Frontiers in Virtual Reality

TYPE Original Research
PUBLISHED 23 January 2025
DOI 10.3389/frvir.2024.1478106

OPEN ACCESS

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RECEIVED 09 August 2024
ACCEPTED 23 December 2024
PUBLISHED 23 January 2025

CITATION
Smith SP, Nalivaiko E, Owen S, Depireux D and Flynn M (2025) Exploring vestibular stimulation to reduce the influence of cybersickness on virtual reality experiences.
Front. Virtual Real. 5:1478106.
doi: 10.3389/frvir.2024.1478106

Exploring vestibular stimulation to reduce the influence of cybersickness on virtual reality experiences

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Introduction: There is increasing use of head-worn displays to support immersive virtual reality (VR) experiences. However, users of such technology often encounter motion sickness-like effects, commonly termed cybersickness. The unpleasant effects of cybersickness can limit the duration of VR technology usage and deter return use after only one bad experience. One explanation of cybersickness is that it is a physiological responses to perceived differences between the visual and vestibular stimulation provided via VR technology and the user's current body positioning and movement, i.e., a mismatch between visual and vestibular senses.

Methods: An exploratory user study is described that investigates the use of technology to influence vestibular cues and change experiences of cybersickness. A vestibular stimulation device using bone conduction was applied to users experiencing cybersickness induced by a VR roller-coaster in a head-worn display. Three conditions were tested: a control group without the device and two groups with the device configured to different vibration force levels.

Results: Results showed that users with the stronger vibration level, when compared to a control group, had different virtual environment experiences with longer ride durations and lower reported nausea scores.

Discussion: Although limited by participant numbers, the results are promising for applying vestibular stimulation to positively influence cybersickness experiences in head-worn displays. Given the spreading application of VR technologies and the need to mitigate cybersickness, there is a need to further evaluate the efficacy of such devices.

KEYWORDS

head-worn display, cybersickness, virtual reality, vestibular stimulation, head-mounted display, VR headset

1 Introduction

The widespread availability of affordable head-worn displays (HWD), also commonly referred to as head-mounted displays or VR headsets, has significantly increased general engagement with virtual reality (VR) (Smith and Burd, 2019; Weech et al., 2018). This has led to increased opportunities for people to have virtual reality experiences and for the VR industry to both increase commercial output of hardware, i.e., head-worn displays and associated accessories, and software products, most notably VR games and educational products. Although each generation of HWD hardware has typically improved technical specifications, the immersive experiences provided in VR are not suited for all users.

Users of virtual reality technology often encounter motion sickness-like effects commonly termed cybersickness (Nesbitt and Nalivaiko, 2024; Rebenitsch and Owen, 2016; Stanney et al., 2020)[1], with feelings of nausea, dizziness and sweatiness (Mittelstaedt et al., 2018). Cybersickness as a result of HWD use has been an ongoing research topic [reviews on cybersickness include (Botha and De Wet, 2024; Davis et al., 2014; Rebenitsch and Owen, 2016; Tian et al., 2022)]. Experiencing cybersickness can be a significant barrier to using virtual reality systems (Woo et al., 2023). Stanney and Kennedy (2009) note that 80%–95% of individuals using HWDs report some type of side effect and up to 50% of users experienced symptoms severe enough to end participation. Also approximately 50% of those that ended their VR experience did so in the first 20 min and nearly 75% did so by 30 min (Stanney and Kennedy, 2009).

Although repeated use of virtual reality has been shown to increase resistance to motion sickness (Mouloua et al., 2004) and cybersickness (Clemes and Howarth, 2003; Howarth and Hodder, 2008), the unpleasant effects of cybersickness can limit the duration of virtual reality technology usage and deter return use after only one bad experience. As there is increasing demand for the use of virtual reality applications in industry, defence, education and consumer markets, new approaches for reducing cybersickness are needed (Weech et al., 2018).

There are three main theories on the causes of cybersickness including (i) the sensory conflict theory, (ii) the poison theory and (iii) the postural instability theory [see (LaViola, 2000; Stanney et al., 2020) for overviews of each theory]. In the work described here, we focuses on the sensory conflict theory (LaViola, 2000; Reason and Brand, 1975) and how it can explain cybersickness as a mismatch between the visual and vestibular senses (Keshavarz et al., 2015; McCauley and Sharkey, 1992). Specifically, that the causes of cybersickness are grounded in physiological responses to perceived differences between the visual and vestibular stimulation provided via VR technology and the user's current body positioning and movement.

