Floor-vibration VR: Mitigating Cybersickness Using Whole-body Tactile Stimuli in Highly Realistic Vehicle Driving Experiences

Sungchul Jung, *Member, IEEE,* Chen Li, Ryan McKee,
Mary C. Whitton, *Life Senior Member, IEEE*, and Robert W. Lindeman, *Senior Member, IEEE*,

Abstract—This work addresses *cybersickness*, a major barrier to successful long-exposure immersive virtual reality (VR) experiences since user discomfort frequently leads to prematurely ending such experiences. Starting from sensory conflict theory, we posit that if a vibrating floor delivers vestibular stimuli that minimally match the vibration characteristics of a scenario, the size of the conflict between the visual and vestibular senses will be reduced and, thus, the incidence and/or severity of cybersickness will also be reduced. We integrated a custom-built, computer-controlled vibrating floor in our VR system. To evaluate the system, we implemented a realistic off-road vehicle driving simulator in which participants rode multiple laps as passengers on an off-road course. We programmed the floor to generate vertical vibrations similar to those experienced in real off-road vehicle travel. The scenario and driving conditions were designed to be cybersickness-inducing for users in both the Vibration and No-vibration conditions. We collected subjective and objective data for variables previously shown to be related to levels of cybersickness or presence. These included presence and simulator sickness questionnaires (SSQ), self-rated discomfort levels, and the physiological signals of heart rate, galvanic skin response (GSR), and pupil size. Comparing data between participants in the Vibration group (N=11) to the No-Vibration group (N=11), we found that Delta-SSQ Oculomotor response and the GSR physiological signal, both known to be positively correlated with cybersickness, were significantly lower (with large effect sizes) for the Vibration group. Other variables differed between groups in the same direction, but with trivial or small effect sizes. The results indicate that the floor vibration significantly reduced some measures of cybersickness.

Index Terms—Cybersickness, motion sickness, simulator sickness, immersive virtual reality, floor-vibration, whole-body tactile, tactile, vibration, floor, reducing cybersickness, mitigating cybersickness

◆

1 INTRODUCTION

Sensory conflict is a well-recognized theory of the cause of cybersickness. In immersive Virtual Reality (VR) systems where users do not physically move about and naturally generate stimulation in their vestibular systems, there is conflict between the visual stimuli provided and the (missing) vestibular stimuli. Our premise is that if we can design a system that will provide some vestibular stimuli through a vibrating floor, and if that vibration is at least somewhat matched to the vibrations occurring visually in the virtual scenario, we will be able to reduce the severity of the conflict between the visual and vestibular senses and, thus, reduce the incidence and severity of cybersickness experienced in that scenario. This work reports on an investigation of that premise.

Immersive VR experiences are used in diverse areas including training, education, entertainment, communication, and science [7, 12, 45, 58]. Generally, users express higher enjoyment with Virtual Environment (VE) representations that are highly realistic [23, 46]. Although enjoyment and presence have been shown to have a positive correlation [54], improving the visual realism of a VE does not necessarily increase the user's sense of presence [19, 30, 33, 49, 55]. Ironically, higher visual realism and complexity can increase the severity of cybersickness symptoms, which, in turn, degrades the user's VR experience [40, 47].

The cybersickness problem is real and widespread: 40-70% of VR users may experience cybersickness after around 15 minutes of exposure, and, as reported by Chang *et al.* [6] and Sawada *et al.* [48], some VR applications result in cybersickness symptoms 100% of the time. Addressing these symptoms is critical, but challenging as no clear causes have been identified. Of the several theories proposed and often employed by VR researchers, i.e., sensory conflict, postural instability [44], poison theory [53] and the rest-frame hypothesis [41], sensory conflict is perhaps the most popular for explaining the degraded VR user experience [29]. Sensory conflict is a good starting place; at this time, developers are unable to synthesize and deliver perfect visual stimuli and we are unable to evoke perfect vestibular stimuli. For a given scenario, neither visual nor vestibular stimuli can be completely realistic, and, because they are different, they cannot be made equivalent, leading to sensory conflict. The question is how to mitigate its effects.

One can argue that modern consumer-grade VR systems do a good-enough job of generating and delivering realistic visual stimuli to the user. However, devices and techniques that stimulate the vestibular system are most often missing. This is a particular problem in systems where users are virtually moving through VEs but are not physically moving. For example, when a seated VR user wearing a head-mounted display (HMD) moves around within a VE using a joystick, realistic visual stimuli are presented, but, because the user is not physically moving, vestibular stimulation is nearly zero. According to sensory conflict theory, this mismatch in sensory stimuli, the conflict between what the two sensory systems are telling the brain, causes cybersickness symptoms [29].

Several cybersickness mitigation techniques have been proposed including manipulating field of view (FOV) and generating tactile feedback around the user's head [4, 16, 32, 37, 57]. Though these methods have been found to reduce cybersickness significantly, they can introduce other problems. Reducing the FOV has been shown to reduce enjoyment of VR experiences [31] and generating tactile feedback around the user's head may be difficult to deploy due to safety or HMD form-factor problems, as well as the noise produced by the tactile elements. The work reported here seeks a cybersickness mitigation technique that avoids these issues.

