closed their eyes during the experiment due to the sensation of falling backwards. Another without-GVS participant felt dizzy and needed to sit down after the experiment. Feedback about not feeling nausea or dizziness, especially by those who have experienced it before in VR, encouraged us to explore bipolar direct current (DC) GVS that is time synchronized with the direction of virtual motion (Section 5) to reduce cybersickness. DC GVS involves delivering electrical current subcutaneously through electrodes placed over the mastoid bones where the direction of current can be manipulated to go from anode to cathode or the other way around. A design concern that emerged from the experiment was the heavy weight of our device due to two 9V batteries attached to the GVS circuit (Figure 2). Participants said the weight constantly reminded them of the device's presence so they found it difficult to feel fully immersed in the virtual experience. The new version of our device does not use any 9V batteries but instead uses a small 3.7V Lithium Polymer (LiPo) battery (Figure 4).

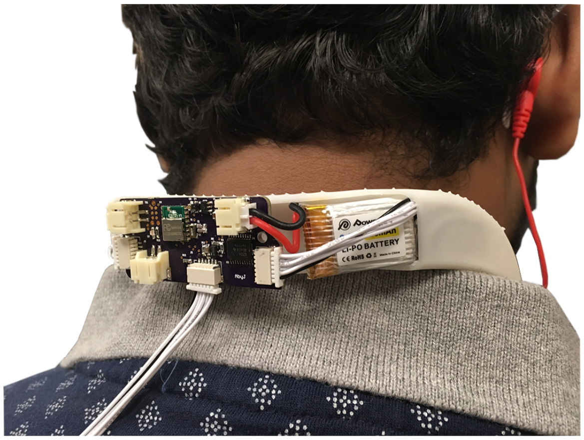

Figure 3: The second and final GVS prototype in the form of a small wearable device that sits on the user's neck, similar to behind-the-head earphones. The red wire connects the circuit to an electrode behind the user's ear. A similar wire connects to a second electrode behind the other ear. The white wires connect to EDA and HR sensors.

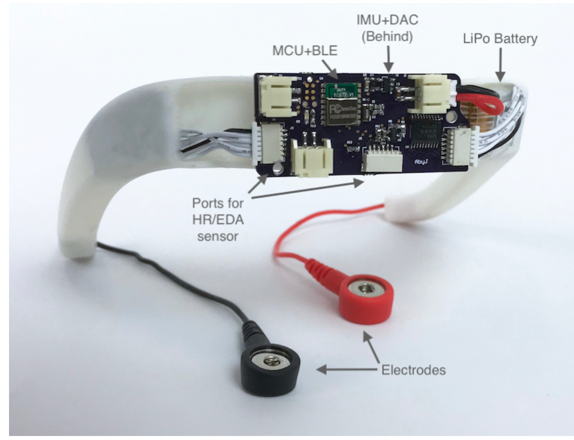

Figure 4: GVS prototype with the 3D printed housing, PCB, LiPo battery, sensor ports, and the electrode connectors.

System Design and Implementation

The objective of this work was to build a system that could provide the physical sensations accompanying different real world motions like driving, flying or riding, in VR. To help readers replicate our design, we now provide the necessary technical details. We custom built our GVS wearable device that sits comfortably on the user's neck and meets the safety compliance recommendations for maximum current output [18]. The electrical stimulation is triggered via a custom app running on an Android device that communicates with the device using Bluetooth Low Energy (BLE). Our system supports multiple combinations of electrode arrays to selectively evoke perceptions of roll, pitch, or yaw. Additionally, our system can use both DC GVS (direct current GVS) and noisy GVS [20, 27] (used in the pilot study) for inducing different vestibular responses. For the study presented in this work, we used bipolar DC GVS to induce yaw during a VR roller coaster experience.