VR applications often attempt to reduce sensory conflict by (i) providing a sympathetic VR use environment, for example, having users stand and move naturally in a small space so their movements mimic the VR presented visuals (Clifton and Palmisano, 2020; Farmani and Teather, 2020), (ii) providing specialised interface-based refinements to block cybersickness inducing visuals, for example, reducing the field-of-view when users engage in real-time lateral movement (Fernandes and Feiner, 2016) or (iii) adding additional feedback to reduce sensory misalignment, for example, providing airflow (Harrington et al., 2019) or proprioceptive (Gardé et al., 2018; Sra et al., 2019) feedback. These approaches limit VR application use due to the need for physical space/movement restrictions, customised user interface design and/or specialised hardware.

We have investigated a more general solution via a core physical determinant of cybersickness, namely the vestibular sense. A prototype vestibular stimulation technology has been developed (Otolith Labs, Washington DC, United States) and shown to reduce motion sickness-like symptoms, for example, decrease nausea in automated vehicles (Salter et al., 2020). Here, we have explored how this technology can interfere with the user's natural physiological vestibular reaction to virtual reality experiences by adding additional vestibular stimulation.

Vestibular stimulation has been shown to improve measures of balance (Stefani et al., 2020) and reduce motor and non-motor symptoms associated with Parkinson's disease (Wilkinson, 2021). Studies have also revealed a modulating effect of vestibular stimulation on mood state, emotional control, and anxiety level (Pasquier et al., 2019). Device induced vestibular stimulation has the advantage of being a non-pharmaceutical method and has been effective as a treatment for seasickness (Gutkovich et al., 2022).

In the current exploratory study, we have investigated the efficiency of vestibular stimulation to influence cybersickness experiences using a portable device equipped with a non-invasive bone conduction transducer that is worn by a user while using a head-worn display. To achieve reliable onset of cybersickness, we used an intentionally highly provocative virtual reality experience, in this case a virtual roller-coaster ride (Nalivaiko et al., 2015; Nesbitt et al., 2017; Sra et al., 2019). We used a verbal protocol to collect *in situ* experiences of nausea. Participant's exit time from the roller-coaster ride was collected in addition to a pre-survey on previous motion sickness experiences and a post-survey on nausea during the current virtual reality experience.

2 Materials and methods

2.1 Study outline

An exploratory user study was conducted on 30 healthy individuals, 9 female and 21 male with an age range of

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[1] Nesbitt and Nalivaiko (2024) note that "cybersickness and simulator sickness share similar symptoms with motion sickness although the conditions are caused by exposure to slightly different situations" where "motion sickness can be brought on by travelling in any type of moving vehicle including cars, buses, trains, aircraft, boats, and submarines and may also be induced on an amusement ride, a spinning chair or simply by using a swing at a playground" and "cybersickness is typically experienced by stationary users that perceive that they are moving in a virtual scene." In the work presented here, we are interested in the latter, with the use of a virtual environment to induce cybersickness. In our experiment method we do use motion sickness surveys as these elicit the user experiences of motion sickness-like symptoms that happen with cybersickness. Exploring the differences/similarities between motion sickness and cybersickness is outside the scope of the work reported here [see (Gavgani et al., 2018; Palmisano et al., 2020)].