Plouzeau *et al.* introduced a single-person vibration platform that generates vibration using devices attached underneath the floor or a seat

---

- *Sungchul Jung is with HIT Lab NZ at the University of Canterbury. E-mail: sungchul.jung@canterbury.ac.nz*
- *Chen Li is with HIT Lab NZ at the University of Canterbury. E-mail: richard-chen.li@polyu.edu.hk*
- *Ryan McKee is with HIT Lab NZ at the University of Canterbury. E-mail: ryan.mckee@canterbury.ac.nz*
- *Mary C. Whitton is with the University of North Carolina at Chapel Hill. E-mail: whitton@cs.unc.edu*
- *Robert W. Lindeman is with HIT Lab NZ at the University of Canterbury. E-mail: gogo@hitlabnz.org*

*Manuscript received 9 Sept. 2020; revised 15 Dec. 2020; accepted 8 Jan. 2021.
Date of publication 24 Mar. 2021; date of current version 7 Apr. 2021.
Digital Object Identifier no. 10.1109/TVCG.2021.3067773*

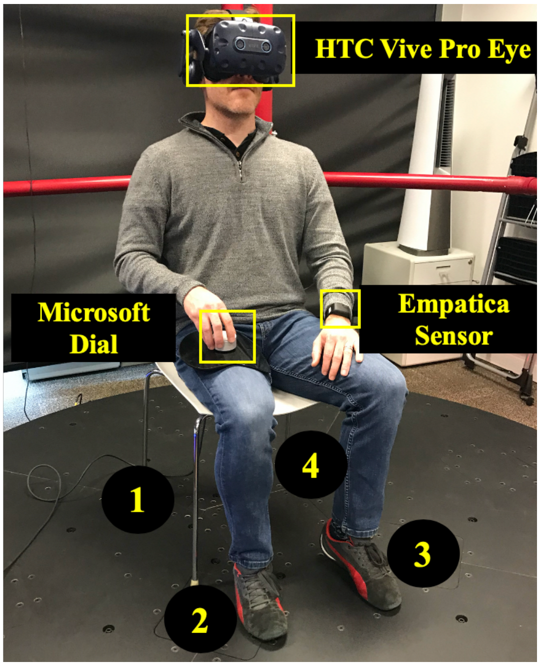

Fig. 1. System setup: Participant views the VE through the HTC Vive Pro Eye (Eye Tracking). An Empatica E4 sensor was used to measure HR and GSR. A Microsoft Dial was used to collect current discomfort level. A raised platform with four low-frequency audio transducers at 250 watts each provided floor vibration, and was controlled through the audio output from Unity, passed through an amplifier.

frame [38,39]. Similarly, we built and integrated a computer-controlled vibration floor into our VR system. The floor enabled our investigation of the impact of whole-body tactile feedback on level of cybersickness experienced by our users.

Our system design goals were to 1) reduce cybersickness, 2) avoid degrading the user-experience, i.e., maintain sense of presence, and 3) support deployability. Note that our goals included neither completely and accurately replicating vibrations experienced in a vehicle, nor exploring whether exposing users to unmatched or totally random vibrations would reduce cybersickness. Rather, we investigated the cybersickness-reducing efficacy of vibration in one axis (vertical) that minimally approximated the vibration experienced in a real vehicle.

Sawada *et al.* recently reported similar work where they investigated the impact of synchronized sound and whole-body tactile feedback for reducing motion sickness in a VR motorcycle driving simulator [48]. They built a vibration module under the mock motorcycle seat, and asked users to sit and hold the handlebars during a five minute riding scenario. Comparing results for a group of participants with vibration and sound to groups with sound only, vibration only, or neither, the results showed that the vibration plus sound stimuli resulted in reduced motion sickness symptoms.

We built on Sawada *et al.*'s [48] findings in three ways. We investigated vibration from a floor (which transmits the vibrations to the skeleton from the feet as well as the seat, hence *whole-body tactile feedback*. We included physiological measures among our dependent variables. We extended the technique to more-general use cases by eliminating posture restrictions (holding handlebars) which Sawada *et al.* imposed [48].

Our work investigates the impact of floor vibration in VR experiences compared to the same experiences without floor vibration in a *realistic, but intentionally cybersickness-inducing VE* (i.e., a VE that produces strong vection due to the scenario's high visual realism and scene complexity, modeled with high-resolution textures, and a "bumpy" ride) [43]. During the study, participants were seated in a chair in the middle of a vibration platform in the physical laboratory (see Figure 1). In the VE, participants sat in the passenger seat of a virtual off-road vehicle. An avatar drove the vehicle multiple times around a course through a virtual park, with vehicle speed increasing each lap.

We collected subjective and objective measures, including cybersickness questionnaire (using the simulator sickness questionnaire (SSQ) [24] before and after exposure), the MEC sense of presence questionnaire (MEC- SPQ) [18], self-rated discomfort level reported using a physical dial in real-time during the experience [34], and physiological measures for heart-rate (HR), galvanic skin response (GSR), and pupil size [26]. Our results show that *floor vibration that is minimally matched with vibration expected in a VR scenario significantly reduces cybersickness compared to the no-floor-vibration condition for changes in the Oculomotor subscale of the SSQ and in GSR*. Our participants reported a strong preference (21/21) for the Vibration condition.

2 RELATED WORK

This section reviews theories of the cause of cybersickness, methods of mitigating cybersickness, and the impact of cybersickness on selected physiological signals.

2.1 Sources of Cybersickness: Sensory Conflict and Postural Instability Theories

Today, the most widely accepted theory explaining the source of cybersickness is sensory conflict theory [42]. In most cases of cybersickness in VR, the senses involved are the vestibular and the visual senses. Sensory conflict theory says when two or more senses are providing inconsistent and contradictory information about the body's orientation and motion, and this perceptual conflict results in symptoms of cybersickness, such as nausea, eye strain, and headache. Using driving simulations as an example, the visual sense provides the participants information about the vehicle kinematics and their self motion. If the participant is not moving physically, or the participant's physical motion does not match the visual stimuli, the vestibular sense will provide either no sense of motion or a sense of motion that conflicts with what the user expects based on current visual input and past experience.