Device

Figure 3 shows the second GVS device we created after receiving feedback from the pilot study with the first prototype (Figure 2). We built our device in the form of a lightweight wearable that is worn around the neck. It rests on the shoulders similar to behind-the-head earphones. The GVS app receives input from the VR application and sends corresponding electrical stimulus to the user's vestibular system through electrodes placed on the mastoids. The electrical stimulus induces the bodily sensations related to virtual motion by manipulating the user's vestibular system. Our device also supports physiological sensing through electrodermal activity (EDA), heart rate (HR) or other sensors which can be easily plugged into the main printed circuit board (PCB). For the user study presented in this work, we read EDA and HR data from the user's body and wrote GVS data to the user's vestibular system.

Hardware Implementation. The wearable device has the form of a neckband (Figure 4). It is comprised of two 3D printed sections that house the embedded electronics and wires. Figure 6 shows the opened up neckband with the PCB and the connected GVS electrodes, EDA electrodes and the HR sensor. The PCB uses a system-on-chip module for sensing, actuating and transmitting data via BLE. There is an on-board boost converter to get high voltage without requiring 9V batteries, a 3-channel current driver and a current sensor for each channel. We integrated a 6-axis inertial measurement unit (IMU), a low power digital-to-analog converter (DAC), and two H-bridge drivers for actuators to accommodate future inputs and outputs. The circuit is powered by a single cell 150mAH LiPo (lithium polymer) rechargeable battery. Under continuous use the device offers around 8 hours of battery-life.

System. We use three controlled voltage sources with a current sensor on each node to create a software controlled current source. The system generates biphasic 15V and we limit the current to a maximum value of ±2mA. Our current limitation follows published medical safety limits [19]. A first order low pass filter with cutoff frequency of 33Hz is used to convert 62.5KHz digital pulse width modulated (PWM) wave into an analog waveform to control each current source. The GVS signals are applied in a ramp style rather then as a step signal so as to minimize any tingling sensation experienced

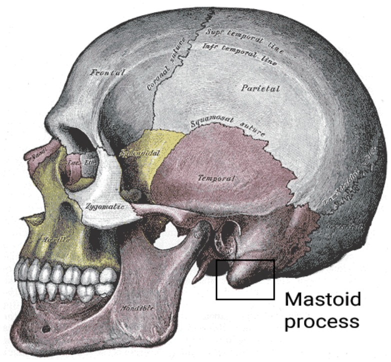

Figure 5: We attach electrodes to the mastoid process on the temporal bone behind each ear to electrically stimulate the vestibular system. Image courtesy: Wikipedia

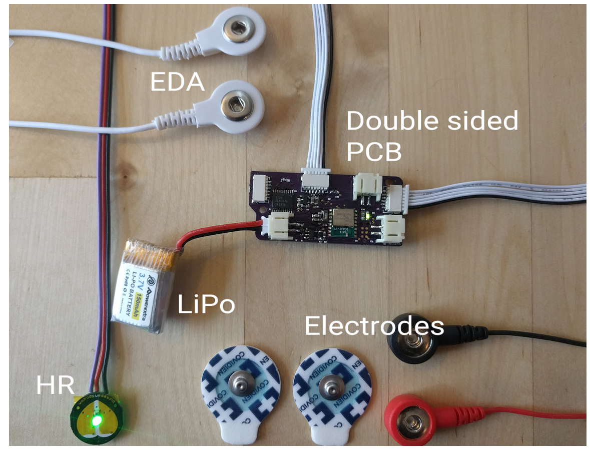

Figure 6: Our GVS device without the 3D printed housing. The image shows the EDA and HR sensors plugged into the PCB using the onboard connection ports.

by the user. Electrical stimulation is delivered through conductive hydrogel electrodes placed on the mastoids. Figure 5 shows the mastoid, which is the back part of the temporal bones situated at the sides and base of the skull.

Upon first use, the device needs to be calibrated for each user by testing the lowest stimulus that still leads to a recognizable sensation. In order to determine what is comfortable and appropriate for a particular user, we continuously increase the current until the user tells us they feel their body turning. Similarly, we calibrate the maximum signal that the user perceives as comfortable. We perform this procedure for GVS delivered as a zero-mean current noise (noisy GVS) or DC GVS, depending on the application scenario. At all times, our GVS system is pain-free.