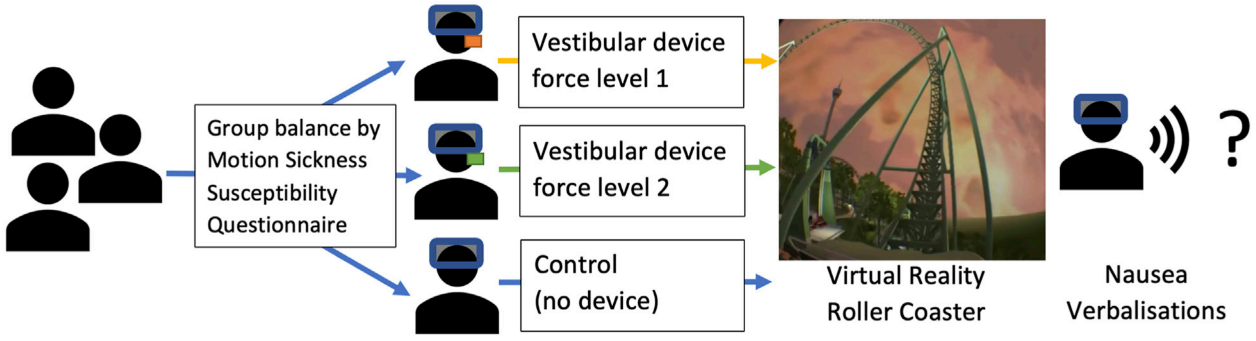

FIGURE 1
Summary of the vestibular stimulation experiment.

TABLE 1 Final participant group allocation by MSSQ-Short score.

Score	Label	Control (n)	Device 1 (n)	Device 2 (n)
0 < = 4.95	Low	5	5	4
4.96 < = 16.75 (−1 stdev to mean)	Medium	4	4	3
16.75 < = 28.55 (mean to +1 stdev)	High	2	1	2
> 28.55(> +1 stdev)	Very high	0	0	0

19–37 years (mean age = 25.80 years, std.dev = 4.77). Participants received either university course credit or a AUD$30 gift voucher for their time. The study protocol was approved by the Human Research Ethics Committee of the University of Newcastle, Australia (H-2019-0245).

An overview of the experimental approach can be seen in Figure 1. After arrival to an air-conditioned room (kept at 21 − 22°C) participants were asked to read the study information sheet and sign a consent form. Subsequently participants were asked to complete the revised short form of the Motion Sickness Susceptibility Questionnaire (MSSQ-Short) (Golding, 2006) and a demographic questionnaire. The MSSQ-Short collects data on previous history of motion sickness as a child (before age 12) and as an adult (last 10 years) across types of transport and entertainment including cars, buses, boats, swings in playgrounds and roller-coaster rides. The MSSQ-Short generates a single score and participants were assigned to three groups (Device setting 1, Device setting 2 and Control) balanced by MSSQ-Short score and gender.

Based on the MSSQ-Short norms determined by (Lamb and Kwok, 2015) with a combined (weighted for gender bias) MSSQ-Short mean of 16.75 (stdev = 11.8), participants were allocated across four clusters with low to very high labels based on MSSQ-Short mean plus/minus 1 standard deviation. Final participant allocation is shown in Table 1.

All participants successfully completed a stereo vision and depth perception test [the Frisby Stereotest (Frisby, 1983)]. After completing the test and confirming stereo vision, participants were fitted with a head-worn virtual display (Oculus Rift CV1[2], Facebook Reality Labs, United States). The interpupilary eye distance (IPD) setting on the CV1 was not adjusted between participants and set at the middle IPS setting of 65 mm. A vestibular stimulation device, provided by Otolith Labs (Otolith Labs, Washington DC, United States), was fitted to each participant in a device group, on the mastoid behind the right ear (see Figure 2). The Otolith device uses bone conduction and has four vibration force level settings, where setting 1 had the lowest vibration force and setting 4 had the strongest vibration force. In the experiment described here, the lowest vibration force level setting (1 on the device) is labelled as *Device 1* and a medium setting (3 on the device) is labelled as *Device 2*. The experiment staff were not made aware of any expected benefits or differences from either vibration force level settings, only that setting 1 on the device had less vibration force than setting 3.

While participants were seated in a stationary office chair, the VR roller-coaster simulation ride (Helix, Archivision, NL) was activated (see Figure 3) and continued for a maximum of 15 min or whenever participants decided to terminate the ride. Participants were asked to verbally report their current nausea level every minute

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[2] The Oculus Rift CV1 has the following specifications: Resolution (1,080 × 1,200 per-eye), Refresh Rate (90 Hz), Display Type (2 x AMOLED binocular), IPD Range (58–72 mm hardware manual adjustable), Visible FoV (87° horizontal; 88° vertical), Rendered FoV (87.95° horizontal; 89.66° vertical; 98.07° diagonal), Binocular Overlap (71.15°).

FIGURE 2
Otolith vestibular stimulation device placement.