Sensory conflict theory does not, however, explain the occurrence of classic cybersickness symptoms such as nausea and dizziness. Postural instability theory posits that those symptoms are a response to postural instability and not a response to sensory conflict [44]. More recently, Dong *et al.*, Merhi *et al.*, and Stoffregen *et al.* have shown that sway/head motion is higher for people who later become motion sick than for those who do not [13,35,52]. One can argue that sensory conflict in immersive VR systems leads to a brain state where normal balance mechanisms and responses are compromised, e.g., while in a driving simulator, you may lean into a turn taken at a high speed, but as there is no countering centrifugal force, you overbalance and become unstable. Postural instability theory says that instability–the inability to maintain balance–is a necessary condition for the onset of cybersickness symptoms such as nausea. Postural instability was proposed initially to refute sensory conflict theory. In an experiment like ours, it is impossible to separate the effects of sensory conflict and postural instability. Exploring their relationship was beyond the scope of this work, but is a direction for future research. Likewise, exploring vibration in the context of rest-frames is out of scope for this work, but would also be a promising area to explore in the future.

2.2 Mitigation of Cybersickness

Currently there are two major ways of mitigating cybersickness in VEs based on sensory conflict theory. Firstly, motion cues can be simulated during VR exposure by using motion platforms. Studies on driving simulators have shown that the use of simulated motion cues can help reduce nausea and dizziness [3, 10]. For example, Aykent *et al.* report that using a six degree of freedom (DOF) dynamic motion platform to simulate motion cues helped reduce the nausea and dizziness experienced by participants. Contradictory results have also been found [14, 27]. The authors suggest these contradictory results are due to the fact that it is challenging to provide motion cues that precisely match vehicle kinematics, and that system latencies and the physical limitations of the motion platforms can lead to asynchronous, and hence conflicting, visual and vestibular sensory stimulation.

Another way of mitigating cybersickness is to add stimuli to another sensory channel, providing multi-sensory stimulation that can reduce visual-vestibular conflicts [1]. For example, Sawada *et al.* recently investigated the impact of synchronized sound and whole-body tactile feedback in a VR motorcycle driving simulator [48]. Similar to Sawada *et al.*'s work, our technique aims to mitigate cybersickness by introducing vibration-driven whole-body tactile feedback.

2.3 Cybersickness and Physiological Data

Questionnaires are the most common way to gather subjective measures of cybersickness, and there are several to choose from [8, 24, 25]. By combining subjective measures and objective physiological data, we expect to achieve more-reliable measures of cybersickness. Previous research has shown that symptoms of cybersickness are associated with changes in physiological measures such as heart rate, skin conductance, respiration rate, eye-blink rate, gastric tachyarrhythmia, etc. Kim *et al.* and Cebeci *et al.* systematically studied these changes [5, 26]. The results showed that the severity of cybersickness had a significant positive correlation with heart rate, eye-blink rate, gastric tachyarrhythmia, and EEG delta waves, and a negative correlation with EEG beta waves. Similar findings were reported by Dennison *et al.* [11].

3 METHODS

In this section we describe our experiment to investigate the impact of floor vibration on users' level of cybersickness, their sense of presence and realism, and their preference for Vibration or No-Vibration in a VE experience. This study was approved by the University of Canterbury (NZ) Human Ethics Committee.

3.1 Study Design

Our primary research question was to investigate whether floor vibration that is minimally matched to expected vibrations in a VE scenario can mitigate cybersickness in realistic, cybersickness-inducing environments. To that end, we designed a virtual experience that we believed would induce cybersickness, but sickness at a level low enough that users would maintain an acceptable level of sense of presence. We chose an off-road driving experience as our cybersickness-inducing virtual experience.

3.1.1 The Virtual Experience

Previous work has shown that in real vehicles, passengers are more likely to experience motion sickness than drivers [56], so we seated our study participants in the passenger seat of a virtual pickup truck. A virtual agent appeared to drive the computer-controlled truck along a pre-defined course approximately 1km long through a virtual park. We designed the course to have typical off-road driving characteristics: frequent and substantial changes in vehicle pitch as the terrain rose and fell and changes in yaw as the truck was steered along its course. The sunlit park scene featured bushes, trees with leaves, rocks, and grass; all were rendered with a high level of detail. In addition to visual feedback, we included engine sounds (through the HMD headphones) and, for participants in the Vibration (V) condition, *minimally matched vibration* from the vibrating floor system. Participants in the No-Vibration condition (N), experienced only visual and audio cues.

Each participant completed up to four laps of the course while the system gradually increased the average speed of the vehicle over time. Participants could signal to end the session at any time and approximately half in each condition asked to stop before the end of the four laps. The total experience took around 500 seconds (slightly over 8 minutes), including a 60 second idle time at the start of the session.

Head Bobbing. Insertion of artificial head bobbing has been suggested as an effective means of mitigating cybersickness caused when a user navigates through a virtual world [32], and in our laboratory we usually include it. Head bobbing, a natural cue occurring during human gait, adds realism. Because our study (ironically) needed to induce cybersickness so that we could observe the impact of our vibration stimulus, we had to decide whether to include head bobbing or not. In informal testing to confirm previous results, nine of ten persons experiencing a short VR experience with and without head bobbing reported that the head-bobbing condition led to less cybersickness. Consequently, we decided not to include head bobbing in our system. We do believe it would be interesting future work to understand the effect on cybersickness of including both vibration and head bobbing in a system.

3.1.2 Overview of Design, Measures, and Hypotheses

Since cybersickness symptoms can last anywhere from one hour to several days [29], and we wished to avoid confounding our results by our participants having two VE exposures back to back on the same day, we designed a 2 x 1, between-subjects study, with two-levels (V and N).