Software and Data. The GVS stimulus is initiated and sensor data (if any) is captured using a custom built Android application. The smartphone and the hardware communicate over BLE. The stimulus timeline and intensity can be read or replayed from the smartphone. Developers can add triggers for GVS stimulation and other controls using any BLE enabled Android device or PC. The current circuit is programmed using an FTDI programmer though we are developing an application programming interface (API) that will allow anyone to program and customize the device.

Modular Design. Our design allows developers to connect new sensors and add more electrodes as needed. A VR roller coaster experience may only need two electrodes to simulate the lateral g-forces while a speed running experience may need three to account for forward acceleration. Figure 6 shows EDA and HR sensors connected to the PCB through the two bands of black and white wires.

Safety Considerations

For safety reasons the system is such that the maximum current cannot not go above 2mA [19]. The micro controller firmware has various embedded safety features like automatic turn off and connection based triggering. Our system defaults to zero stimulation if it receives no external command within a 2 second window. If the BLE connection is terminated by closing the Android application, the system halts all stimulation. This acts as a kill switch. Furthermore, the battery is easily removable to kill all power throughout the system. During the study, two researchers were present in the room, ready to stop the experiment at a moments notice or assist as needed. We also made sure that there were no physical obstacles near the participants.

5 EVALUATION

We conducted a user study in order to (1) validate our core idea of using GVS for adding proprioceptive feedback in VR, and (2) to test the impact of GVS on cybersickness and *presence* in VR.

Participants

We invited 20 participants (12 female, age range: $18 - 42$) to test the experience. Criteria for exclusion were epilepsy or a history of vestibular issues. Six of the participants did not have prior VR experience other than viewing 360 videos on devices like the Google cardboard. Nine participants reported being sensitive to real world motion sickness as experienced in moving vehicles. Six participants mentioned having had nausea or dizziness in VR even when using low latency VR devices like the Oculus Rift or the Vive.

Apparatus

We used the HTC Vive HMD, connected to a desktop PC with an Nvidia 1080 Ti graphics card. The experiment was conducted in a quiet room. The tracking area was configured for room-scale experiences and limited to 2.2m × 2.4m in size, providing enough space to allow participants to sway without hindrance. Disposable MyoWare hydrogel electrodes (30x20mm) were placed on the user's mastoid process behind each ear as shown in Figure 5.

VR Application. We used the NoLimits 2 Roller Coaster Simulation Demo from Steam[4] for the user study. The demo includes an editor mode which allows creating new roller coasters or modifying the included roller coasters. The demo also supports changing weather parameters like clouds, fog, or thunder.

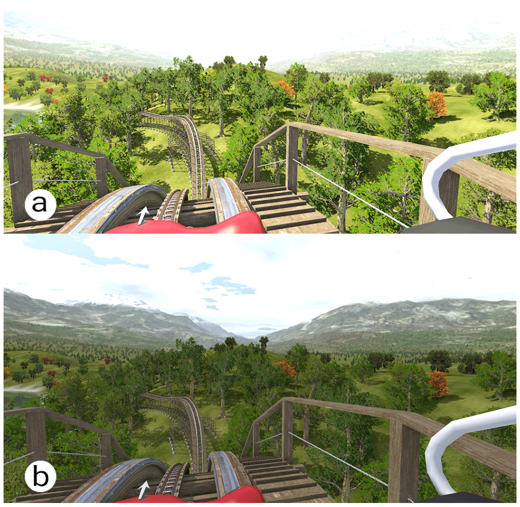

Figure 7: VR scenes for the with-GVS and without-GVS trials. (a) Full visibility, breezy sunny day. (b) Full visibility, overcast day with occasional thunder in the distance.