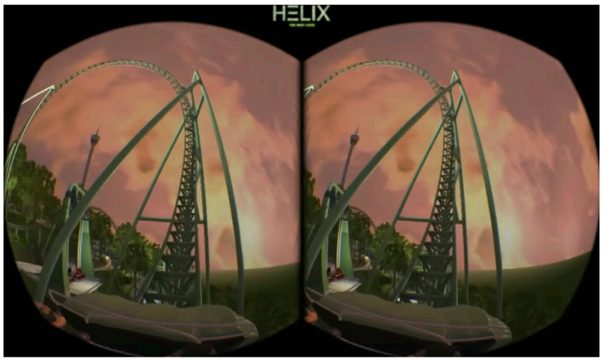

FIGURE 3
Example stereo view of the Helix VR roller-coaster ride.

during the exposure on a scale from zero (no effect) to 10 (severe nausea—just about to vomit). The ride was also terminated by the experiment staff if the participant verbalised a nausea score of 8.

Directly after the ride, participants completed a Motion Sickness Assessment Questionnaire (MSAQ) (Gianaros et al., 2001). Participants were asked to complete the questionnaire thinking about the very end of the ride, i.e., just before they or the experiment staff terminated the ride. In the MSAQ, post-session symptoms are categorised into four clusters: gastrointestinal (nausea, feeling sick in the stomach, feeling queasy, about to vomit), central (faint-like, light headiness, disoriented, dizzy and spinning), peripheral (sweaty, hot, clammy, cold sweat, temperature discomfort) and sopite (annoyed, drowsy, tired, uneasy). When answering each question of the MSAQ, the participant assigns a value from a range of 1 (not at all) to 9 (severe). These ratings are then summed for each group of related questions and used to generate an overall MSAQ score.

2.2 Study analysis

Virtual roller-coasters can be very unpleasant, particularly when they are selected to induce cybersickness. This can impact participant recruitment and therefore data analysis. This is particularly the case for within-subjects designs, as participants' dropout and fail to return for additional roller-coaster sessions. For this exploratory study we used a between-subjects design to avoid participant dropout.

Our focus is on exploring whether the vestibular device, with its different vibration levels, indicate any differences when compared to a control group. Thus our analysis is matched to our smaller sized participant group, and specifically looking for differences in correlations between relevant metrics, rather than group wide significance. As an exploratory study with a new technology, we are looking for indicative evidence of difference on the participants' virtual reality experiences to motivate further studies with larger numbers of participants. Without evidence of usefulness there are ethical implications for exposing large participants groups to unpleasant experiences such as virtual roller-coasters.

In evaluating the vestibular device, we were interested in four primary measures, (i) the previous history of motion sickness (MSSQ), (ii) the *in situ* virtual roller-coaster experience (the verbal reports of nausea), (iii) the duration of the roller-coaster ride and (iv) the reports of experience, collected post-session (MSAQ).

Our expectation is that participants with a previous history of motion sickness will experience more cybersickness (Jang et al., 2022) and that this will limit their ride duration (Nalivaiko et al., 2015; Nesbitt et al., 2017). Also, these participants will report higher scores in the post session reports of cybersickness effects. We expect that the control group (with no vestibular stimulation) will have similar cybersickness experiences to those reported in previous research (Nalivaiko et al., 2015; Nesbitt et al., 2017). We have formed the following hypothesis to determine whether the device groups have produced evidence of different experiences, i.e., from the additional vestibular stimulation.

H1: Participants with previous experiences of motion sickness will feel similar negative cybersickness effects in the roller-coaster simulation. We expect that reported history of previous motion sickness (MSSQ) will:

- H1a: positively correlate to verbal reports of nausea (i.e., the *in situ* nausea measure).
- H1b: negatively correlate to ride duration (time in seconds), i.e., as participants' exit the virtual environment early.
- H1c: positively correlate to post-session recall of motion sickness-like symptoms (via the MSAQ) that are indicative of cybersickness.

TABLE 2 Participant results, as mean and standard deviation (SD), across groups.

