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Using Galvanic Vestibular Stimulation to Enhance User Experiences in HMD-Based Virtual Reality

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ABSTRACT

Research shows that visual-vestibular interactions can have profound effects on experiences of self-motion, presence and cybersickness in virtual reality (VR) using head mounted displays (HMDs). We review some of this literature and provide new insights into how Galvanic Vestibular Stimulation (GVS) could help to improve user experiences in HMD VR.

1 Introduction

Head-mounted displays are fast becoming popular devices used by consumers for engaging in immersive VR. However, user experiences are often impaired due to enduring visual-vestibular conflicts generated by these systems (Kim et al., 2015, 2020, 2021, 2022). How can these potentially adverse effects be mitigated or avoided altogether? We review some of our recent research and identify potential benefits of using GVS as an innovative tool for enhancing user experiences in HMD VR.

In our initial research using the Oculus Rift DK1 in seated participants, we imposed visual-vestibular conflicts by systematically modifying the gain of visually simulated changes in angular head orientation as participants actively rotated their heads (Kim et al., 2015). Radial flow displays simulated self-motion in depth, and visually simulated changes in head orientation either compensated for physical head rotation (no sensory conflict), did not compensate (moderate sensory conflict), or inversely compensated for head rotation (high sensory conflict). Increasing visual-vestibular conflict generated a modest but significant decline in the strength of *vection* – the illusion of self-motion experienced when engaging in HMD VR while stationary (see Palmisano et al., 2015).

One potential explanation for the limited decline in vection observed with increasing sensory conflict was saturation from the underlying display lag. The Oculus DK1 has a relatively high system latency (i.e., display lag) that was optically estimated to be ~60-70 ms (Palmisano et al., 2017). Hence, studies using the Oculus DK1 likely explored the effects of adding more sensory conflict to already significant conflicts due to display lag.

To explore the effects of display lag in isolation, we turned our attention to the Oculus CV1, which has a very low baseline display lag (~5 ms - Feng et al., 2019). Inflating display lag above this baseline level has been found to significantly increase the likelihood and severity of reported cybersickness during angular head rotation (Kim et al., 2020, 2022). These studies found that angular visual-vestibular conflicts also appeared to impair experiences of *spatial presence* – the sense of "being there" in the virtual environment (Witmer & Singer, 1998). Kim et al. (2022) also found these sensory conflicts reduced reported vection strength.

By contrast, linear visual vestibular conflicts do not appear to either generate strong increases in reported cybersickness or significantly alter feelings of presence (Kim et al., 2021). In that study, participants viewed an environment containing 3D cube objects using the Oculus Quest HMD while oscillating their heads from side-to-side along the interaural axis. Correct and inverse visual compensation was imposed during these linear head movements. Despite generating significant increases in perceived scene instability, Kim et al. (2021) found presence remained invariant, and significant cybersickness was only observed during stereoscopic viewing conditions. This suggests that linear visual-vestibular conflicts might not be as provocative for cybersickness as angular conflicts.

It is important to note that participants in the Kim et al. (2021) study could only move their heads linearly over a small distance due to biomechanical constraints. One way to simulate larger changes in head position would be to present passive simulations of self-motion throughout a larger virtual environment. This is where GVS could potentially provide huge benefits for improving user experiences of self-motion during seated/standing HMD VR, as GVS artificially stimulates the primary vestibular sensory neurons (see Kim & Curthoys, 2004) without the need for any head movement.

Previous research has found that the direction of GVS flow relative to the inner ear can induce predictable directional experiences of self-motion perception (Aoyama et al., 2015). This stimulation can be conveniently synchronised with visually simulated inertial forces applied to the head in HMD VR, as the same authors demonstrated at Siggraph in 2017 (Aoyama et al., 2017). Nakayama et al. (2018) synchronised GVS with the visual display of self-motion in a “virtual roller coaster”. They proposed this synchronisation of GVS with HMD VR could enhance user experiences of presence. However, they did not formally report on any direct measures of presence, relying on informal self-reports from participants in their “GVS RIDE” demonstration.

Some studies have synchronised changes in GVS intensity with visual simulations of angular rotations of the head, finding that presence is improved and cybersickness mitigated (Sra et al., 2019; Groth et al., 2022). Other studies found that vection onset latency could be reduced during delivery of ‘noisy’ GVS at the onset of a simulated rotation of the head around the roll axis (Weech & Troje, 2017). However, no study has yet examined the effects of GVS synchronization on the experience of presence, vection and cybersickness during visually simulated linear self-motion. The aim of the current pilot study was to investigate whether GVS, delivered in ways that are either consistent or inconsistent with visually simulated linear changes in head position, differentially affects these outcome measures during HMD VR.