Experiment Design

To compare the difference between using our GVS device and the default VR experience, we used a within-subjects design. All participants did two trials, one with-GVS and one without-GVS, with a break in between. The order of the trials was counterbalanced between participants to account for carryover effect. The roller coaster experience used in the study offered a medium level of difficulty. To make sure participants were fully immersed in the virtual experience, we used headphones to cancel out any sounds from the experiment space. The study was conducted in a quiet room with only the participant and the experimenters present. Participants were encouraged to do a different activity during the break between trials like watch online videos or grab a snack to take their mind off the virtual experience. For the first trial, participants experienced the roller coaster with the default weather settings. In the second trial, we changed the weather conditions to include some thunder and clouds in order to change the virtual environment slightly without changing the actual roller coaster experience (Figure 7). This was done to add some variation without changing the experience and minimize any carryover effect.

Questionnaires. All questionnaires included a self-report checklist of symptoms, with subjects rating items on a Likert scale, with higher numbers indicating greater item intensity.

- 13 questions from the SSQ or the Kennedy Simulator Sickness Questionnaire, rated on a 0-4 point Likert scale (None - Severe) [31]. We excluded 3 SSQ questions that established the baseline and did not change throughout the experiment from analysis.
- 6 questions from the SUS or the Slater-Usoh-Steed VR *presence* questionnaire, rated on a 1-7 point Likert scale [54]. Questions were slightly modified according to the virtual environment used in the study.
- 14 questions from the core module of the GEQ or Game Experience Questionnaire, rated on a 0-4 point Likert scale (Not at all - Extremely) [26]. We excluded those GEQ questions that were not relevant to the VR experience.

GVS Parameters. The GVS current stimulus values vary across people which is why a calibration process is needed. The calibration took about 2 minutes per user and was based on perceived turning as reported by them. For roller coaster turns greater than 45 degrees, we used the higher intensity value as set during calibration while for all other turns we used the lower intensity value for that user. While we hardcoded the GVS stimulus triggers (direction of current and intensity) into the Android app for the user study, we are developing an API that will allow triggers to be easily programmed into a VR application during development as well as added post hoc to applications already available on the app store.

Procedure

In order to maintain equivalent exposure to the VR experience, the duration of each trial was set to 3 minutes, which was the time taken to complete a full roller coaster ride. Before each trial, participants were asked to sign a consent form and were presented with an information sheet about GVS. At this point, we also answered any questions participants had about the experiment and the GVS device. Following this, we

[4]Steam: https://store.steampowered.com/

asked participants to fill out a biographical information questionnaire and a pre-SSQ [31] regarding their current state. After each trial, participants were asked to fill out a post-SSQ along with the SUS [54] and GEQ [26] questionnaires.

Before the first trial began, experimenters introduced the study process and explained the VR experience. Since the placebo effect is the self-fulfilling effect of a user's expectations [33], to minimize it, the experimenters did not discuss the physical sensations that the participant might experience apart from the slight tingling on their mastoids. As reported at the end of the study, some participants did not even feel the tingling. Electrodes were placed on the participant's mastoids and connected to the GVS wearable. Electrodes were attached to two fingers for capturing EDA data and HR data was collected through a sensor placed on a fingertip. We helped the participants put on the HMD and headphones and started the VR application once the participant felt ready and comfortable. There were no handheld controllers needed and participants were asked to stand during the VR experience so as to amplify the responses of the vestibular system for the experiment. At the end of the study, participants were asked to fill out a final questionnaire asking them to compare their experience between the two trials and provide any feedback about their experience. Overall the trials took approximately 15 minutes each and the total duration of the study was about 40-45 minutes. Each participant completed nine questionnaires.

Hypotheses

Our hypotheses revolved primarily around the sense of *presence*, realism of the experience, and cybersickness. **(H1)** The with-GVS condition would be perceived as more realistic than the baseline condition. **(H2)** The with-GVS condition would lead to higher *presence* than the baseline condition. **(H3)** The with-GVS condition would cause less cybersickness than the without-GVS condition. **(H4)** The with-GVS condition would make users feel fewer negative emotions.