Results/Group	Control	Device 1	Device 2
MSSQ: Total	8.83 (7.72)	8.51 (7.70)	9.02 (7.74)
MSSQ: Child	5.64 (5.26)	4.47 (4.92)	5.30 (4.24)
MSSQ: Adult	3.19 (2.95)	3.94 (4.22)	3.72 (3.60)
Ride duration (s)	478.18 (302.29)	568.30 (307.73)	623.11 (291.99)
Reported nausea	6.47 (2.50)	5.39 (3.34)	5.47 (2.66)
MSAQ	55.43 (23.71)	43.47 (20.38)	53.24 (11.41)

H2: Reported nausea by participants will influence the time spent in the virtual roller-coaster and that this experience will be reported post-session. We expect that the verbal nausea rating will:

- H2a: negatively correlate to ride duration (time in seconds), i.e., more *in situ* feelings of nausea should shorten ride duration.
- H2b: positively correlate to post-session recall of motion sickness-like symptoms (via the MSAQ) that are indicative of cybersickness, i.e., more actual feelings of nausea should mean higher scores recalled in the post-session questionnaire.

H3: The time that participants spend in the roller-coaster will effect the participants' experience reported post-session. We expect that ride duration (time in seconds) will negatively correlate to the post-session MSAQ scores, i.e., shorter ride time implies more motion sickness-like symptoms that are indicative of cybersickness.

The reported nausea ratings were only collected while participants were in the virtual roller-coaster. Thus if participants' exited early, this would impact any rating average to create a standard nausea score [as in (Nesbitt et al., 2017)]. Therefore we have padded the nausea ratings up to 15 min with the highest rating, i.e., "10," to indicate significant cybersickness that stopped the roller-coaster experience. Thus a participant who exited the roller-coaster after 3 min would have "10" added to ratings for 4–15 min before an average nausea score for their experience was generated.

3 Results

Statistical analyses were performed using IBM SPSS Statistics (v29). Shapiro-Wilk tests determined that the data was not normally distributed and thus, the non-parametric Spearman's rho was used to generate correlations. Statistical significance was set to $p < 0.05$. Table 2 shows the participants' results.

3.1 Control group, no vibration device

There was a strong, positive correlation between previous motion sickness (MSSQ) and reported nausea, which was statistically significant $(rs(9) = .80, p = .003)$, a strong, negative correlation between MSSQ and ride duration, which was statistically significant $(rs(9) = -.88, p < .001)$ and a moderate, positive correlation between MSSQ and ride experience reported post-session (MSAQ), which was statistically significant $(rs(9) = .79, p = .004)$. H1a-H1c were confirmed.

There was a strong, negative correlation between reported nausea and ride duration, which was statistically significant $(rs(9) = -0.92, p < .001)$ and a strong, positive correlation between reported nausea and ride experience reported post-session (MSAQ), which was statistically significant $(rs(9) = .81, p = .002)$. H2a and H1b were confirmed.

There was a moderate, negative correlation between ride duration and ride experience reported post-session (MSAQ), which was statistically significant $(rs(9) = -.68, p = .022)$. H3 was confirmed.

3.2 Device group 1, low vibration setting

There was a weak, positive correlation between previous motion sickness (MSSQ) and reported nausea, which was not statistically significant $(rs(8) = .31, p = .385)$, a weak, negative correlation between MSSQ and ride duration, which was not statistically significant $(rs(8) = -.30, p = .399)$ and a moderate, positive correlation between MSSQ and ride experience reported post-session (MSAQ), which was not statistically significant $(rs(8) = .49, p = .150)$. H1a-H1c were not confirmed.

There was a strong, negative correlation between reported nausea and ride duration, which was statistically significant $(rs(8) = -0.91, p < .001)$ and a strong, positive correlation between reported nausea and ride experience reported post-session (MSAQ), which was statistically significant $(rs(8) = .82, p = .004)$. H2a and H1b were confirmed.

There was a strong, negative correlation between ride duration and ride experience reported post-session (MSAQ), which was statistically significant $(rs(8) = -.86, p = .002)$. H3 was confirmed.

3.3 Device group 2, medium vibration setting

There was a weak, positive correlation between previous motion sickness (MSSQ) and reported nausea, which was not statistically significant $(rs(7) = .05, p = .898)$, a weak, positive correlation between MSSQ and ride duration, which was not statistically significant $(rs(7) = .08, p = .831)$ and a weak, negative correlation between MSSQ and ride experience reported post-session (MSAQ), which was not statistically significant $(rs(7) = -.08, p = .831)$. H1a-H1c were not confirmed.