Before VE exposure we collected demographic data and administered the simulator sickness questionnaire (SSQ). After VE exposure we administered the SSQ again and the MEC Spatial Presence Questionnaire (MEC-SPQ). During VE exposure we logged self-rated discomfort level and the three physiological signals, HR, GSR, and pupil size.

After completing the main part of the study, we invited each subject to make one lap of the course in the condition they had *not* yet experienced (V or N). We then asked for their *preference* between Vibration and No-Vibration modes, and why they made the choice they did.

As our system is much like Sawada *et al.*'s [48], we expected to find, as they did, lower cybersickness levels in the V group. We expected that measures of sense of presence would be similar for the two groups, since increasing the level of realism, as we did by adding matched vibration, does not necessarily increase measured presence. In addition, we expected a higher participant preference for the experience with vibration, because of increased realism. Based on these expectations, our hypotheses were:

H_1 : Minimally matched floor vibration (V) will reduce the level of cybersickness compared to no vibration (N).

H_2 : The use of floor vibration will not influence the level of presence.

H_3 : Minimally matched floor vibration (V) will be preferred to no vibration (N).

3.2 Participants

Before recruiting participants, we conducted an *a priori* power analysis to compute the required sample size. The effect size in this study was set to 0.8, considered *large* using Cohen's criteria. For the simplest between-group comparison and with $alpha = 0.05$ and $power = 0.80$, the projected sample size needed was about $N = 40$ [17].

We recruited participants using on-campus fliers at the University of Canterbury. Participants received a small monetary compensation for participation. Because of the timing of the New Zealand shelter-in-place order due to the COVID-19 pandemic, we were able to enroll only 22 participants in the study: seven males and four females in the V group (age $M = 27.64$, $SD = 7.92$), and seven males and four females in the N group (age $M = 26.45$, $SD = 4.87$).

While gender balance is desirable, we were unable to achieve it. We tried to balance any bias resulting from females' known higher sensitivity to cybersickness; we had an equal number of males (7) and females (4) in each condition group [9, 36].

Since physiological signals are sensitive to human health conditions and behavior [28], we asked participants to follow some general good-health guidelines prior to participation. We asked them to try to follow normal sleep patterns the night before, to not consume alcohol during the 24 hours prior to the study, to not consume caffeinated drinks during the two hours prior to the study, to not eat a meal during the two hours prior to the study, and to not participate in intense physical training during the 24 hours prior to the study.

We provided participants with a health check list before the study and asked them to report their health status on the demographics form.

		V	N
Age (M, SD)		27.6 (7.92)	26.5 (4.87)
W (kg) (M, SD)		78.5 (34.38)	74.6 (20.43)
H (cm) (M, SD)		171.7 (10.50)	169.1 (6.41)
Motion (M, SD)		2.5 (1.13)	3.0 (1.41)
HMD Use	Yearly	8	7
	Weekly	2	2
	None	1	2
		Yes (No)	Yes (No)
Vision		11 (0)	11 (0)
Sleep		10 (1)	10 (1)
Alcohol		9 (2)	9 (2)
Caffeine		8 (3)	10 (1)
Meal		8 (3)	8 (3)
Training		10 (1)	11 (0)
Smoking		10 (1)	11 (0)
Heart Medication		0 (11)	0 (11)

Table 1. Demographics table: We provide mean and standard deviation for Age, Weight (W), Height (H), and Motion sickness level (Motion). HMD represents the average frequency of HMD usage of Yearly, Weekly, and None. We provide the answers in Yes (No) format for Vision, Sleep, Alcohol, Caffeine, Meal, Training, Smoking, Heart Medication.

Data from the demographics form are reported in Table 1. Many of the questions were asked using fill-in-the-blank or Yes/No format, and the self-rating on sensitivity to cybersickness was reported on a 5-point Likert scale (1-not sensitive to 5-very sensitive). Observation shows that demographic data for the two groups were very similar at the time of the study.

3.3 Materials

Figures 1 and 2 provide an overview of the physical system setup for the study. We used a single computer, an Intel core i7 CPU with an NVIDIA GeForce RTX 2080 GPU and 32GB of RAM, to render the VE (using the Unity 3D engine), log data, and control the overall system. We used an HTC Vive Pro Eye, with 1080 x 1200 pixel resolution (per eye),refresh rate of 90 Hz, and field of view of 110 degrees. Participants used the Vive's built-in headphones for audio. We provided a Microsoft Surface Dial[1] for participants to provide real-time feedback for their discomfort level at that moment; we logged dial output every 30 seconds with corresponding timestamps.

3.3.1 Floor-vibration Platform

Our custom-built floor-vibration platform is composed of multiple layers of interleaved plywood supported on the lab floor by industrial rubber vibration isolators (see Figure 1). The round platform is roughly 2.4m in diameter and has provision for up to nine audio transducers to generate vibration. We currently use four transducers (ButtKicker® Advanced[2]) in conjunction with a 1000w amplifier (Dayton Audio[3]), and the transducers are driven by an audio signal from the PC.

Unity3D software controlled the experiment, including playing spatial audio for the HMD and the floor (see Figure 2). Sound effects exclusively for the HMD ("FX HMD Only" in the figure) are given a digital high-pass filter in Unity so that low frequencies, for instance, voice sound effects, do not become part of the signal driving the floor vibration. This filtered-HMD audio signal is combined with all other full-frequency sound effects in the Unity3D scene into a single sound signal source, which is divided between the floor and HMD equally and synchronously. The floor, through its low-pass filter on the amplifier, will not play high frequency sounds, while the HMD headphones naturally will not play low frequency sounds. This enables us to virtually split the single audio signal to two different channels around 200-250Hz, utilising various mechanical and digital pass filters in the system. This scheme allows the floor to play audio under 250Hz, and the HMD to play audio over 250Hz from the same sound source.