Data	wGVS	woGVS	Wilcoxon Test
Presence	3.60 ± 2.16	2.40 ± 2.19	$V = 110.5$, $p^* = 0.027$
Positive Aff	3.03 ± 0.88	2.55 ± 1.12	$V = 135$, $p^* = 0.032$
Flow	2.72 ± 0.82	2.37 ± 1.03	$V = 134.5$, $p^* = 0.034$
Negative Aff	0.59 ± 0.63	0.86 ± 0.84	$V = 37.5$, $p = 0.21$

Table 1: Mean scores and results of a pairwise Wilcoxon Test between with-GVS and without-GVS conditions for Presence, Positive and Negative Affect, and Flow.

6 RESULTS

We selected the roller coaster experience to be somewhat challenging with several twists, rises, and dips but without any 360 degree loops. All participants completed the experiment with two of them feeling quite nauseated and dizzy after the without-GVS condition. All statistical tests are two-tailed with a significance criterion of $P < .05$. We did not include an ANOVA because our data is not normally distributed according to the Shapiro Wilk normality test.

Presence

Presence is defined as the sense of "being there" [51]. Presence was determined using questions from the SUS inventory [54] presented after each trial. The scores reflect how many questions (out of six) were answered with a score of 6 or higher (on a scale of 1 to 7). A score of 2, thus means that a participant reported a high score (≥ 6) on two of the six protocols in the questionnaire. Figure 8 shows the boxplot of 20 participants' scores for both trials. A Pairwise Wilcoxon test indicates that participants had significantly higher presence when using the GVS device with the virtual experience (see Table 1). This confirms our hypothesis **H2**.

Game Experience

The GEQ core module probes the players' feelings and thoughts while playing the game. We used 14 questions to assess the gameplay experience on three components: Flow (5 questions), Positive Affect (5 questions), and Negative Affect (4 questions). A Pairwise Wilcoxon test shows Positive Affect and Flow as significantly higher in the with-GVS condition with respect to the without-GVS condition (see Table 1). The difference between the Negative Affect in both conditions was not significant. Using the GVS device during VR did not cause any more negative emotions than not using it (confirms hypothesis **H4**). Figure 9 shows the results of Flow in the two conditions. Participants experienced significantly more Flow in the with-GVS condition.

Cybersickness

The SSQ questionnaire has 13 questions that are sub-categorized into three specific symptom clusters: Nausea (N), Oculomotor (N), and Disorientation (D). Nausea includes symptoms of feeling of nausea, stomach awareness, increased salivation and burping; Oculomotor includes eyestrain, difficulty focusing, blurred vision and headache; and Disorientation includes feelings of dizziness and vertigo. The scores for each sub-category and the total score are determined using the procedure as described in the original paper [29]. Participants assigned a score of $0 - 4$ on a Likert scale with values ranging from None to Severe to the individual symptom variables in the questionnaire. This score was multiplied by the appropriate weight as listed in the paper and cumulated for each participant. The Total Score was calculated using the formula

$$TS = N * O * D * 3.74$$

The difference between pre and post trial scores (Table 2) shows the overall sickness build during the experience. The results show significantly lower cybersickness during the with-GVS trial. This confirms our hypothesis **H3**.

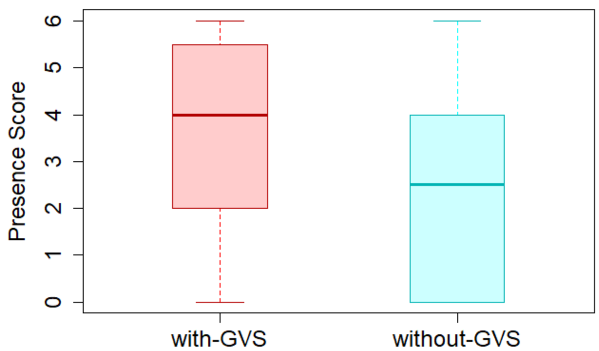

Figure 8: Participants had significantly higher presence when using the GVS device than without.