There was a strong, negative correlation between reported nausea and ride duration, which was statistically significant $(rs(7) = -0.92, p < .001)$ and a weak, positive correlation between reported nausea and ride experience reported post-session (MSAQ), which was not statistically significant $(rs(7) = .32, p = .406)$. H2a was confirmed and H1b was not confirmed.

There was a moderate, negative correlation between ride duration and ride experience reported post-session (MSAQ), which was not statistically significant $(rs(8) = -.53, p = .145)$. H3 was not confirmed.

TABLE 3 Summary of correlation results. Statistically significant results supporting hypotheses are bolded.

Hypothesis	H1: MSSQ vs.			H2: Nausea vs.		H3: Duration vs.
/ Condition	Nausea reports	Ride duration	MSAQ	Ride duration	MSAQ	MSAQ
Control: no vibration	**+ve p= .003**	**−ve p < .001**	**+ve p= .004**	**−ve p < .001**	**+ve p= .002**	**-ve p= .022**
Device 1: low vibration	+ve p = .385	−ve p = .339	+ve p = .150	**−ve p < .001**	**+ve p= .004**	**−ve p= .002**
Device 2: medium vibration	+ve p = .898	+ve p = .831	−ve p = .831	**−ve p < .001**	+ve p = .406	−ve p = .145

3.4 Summary

Table 3 provides a summary of the results of the correlation tests. Similar to other studies with virtual roller-coasters, the Control group exhibited the expected behaviour with previous higher motion sickness being predictive of cybersickness, resulting in higher nausea ratings and shorter ride duration. This provides a baseline for the other two groups where vestibular stimulation had been applied. In both the device groups, there were no statistically significant trends for previous motion sickness and negative cybersickness effects. This indicates the vibration from the device was having some influence on the experience, i.e., interfering with the baseline experiences.

Participants across all the groups had a negative correlation of nausea rating versus ride duration. This is expected with provocative stimuli, like virtual roller-coasters, that was intentionally selected to induce cybersickness. What is more interesting is that participants in Device group 2 (moderate vibration) did not have a significant correlation between their reported nausea or ride duration versus their post-session experience questionnaire. Unlike the Control and Device 1 (low vibration) groups, this indicates a different experience for these participants.

4 Discussion

Overall, the vestibular stimulation device with a medium vibration force level (Device group 2) induced a different *in situ* experience in the virtual reality roller-coaster with participants' having fewer significant correlations to the metrics collected. After data collection and analysis were completed, Otolith Labs indicated that the device vibration force on setting 3 was calibrated to 96 dB (re:1 dyne[3]) and 50 Hz[4]. Thus the results are indicative of a positive influence of vestibular stimulation technology with a calibrated vibration force setting of 96 dB (re:1 dyne) and 50 Hz in a cybersickness provocative virtual environment.

In contrast to other research on the use of bone-conducted vibration (Weech et al., 2018), our experiment (i) used a commercial grade HWD, the Oculus CV1 compared to the Oculus Development Kit (version 0.8.0), (ii) applied constant vibration stimulation to the participants rather than brief random bursts of stimulation or stimulation bursts linked to angular acceleration thresholds within the virtual environment, (iii) used a commercial virtual environment in contrast to building a custom environment in a game engine, for example, Unity3D and (iv) included *in situ* participant's verbal rating of current nausea rather than relying on post-session participant feedback. The aim was to differentiate our work from (Weech et al., 2018), specifically with the use of constant vestibular stimulation and capture a more ecological valid (McMahan et al., 2011) use of virtual reality technology with commercial off-the-shelf software and hardware.

However, the study was likely impacted by self selection bias, i.e., participants who know they have significant motion sickness or previous poor VR experiences are unlikely to volunteer for a VR roller-coaster study. These participants are likely to be those whom would get the most benefit from using vestibular device, i.e., more likely to have more cybersickness (Jang et al., 2022). One alternative approach would be for all participants to encounter all conditions, i.e., move from a between-subject to a within-subject design. Unfortunately, when using provocative stimuli, like a roller-coaster, participants with poor experiences are likely to opt out of future sessions, thus impacting recruitment. Also repeated VR experiences are known to have habituation effects (Clemes and Howarth, 2003; Howarth and Hodder, 2008), although this can be managed by extending the time between VR exposure sessions.