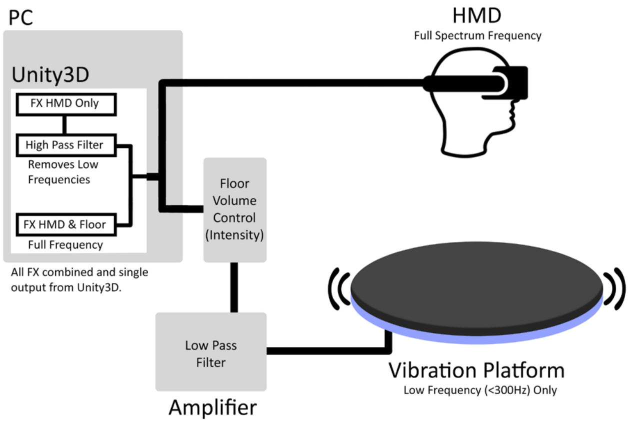

Fig. 2. Audio System: Unity3D provides spatial audio sound effects. The HMD will not naturally play low frequencies, and the floor will not play high frequencies, so it is safe to have the complete frequency spectrum sent to both. To prevent any high frequency components of the sound effects from playing on the floor, the amplifier performs a low pass filter before it is passed to the floor.

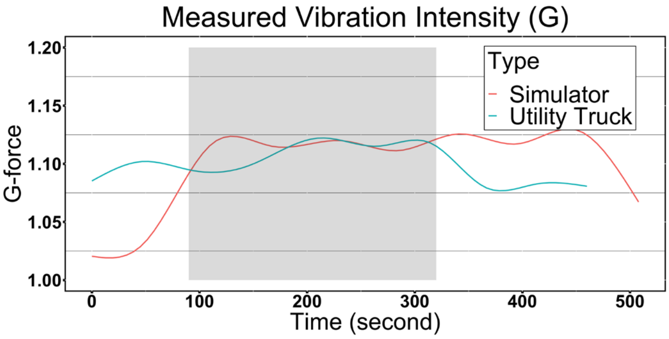

Fig. 3. Vertical vibration intensity. When the virtual vehicle drove in the virtual park, we generated an average 1.15g vibration intensity. The red line shows a fitted line to the data for the vibration data from the floor vibration VR experience, and the blue line shows vibration data from a real pickup truck. The grey shaded area (100-300 seconds) is the part of both capture sessions where the vehicles were driving at the same speed profile.

The single Unity3d audio signal is split through the computer hardware. The HMD runs off of an HDMI cable. That signal is mirrored to a standard audio output jack that goes to the floor. The overall intensity of the audio signal to the floor is adjusted by a volume mixer box (Behringer MicroMix[4]).

In order to create more realistic floor vibrations, we manually modified certain audio files to amplify the low frequency signals that drive the floor only. This required that certain sound effects be custom mixed for the application that set wave-forms in the low end of the frequency spectrum.

Vibration Intensity. To establish a vibration intensity that was perceptible to users and that matched the vibration intensity experienced in a real vehicle, we measured vibration in a real truck and on our vibration floor. We placed a vibration datalogger[5] on the unoccupied

---

[1] https://www.microsoft.com/en-us/p/surface-dial/925r551sktgn

[2] https://www.amazon.com/ButtKicker-Advance-BK4-4-Frequency-Transducer/dp/B0002GY7QA

[3] https://www.daytonaudio.com/product/782/sa1000-subwoofer-amplifier-rack-mountable

[4] https://www.behringer.com/product.html?modelCode=P0390

[5] http://www.extech.com/products/VB300

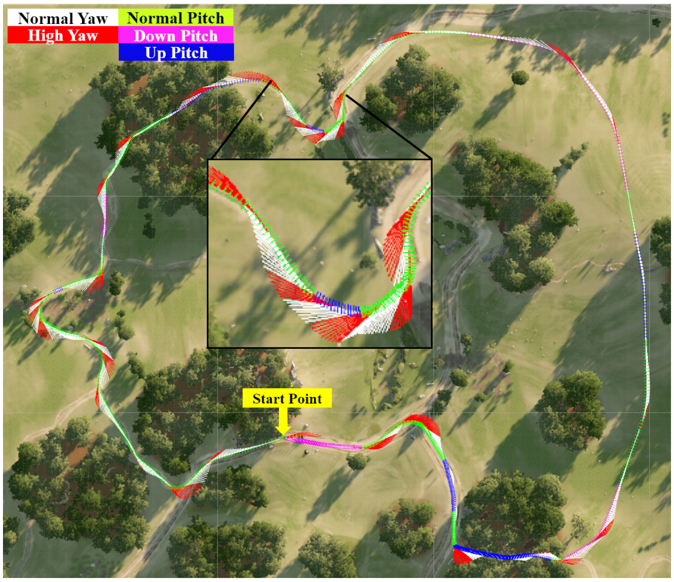

Fig. 4. Driving course in the virtual park: Experiment scene rendered through Unity. Course is 1km long with multiple elevation, direction, and velocity changes. Key: white–little/no turning; red–tight turn; green–relatively flat terrain; magenta–downhill terrain; and blue–uphill terrain.