User Preference and Realism of Experience

When asked about their preference between GVS and the baseline VR experience, 85% (17 out of 20 participants) of the participants chose the with-GVS experience as their preferred choice (Figure 12). More participants rated the realism of their experience higher when using the GVS device (Figure 11). We believe this is because they could feel the lateral g-forces in their body that they would feel on a real roller coaster but the baseline VR experience did not provide any physical sensations.

Users provided open-ended feedback in the final questionnaire, at the end of the study session. Most participants could tell the difference between both conditions though one noted, "The difference was a lot more subtle than I expected (P3)." One participant said, "I prefer GVS since it gave me the feel of a roller coaster than just the visuals and music (P2)." From a participant who did the without-GVS trial first, "I felt less shakey (legs) the second time around (P4)." Comparing their experience in both trials, a participant remarked, "much better the gvs experience more realistic and less sick feeling after it (P10)." P19 said, "I prefer the GVS it felt more immersive." Regarding gameplay with GVS, P16 remarked, "I really enjoyed it!" One participant preferred the without-GVS experience because, "the wires on the sensor pulled on my skin a bit so it was hard to forget that they were there

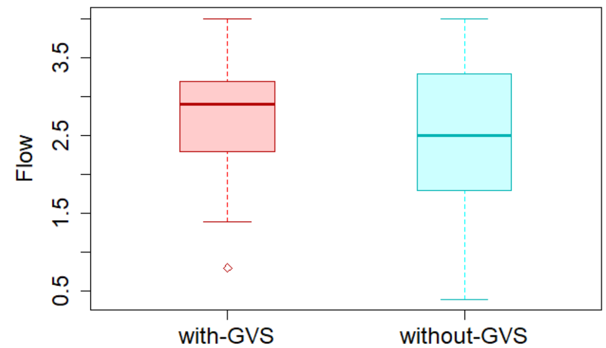

Figure 9: A Pairwise Wilcoxon test shows Flow was significantly higher in VR with the GVS device.

(P14)." Familiarity instead of novelty was the highlight for one participant who said, "I also think knowing how the roller coaster would turn out made the second round much more enjoyable P16)." This is not unlike real world roller coasters which people tend to enjoy over and over.

None of the participants reported residual tingling or any physical sensations after GVS was disabled. We requested them to inform us if they noticed anything after an hour and after 24 hours and did not hear back from anyone. Noisy-GVS on the other hand, as used in the pilot study, had some residual effects which faded within the hour. Cybersickness is a pervasive VR issue and GVS has the potential to help users who may otherwise be unwilling to try VR after an initial uncomfortable experience. Immersive visualizations of, for example, cancer cells or neuronal cells in 3D require researchers to navigate through the visuals using either a keyboard, a joystick or teleportation, techniques that all lead to a visuo-vestibular conflict resulting in cybersickness. Not only can GVS help enhance VR with haptic feedback, it has the potential to make the fundamental task of navigation in VR, comfortable and usable.

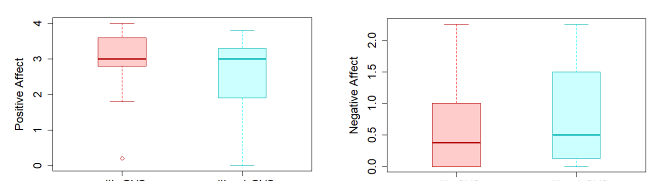

Figure 10: Positive Affect was significantly higher and there was no significant difference in the Negative Affect between the with-GVS and without-GVS conditions.