The study was also limited by the small participant pool. This suited the exploratory nature of investigating the new vestibular device but restricted the use of rigorous inferential testing. However, virtual roller-coasters can be an unpleasant experience and recruitment is thus difficult and, as noted above, potentially biased. However, we have balanced the smaller participant size with appropriate statistical measures and note that the results are only indicative of the changed VR experience for the participants with the stronger level of vibration. This motivates the need for further research in the use of such technologies. Based on the findings here, there is scope for further studies, with a larger number of participants, specifically focused on VR users with high MSSQ-Short scores.

The VR environment used in the research reported here was intentionally provocative, i.e., a VR roller-coaster, in order to elicit cybersickness within a short duration. This environment is not representative of many VR experiences. However, even with newer HWDs, users do report cybersickness after short durations of use.

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[3] A unit of force in the centimeter-gram-second system equal to the force that would give a free mass of 1 g an acceleration of 1 cm per second per second (Merriam-Webster, 2024).

[4] Force level was measured using a *Artificial Mastoid Type 4930* (Brüel and Kjær, Denmark). The Artificial Mastoid supports the calibration of bone-conduction devices by simulating the mechanical impedance of the human mastoid. The 96 dB force level is in reference to 1 dyne. This is not a sound pressure level. It is a force level with respect to 1 dyne.

With the positive correlations found here between previous motion sickness and nausea ratings, participants with a history of motion sickness may get more benefit from the use of vestibular stimulation technology.

The impact of when to introduce vestibular stimulation (in the work described here, the stimulation was started before the VR experience), the appropriate duration of the stimulation (i.e., constant versus intermittent vibration) and the best level of vibration for an individual are all open research questions. Dynamic vestibular stimulation, both in duration and intensity, triggered by activity in the virtual environment and/or physiological changes of the user may also be useful areas of research. In our current work, we are exploring a more ecological valid (McMahan et al., 2011) VR environment and will repeat our approach to measure the influence of vestibular stimulation with a commercial off-the-shelf VR video game that supports active user interaction including VR walking and object selection/manipulation, rather than the seated, more passive, experience as in the VR roller-coaster used here.

5 Conclusion

The widespread availability of affordable HWDs and easy access to VR applications and games has significantly increased the use of VR technologies by the general public. Explicit negative effects of HWD use, such as cybersickness, often leads to self-selection opt out as users who experience negative effects stop using or avoid the technology (Stanney et al., 2020; Woo et al., 2023). However, opportunities to self-select away from VR use may be increasingly limited if VR technology is integrated into mainstream usage, e.g., training, general education and telepresence activities.

The work presented here has explored the use of vestibular stimulation to influence cybersickness experiences using a portable device equipped with a non-invasive bone conduction transducer that is worn by a user while using a head-worn display. Participants experienced a VR roller-coaster, to induce cybersickness. Data on participants' experiences was captured via qualitative verbalisations in-session and a post-session survey. Three condition groups were investigated, namely control (no device) and two vestibular device groups with different vibration force settings.

Results indicated positive influence of a vestibular stimulation device, compared to a control group baseline, with a calibrated vibration force level on participants using a head-worn display. However, this was only an exploratory study and with a limited participant pool. Use of such vestibular technologies may be useful to support VR use if bone conductor technology could be built into HWDs or offered as an accessory. However, more research is needed in this area to map out individual user requirements. Future work will explore more typical VR environments, i.e., VR video games, and look for a larger participant pool to consolidate the results reported here.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Human Research Ethics Committee of the University of Newcastle, Australia. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

SS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing–original draft, Writing–review and editing. EN: Conceptualization, Funding acquisition, Methodology, Resources, Writing–review and editing. SO: Conceptualization, Funding acquisition, Methodology, Resources, Writing–review and editing. DD: Conceptualization, Funding acquisition, Methodology, Resources, Writing–review and editing. MF: Conceptualization, Funding acquisition, Methodology, Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported in part by an Australian Academy of Technology and Engineering: Global Connections Fund—Bridging Grant (#512035161).

Acknowledgments

The authors would like to thank the participants for their perseverance when experiencing the VR roller-coaster and Alireza Mazloumi Gavgani for his help during data collection.

Conflict of interest

Otolith Labs provided the prototype vestibular stimulation device but formed no part of the results analysis or conclusions on the device's efficacy as reported here.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

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