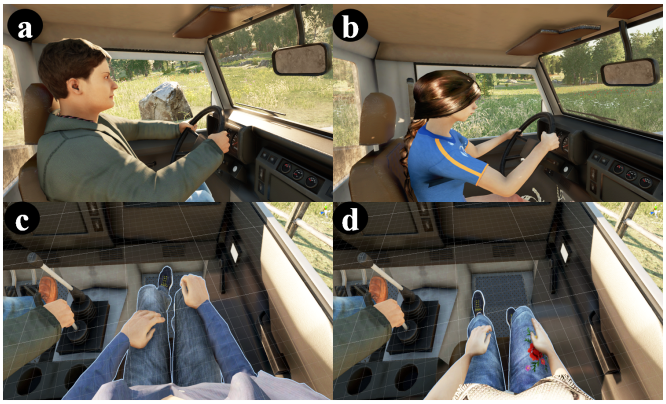

Fig. 5. Driver Agent and Passenger Avatar: Male and female driver agents are shown in (a) and (b). Driver agent animation included steering input, accelerator input, and torso pitch/gravity correction. Passenger avatars are shown in (c) and (d). Passenger avatar position was static, i.e., they were not animated.

passenger seat of a real pickup truck to measure vibration during a drive on a paved road at around 40km/h. The average vibration intensity in the moving pickup truck was $M = 1.14g$ ($SD = 0.08$). This value is similar to the 1.2g (G-Force) vibration previously reported for mild real driving conditions (i.e., driving on a paved road with little or no sudden acceleration or sharp turns) [15].

After tuning the signals that drive our vibration floor, we measured the vibration intensity generated during the ride around the park in the Vibration condition by placing the datalogger in the center of the floor. The average vibration in our simulator during vehicle movement was $M = 1.15g$ ($SD = 0.08$). See the shaded area in Figure 3. We conclude that the vibration intensity generated by the floor and simulator was sufficiently similar to that of a physical vehicle in motion to support the aims of our study.

3.3.2 Virtual Environment

The virtual park environment through which the participants were driven was a roughly 512m x 512m space created with natural looking 3D assets including trees, bushes, grass, trails, and fences. The modeling goal was a pseudo-realistic environment with a neutral aesthetic which included minimal distractions. The course the vehicle followed was 1km long and was designed with multiple elevation, direction, and velocity changes (slower in turns, faster on straights) to move the passenger-participant through a broad range of motions that would elicit a stronger cybersickness response.

The bird's-eye-view visualization of the driving profile in Figure 4 was created in Unity3D by superimposing colored lines at the position of the vehicle at 1-second intervals. A yaw line is projected from the front of the vehicle, creating a fanned display of mild to aggressive turns. Another line is projected laterally from the vehicle, indicating terrain steepness or pitch. The steps between the lines indicate the relative speed, i.e., faster as spaces grow further apart. The color key indicates: white–little/no turning; red–tight turn; green–relatively flat terrain; magenta–downhill terrain; and blue–uphill terrain.

Agent and Avatar. To avoid participant anxiety due to not having a driver in the vehicle (or anxiety due to the participant sitting in the driver's seat, but having no control over the speed and direction of the vehicle) we provided gender- and race-matched virtual avatars for both the driver and passenger (participant) (Figure 5). The skin tone of the avatars was interpolated between White Caucasian and Black African based roughly on participant skin tone. We did this to provide a level of inclusiveness and immersion and remove any distractions resulting from an avatar of an unfamiliar race [20–22]. The experimenter adjusted the gender and skin color before the participant began the experience, and the driver and passenger avatars were created as a pair based on the gender and skin tone information entered. For example, for a White Caucasian male participant, there were male driver and passenger avatar bodies, both with the same white skin color.

	Lap1	Lap2	Lap3	Lap4
Duration (sec)	173.9	101.8	81.2	69.8
Speed (km/h)	21.8	34.3	43.1	50.5

Table 2. Duration and Average driving speed for each lap

Driving Simulation. We seated our participants in the passenger seat of a left-hand drive vehicle [56]. The algorithm controlling the movement of the truck was based on a way-point seeking system. The vehicle stayed on the ground following the virtual terrain changes, but translated and rotated to reach the next way-point. The vehicle automatically reduced throttle response (speed) when the turning radius was above a certain threshold. Vehicle speed was governed by a globally-set multiplier that was referenced by equations controlling the instantaneous speed of the vehicle. The multiplier ramped up over time, slowly increasing the speed of the vehicle over the four laps spent on the course. Atypical to driving simulations, the vehicular dynamics were coded procedurally rather than utilising a physics system. This was to keep course speeds and positions consistent across all participant runs. In Table 2, we provide the duration and average speed of the vehicle for each lap of the experience.

3.4 Measures

We automatically logged and time-stamped the subjective discomfort level data (from the dial) and the objective physiological measures during the VE experience. To avoid confounds from volatile or lasting cybersickness, we minimized the time between when the participant experienced the VE and the time we collected post-experience data. After participants were seated in the chair on the vibration platform, we provided them with a tablet so they could enter their post-experience responses to the SSQ and the MEC-SPQ immediately after the VR experience ended.

3.4.1 Subjective Responses

To report the *self-rated discomfort level*, we used an approach first employed by McHugh *et al.* [34]. Their self-rating system was composed of a physical dial controlled by the participant's dominant hand

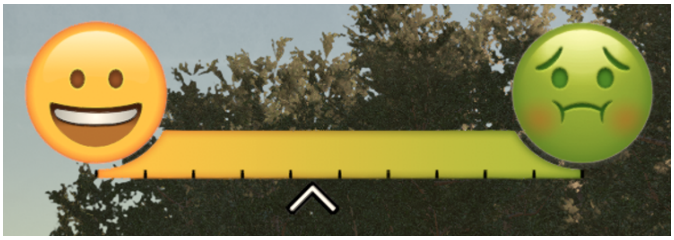

Fig. 6. Discomfort Level: Visual indication of absolute discomfort level. The yellow emoji was used to indicate normal, and the green emoji was used to indicate maximum discomfort. Every 30 seconds, the participant was prompted to use the dial to move the white arrow left or right to report their current level of discomfort.

and wirelessly connected to the PC. Participants were also cued by the software to make a dial adjustment every 30 seconds. Throughout the experience, the participants could adjust the dial at their discretion. Dial data, clamped to an internal scale of 0.0 to 1.0, was recorded in the data log and translated into a visual cue as in Figure 6. The position of the white arrow on the scale between the yellow (“happy”) and green (“nearly vomiting”) emojis shows the current response value.