Data	Trial	with-GVS	without-GVS	Wilcoxon
Nausea	Pre	4.08 ± 5.58	1.90 ± 2.56	V = 29
	Post	8.05 ± 11.28	15.52 ± 20.22	*p = 0.046
Oculo-motor	Pre	5.67 ± 7.54	4.60 ± 5.97	V = 13
	Post	4.64 ± 5.46	8.09 ± 8.30	*p = 0.025
Dis-orientation	Pre	5.72 ± 7.75	5.62 ± 9.72	V = 22
	Post	9.91 ± 7.83	23.71 ± 26.13	*p = 0.033
Total	Pre	5.90 ± 6.19	4.51 ± 5.81	V = 21
	Post	8.04 ± 7.08	16.32 ± 17.82	*p = 0.0092

Table 2: Mean scores of evaluation and results of a Pairwise Wilcoxon Test for with-GVS and without-GVS conditions.

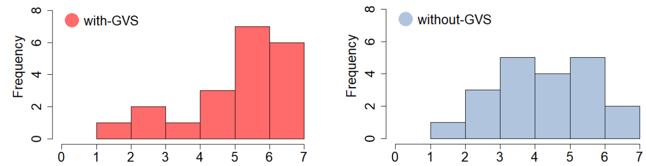

Figure 11: Perceived realism of experience is higher as indicated by responses to related questions in the SUS inventory for with-GVS and without-GVS conditions.

Physiological Sensing

Physiological sensors like HR and EDA can be easily plugged into our GVS device and controlled from the Android app. Sensor data is saved on the mobile device and can be exported for analysis. To collect EDA data, electrodes need to be attached to the fingers or the wrist while HR data can be captured by attaching the sensor to the ear lobe or to a finger. Unfortunately, we only managed to capture HR and EDA data for 6 out of the 20 participants, losing the rest to a faulty HR sensor. While we did not have enough data to analyze the relationship between cybersickness, heart rate and arousal, it was nonetheless a successful test of our device's modularity allowing us to plug in two new sensors and collect data.

Prior research has shown a correlation between heart rate and motion sickness in non-VR scenarios. Holmes et al. [25] found that heart rate varied significantly with the subjective ratings of motion sickness in an optokinetic drum experiment. The increase in heart rate was generally attributable to increasing ratings of motion sickness. Another study showed changes in autonomic responses (heart rate, respiration rate, finger pulse volume, and basal skin resistance or EDA) as a function of motion sickness. The physiological response levels changed rapidly at the onset of sickness with early changes in HR being the most consistent predictor of motion sickness [14]. Thus, inclusion and analysis of physiological sensor data can provide useful information in understanding the autonomic responses of humans to VR. Inspired by this research, we plan to explore the relationship between heart rate variability and cybersickness in VR with the goal of being able to predict a user's response to the VR experience.

7 DISCUSSION

The aim of this study was to explore the impact of GVS stimulus on *presence* and cybersickness in a VR experience. Despite being used to study the vestibular system since the early 19th century, GVS has only recently been explored in HCI research. To the best of our knowledge, the role of GVS on mitigation of vestibuloautonomic symptoms and impact on immersion and *presence* in VR has never been formally studied. In the present work, the results show that providing GVS stimulus in a virtual roller coaster experience mitigates all sickness categories as expressed in the SSQ [29] (see Table 2). Of special note are the significantly high means and variance in the post-trial without-GVS condition. This indicates that participants felt much worse after riding the virtual roller coaster when they received only visual and audio feedback. In addition, the results show that participants had a significantly higher sense of *presence* with GVS-induced proprioceptive feedback than the no-GVS baseline experience. Since a system that accommodates multiple sensory modalities increases the user's sense of presence [53], the data suggests that adding the physical sensations corresponding to the g-forces in the VR ride enhanced the user's experience.