2 Experiment

This pilot experiment aimed to: (i) create a cost-effective GVS device; and (ii) assess some of the perceptual effects and postural responses generated by the application of GVS during HMD VR in standing participants.

2.1 Participants

Six adult participants were recruited who had normal or corrected-to-normal vision and no known neurological impairments. Procedures were approved by the Human Research Ethics Advisory Panel of UNSW Sydney.

2.2 Galvanic vestibular stimulation

We initially created a cost-effective GVS device from components that are readily available through local electronics suppliers. The device was powered by a stack of four AA batteries that provided a safe isolated current source. The initial collective input voltage of 6V was multiplied by a boost module to set the rail voltage range from 0V to ~18V DC for an operational amplifier. The command voltage to drive the operational amplifier output was generated by separate channels of a PMD-1208LS digital to analog converter (Measurement Computing™). Thereby, output voltages achieved up to 12V DC with the output current from the operational amplifier limited to a maximum current intensity of 2mA. An H-bridge was constructed from a set of NPN and PNP transistors (Figure 1A) to direct polarities of GVS between surface gel electrodes placed over each mastoid (Figure 1B).

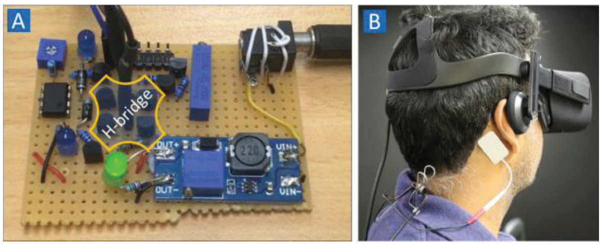

Fig. 1: A battery-powered current generator with H-bridge (A) used to deliver trans-mastoidal GVS (B).

2.3 Virtual environment

The virtual environment was identical to that used in a previous study (Chowdhury et al., 2021). An Nvidia GeForce RTX2080 graphics card on a PC simulated self-motion over a bumpy 3D terrain illuminated by a surrounding sky texture. The terrain was created using a 3D mesh of vertices whose heights were adjusted according to a cloud-noise texture. A *pure radial flow* condition simulated self-motion in depth by increasing the z-coordinate of the texture map position over time. Heights of the vertices were adjusted in real-time by an OpenGL Vertex Shader. Simulated inter-aural head translations were added to radial flow patterns in *viewpoint oscillation* conditions by sinusoidally modifying the texture’s x-coordinate at 0.4 Hz over time.

2.4 Procedure

Participants stood upright wearing the HMD to view four 90 s trials (the first 30 s involved stationary stance with no optic flow). Four counterbalanced conditions were presented (pure radial flow, viewpoint oscillation without GVS, viewpoint oscillation with consistent [+]GVS, and viewpoint oscillation with inconsistent [–]GVS). The signs of these GVS polarities were based on known human postural responses to the inertial forces ‘simulated’ in the vestibular stimulation by GVS (Fitzpatrick & Day, 2004). Consistency in GVS was determined by the anodal-cathodal polarities between the left and right ears simulating inertial linear forces applied to the head that were congruent with visual simulation of inertial forced during viewpoint oscillations.

Psychophysical ratings on presence, vection and cybersickness were obtained using 21-point scales as used a recent study (Kim et al., 2022). Cybersickness was measured using the Fast Motion Sickness questionnaire (FMS – see Keshavarz & Hecht, 2011).

3 Results

Mean and standard errors for each condition are shown for vection strength, presence and cybersickness in Figure 2. A repeated-measures *t*-test found mean vection strength was significantly greater in the viewpoint oscillation condition, compared to the radial flow condition (t_{10} = 3.13, $p < .05$). Vection strength was significantly greater for the [+]GVS condition, compared with the viewpoint oscillation condition (t_{10} = 2.80, $p < .05$). However, mean vection strength was not significantly greater for the [-]GVS condition, compared with the viewpoint oscillation condition (t_{10} = 1.22, $p = .25$).