We used Kennedy’s *Simulator Sickness Questionnaire* (SSQ), which asks the participant to score 16 symptoms with scores from 0 (none) to 3 (severe) [24]. On the SSQ, the 16 symptoms are categorized into three groups: Nausea, Oculomotor, and Disorientation. We collected SSQ data before and after the virtual driving experience [32, 37]. This allowed us to use the change in SSQ (Delta-SSQ) scores for each participant as our statistical variable, reducing the effect of individual differences in the participant population.

To measure the *sense of presence*, we administered the MEC Spatial Presence Questionnaire (MEC-SPQ).This questionnaire reports on three factors: Attention Allocation (AA), Spatial Situation (SS), and Spatial Presence (SP). We used the shorter (four items per factor) version of the questionnaire to reduce the mental load on the participants as we administered this questionnaire at the end of the study. In previous studies, responses to this questionnaire have been validated as correlating with GSR and HR [2, 18].

To determine whether our participants had a *preference* for the Vibration or No-Vibration conditions, after data collection was complete, we invited each of them to experience one lap (the first) around the park in the vibration condition (V or N) they had not yet experienced. Once the participant finished this additional lap, we immediately asked them which, in terms of the overall VE experience, they preferred, and the reasons for their choice.

3.4.2 Objective Responses

Since *heart rate* (HR) and *galvanic skin response* (GSR) have been shown to be correlated with cybersickness [26], we collected both measaures during the experiment using an Empatica E4 wrist band[6]. The photoplethysmography (PPG) sensor on the device collects HR at a 64Hz sampling rate, and the electrodermal activity (EDA) sensor on the device collects GSR data at a 4Hz sampling rate. Both of these were logged during exposure.

Pupil size data was captured using the Vive headset’s built-in eye tracker (manufactured by Tobii[7]), at a sampling rate of 120Hz. The definition of pupil size may vary among different studies or eye tracker manufacturers. In our case, pupil size is defined as the actual, internal physical size of the pupil and not the size it appears to be when looking at the eye from the outside. This definition does not affect the analysis of the result, since we only compare the *change* in pupil size during the entire VR exposure to the baseline measures. Our work with pupil size is an experimental evaluation of the possible utility of pupil size as a response to cybersickness. Previous studies have suggested the changes of pupil size are promising indicators of subjects’ emotion [5]. But, since our study does not attempt to change subjects’ emotions, if pupil size changes are observed, we will need to test whether the changes are correlated with cybersickness.

3.5 Experimental Procedure

We sent an information sheet for the study, including the requirements for health conditions, to participants a day in advance of their session. Once the participant arrived, they were asked to fill out an informed consent form and to read the information sheet again. Then they filled out a demographic questionnaire and the pre-experience SSQ using a tablet. After that, we provided a five-minute break on a couch to allow participants’ physiological signals to settle so that we collected correct baseline data during the Idle time portion of the study. After the break, we officially gave instructions verbally using a script and asked the participant to sit in the chair in the middle of the platform. We asked the participant to put the Empatica E4 on their non-dominant wrist and hold the Surface dial on their dominant-hand thigh. Then we put the participant in the HMD, and immediately calibrated the integrated eye-tracker. After we completed the calibration process, we started the virtual vehicle simulation in the appropriate condition (V or N).

In the virtual park, we provided a one-minute idle time (Pre) with no virtual vehicle and no virtual body. This further allowed the participant’s physiological measures to stabilize, especially the pupil size reading, because it can be susceptible to changes in lighting conditions such as when wearing an HMD. We collected baseline physiological data for HR, GSR, and pupil size during this time. After one-minute, the virtual vehicle, agent and avatar body faded into the scene and the vehicle started to move with speed increasing slowly over time. The whole VE session lasted four laps, unless the participant asked to stop the session early.

After completing the VE experience part of the study, the participant was asked to remain in the chair, take off the HMD, and to use the tablet to answer the SSQ again (post-experience) and the MEC-SPQ. After all of the data was collected, we asked the participant if they would like to experience the system again in the other vibration condition. If they agreed, we provided the same experience with the opposite condition, but for only one lap. Otherwise, the study was concluded. At the end of the extra experience, we asked the participant which condition they preferred, considering the overall experience, and also for future VR systems. After recording their response, we debriefed participants on the study and they left with their voucher.

4 RESULTS

This section begins with a discussion of the pre-processing we did on our collected data to generate the variables we used in our statistical tests. Then we report the results of the statistical analysis of the data collected in real time: self-rated discomfort level, HR, GSR, and pupil size. These results are followed by analysis of the subjective responses for the SSQ, the MEC-SPQ, and the user preference question. We analysed data from twenty-two participants, 11 in the Vibration condition (V group) and 11 in the No-Vibration condition (N group). All statistics were computed using R, version 3.6.1. Though we collected demographic data, due to the low number of participants, we did not perform any analyses using this data.

Data Pre-processing. The main part of the study had two time periods, *Pre* and *Post*. Pre was the one minute idle time ($t = 0 - 60$ seconds) before the vehicle began moving, and Post was the time while the vehicle was moving through the park. Post time ran from $t = 60$ seconds until the participant asked to stop or all four laps were completed.