During the study, participants staggered, leaned, and swayed in the without-GVS condition. Interestingly, several participants reported feeling similar movements of their body, especially leaning and sway, during the with-GVS condition even though there were no such movements observed. While we did not measure the changes in the amount of sway, prior work has shown that exposure to GVS induces prolonged postural stability in static or walking users [20, 69]. Our results suggest that matching the virtual motion with vestibular stimulation induces movement related proprioception thereby enhancing the overall experience which would otherwise be limited to the visual and aural senses. The muscle activity or proprioception evoked by GVS is not just limited to the head or neck but takes into account the orientation of all body segments from the head to the feet [18]. Thus, GVS induced proprioception may be a new type of feedback mechanism for enhancing VR experiences. The fact that our device is small and light and can be easily integrated into existing VR devices, makes it a possible real world solution to the challenging problem of VR sickness.

We took into account four considerations when designing the study: carryover effect, habituation, placebo effect, and novelty effect. To neutralize the possible carryover effect we counterbalanced the study where each participant started trial 1 alternately with or without GVS. Each trial was

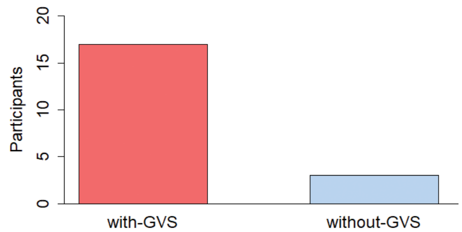

Figure 12: Results show that 85% of the users preferred the VR experience with the GVS device.

also separated by about 20 minutes which included the time participants spent filling out questionnaires after the first trial and a ten minute break. Separating two trials in time has been shown to be effective in reducing inter-trial carry-over effect for non-permanent effects [21]. Jang et al. [28] found that participant EDA increased steadily until around 7-8 minutes, at which point it leveled off. They argued that at this point the participants were likely habituated to the virtual environment. Prior work shows habituation of complex behavior like heel-toe walking [16] and body sway [4] occurred from long term GVS exposure (30min+). However, users did not get habituated to the illusory sensations of tilt and vestibulo-ocular reflexes [16]. Fujimoto et al. [20] showed that habituation of postural stability occurred after two sessions of 30 min long noisy-GVS stimulation. We were less concerned about habituation given the very short duration of our stimulus (max 6 sec and avg 3 sec per roller coaster turn) with a total VR exposure of 3 minutes per trial. Including a sham condition in the user study was challenging because participants had gone through a calibration process and knew how GVS induced physical sensations would feel. Despite that, there may have been a possible placebo effect on *presence* in the without-GVS condition. However, prior work shows no effect on the physical correlates of motion sickness in a balanced placebo design [67]. As for novelty effect, our results show that participants had high presence in both trials (Figure 8).

8 LIMITATIONS AND FUTURE WORK

We see this research as a first step towards more physical virtual realities with proprioceptive feedback. The next steps might include combining this approach with tactile and force feedback for a multimodal haptic experience. It might be worth exploring whether there are beneficial gains in task performance due to reduced cybersickness. Applications in training for unusual environments such as zero-g space travel are also worth investigating. We designed our study using bipolar GVS with two electrodes placed on the mastoids behind the ears. These two electrodes were sufficient to create the g-forces for the roller coaster experience. Adding more electrodes will result in more complex effects and sensations of yaw, pitch and roll. While this is something we have informally tested, we plan to conduct a more formal evaluation in the future. In addition, we plan to release an API that will allow others to program GVS triggers into new or existing VR applications. Lastly, we want to explore different form factors for our wearable device.

9 CONCLUSION

In this paper, we presented a new approach to rendering proprioceptive feedback related to virtual motion by means of galvanic vestibular stimulation. We introduced a wearable GVS device that works with an Android app to subcutaneously deliver electrical stimulus to the user's vestibular system via electrodes placed on the mastoids. Our device is modular and offers a plug and play design that supports adding physiological sensors and multiple electrodes as needed. The user study demonstrated that our GVS device not only enhances the user's sense of *presence* in VR, it also reduces cybersickness. Besides the direct implications for increased realism in VR gaming, our device might be able to provide a practical solution to the challenging and pervasive problem of cybersickness. Additionally, GVS based haptic feedback may uncover new terrain for proprioception based interaction design.

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