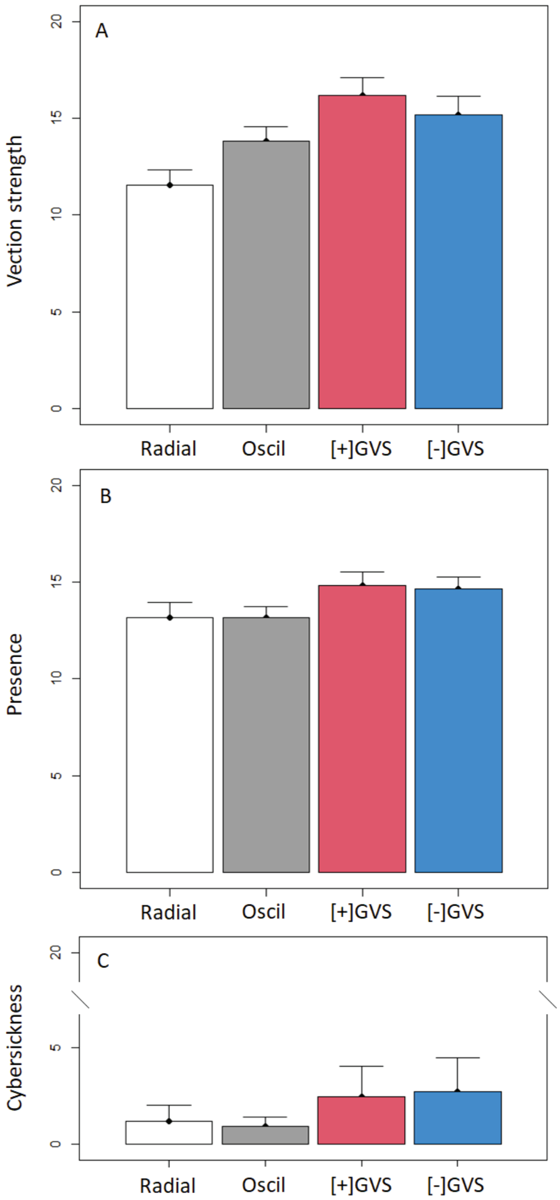

Fig. 2: Means and standard errors of the Vection Strength ratings (A), Presence ratings (B) and Cybersickness ratings (C) for the four test conditions.

Mean presence ratings were not significantly different between the radial flow and viewpoint oscillation conditions (t_{10} = 0.00, p = 1.0). Mean presence was greater for the [+]GVS condition and the [-]GVS condition, compared to viewpoint oscillation condition, but did not reach significance ($p > .05$). No significant cybersickness was found in any condition ($p > 0.05$).

We examined the relationship between the three subjective outcome measures using Pearson's correlations (Table 1). There was a significant positive linear relationship between vection and presence (r_{42} = +0.71, $p < .001$). There was also a significant positive linear relationship between presence and cybersickness (r_{42} = +0.31, $p < 0.05$). There was no significant correlation found between vection and cybersickness ($p > 0.05$). These results provide support for the existence of a strong positive linear relationship between presence and vection, even when conditions involving the delivery of GVS are considered.

Table 1: Inter-correlation between the subjective outcome measures (df=42; *p<0.05, **p<0.001).

	Vection	Presence	Sickness
Vection		+0.71**	+0.28
Presence			+0.31*
Sickness			

4 Discussion

Consistent with previous vection literature, we found that adding visually simulated viewpoint oscillation along the inter-aural axis improved vection strength (relative to the presentation of smooth radial flow that simulated the same self-motion in depth – see Palmisano et al., 2011 for a review). In terms of the effects of vestibular stimulation, our results appear to show that GVS best increases vection when it occurs in the same inertial direction as the visually simulated changes in linear head velocity. Applying inverse GVS (i.e., GVS which is inconsistent with visually inferred inertial direction) generated comparatively lower mean vection strength.

These preliminary findings build on those of previous studies reporting that synchronisation of GVS with visually simulated *angular* head rotations reduces vection onset latency (e.g., Weech & Troje, 2017). Here, we find vection strength can be improved during synchronisation of constant-current [+]GVS with visually simulated *linear* head movements. Our data further suggest that sensory conflicts could be generated during [–]GVS that might limit the potential benefits of applying synchronised GVS, relatively to the simulated viewpoint oscillation advantage for vection (Palmisano et al., 2011).

Similar to vection data, presence was overall greater during [+]GVS or [–]GVS, compared to the other conditions. The positive linear relationship between vection strength and presence is consistent with the possible co-dependence of these outcome measures in the mid-level visual processing of visual environments and our experiences within them. No significant relationship was found between vection and cybersickness, consistent with another recent study that added simulated angular head rotations to simulated self-motion in depth (Keshavarz et al., 2019). The positive relationship between presence and cybersickness disagrees with our previous work (Kim et al., 2020), though this is likely attributed to the conditional differences between studies.

5 Conclusion

Unlike other studies with noisy GVS or constant-current GVS, delivery of GVS did not mitigate reporting of cybersickness in our pilot study. However, this may be due to lower rates of cybersickness generally being reported during presentations of linear (as opposed to angular) visual-vestibular conflicts (Kim et al., 2021). We propose GVS should significantly reduce cybersickness in simulations involving angular head rotation, which are likely to generate severe cybersickness (see Palmisano et al., 2020). Further research will help determine the optimal parameters of GVS required to enhance user experiences and minimise cybersickness in HMD VR.

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