Each of the 22 participants had six data sets for physiological measures that were logged in real-time, three parameters (HR, GSR, and pupil size), each measured over the two time periods (*Pre* and *Post*). We first reduced each of the logs of time-series data to a single value by averaging, giving us six data points per participant. Then we generated three new variables, *change in HR, change in GSR, and change in pupil size*, by subtracting the average *Pre* value from the average *Post* value for the appropriate pairs of data. Unlike for discomfort data, as discussed below, we allowed the number of samples used when computing

---

[6] https://www.empatica.com/research/e4/

[7] https://www.tobii.com/

the averages to differ according to how long the participant was in the experience (full time or stopping early). We felt we had no justifiable rationale for altering the data sets.

For SSQ scores, we created *Delta SSQ scores for Nausea, Oculomotor, Disorientation, and Total* scores by subtracting participants' results from the first (pre-VR experience) administration of the questionnaire from the results from the second (post-experience) administration, clamping the results to zero if the difference was negative. This process follows the guidance provided by Liu *et al.* and Peng *et al.* [32, 37].

Self-rated discomfort was collected every 30 seconds during the VE experience. Participants were allowed to stop the VR experience at any time, particularly if they felt ill. All who asked to stop early ($N = 13$: 6 in V and 7 in N) had indicated maximum discomfort in their most recent discomfort report. We believe that had these participants completed the full experience, they would have continued to report maximum discomfort (and get even sicker). Because we wanted our average-discomfort data to reflect the full length of the experience, we padded the missing values in the "stopped-early" data sets with the response for maximum discomfort. We created an *Average Discomfort* variable for each participant by averaging.

Data from our final measure, the MEC-SPQ, did not require preprocessing. The questionnaire returns a single value score for each of its three subscales: (*Attention Allocation, Spatial Situation,* and *Spatial Presence*).

In summary, all of our final dependent variables appear in *italics* in the previous paragraphs, and we tested each of the final data sets for *homogeneity of variances and normality* using the Levene's and Anderson-Darling tests. If the data sets passed both tests, we compared data from the V and N conditions with a parametric independent-samples t-test, otherwise we used the non-parametric Mann-Whitney U test. We also confirmed that there were no significant differences in the *Pre* logged data sets (discomfort level, HR, GSR, and pupil size) between the V and N groups.

For the purpose of revealing patterns over time in discomfort, HR, GSR, and pupil size, we present the data as curves generated by using a local polynomial regression fitting method for each of the results (Figures 7, 9, 8, and 10). The descriptive statistics for *Post* and change data for those variables are shown in Table 3 .

4.1 Data Captured in Real-Time

In this section, we report results of analyses of the data captured in real time for the dependent variables self-rated discomfort level (subjective) and the physiological signals HR, GSR, and pupil-size (objective).

4.1.1 Average self-rated discomfort level

The average discomfort level data passed both Levene's test and the Anderson-Darling test ($F(1,19)$=0.19, p=0.67 and p=0.56). Thus, we used the independent-samples t-test to compare the V and N data.

Average discomfort levels were not statistically significantly different between the V and N groups: $t(18.84) = -0.23, p = 0.82$; d=0.1. The effect size (d=0.1) met Cohen's convention for a *trivial effect*. Observation of Figure 7 shows that discomfort levels are very similar and, in both conditions, increase as time in the VE experience increases. This observation confirms that we achieved our goal of creating a VE scenario that evokes discomfort (presumed to be cybersickness) in our participants.

4.1.2 Physiological Responses

Change in HR. Levene's test showed that the variances for HR level were not equal, $F(1,20)$=4.26, p=0.05, but Anderson-Darling normality test showed a normal distribution, p=0.92. Thus, we used the Mann-Whitney U test to compare the V and N data.

Measured HR (beats per minute) was not found to be statistically significantly different between the V group and the N group: $U(V = 11, N = 11)$=70, p =0.56; d=0.29. The effect size was (d=0.29) which met Cohen's convention for a *small effect*. Figure 8 shows that, though not significant, for our sample, individuals in the V group ($M = 80.79, SD = 7.40$) experienced a faster HR than the N group ($M = 77.39, SD = 14.78$).

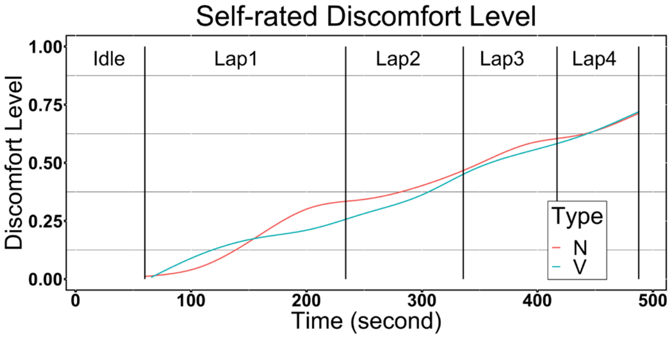

Fig. 7. The average discomfort level in the V group (Blue line) appears lower than the N group (Red line) but the difference was not significant. The discomfort level of both groups rose as time in the VE experience increased.

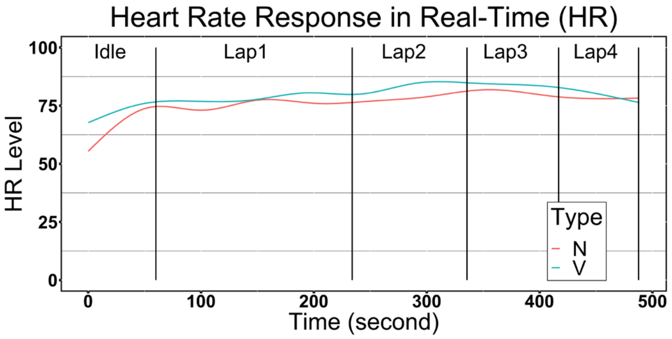

Fig. 8. The average HR in the V group (Blue line) was faster than the N group (Red line). The difference was not statistically significant and the effect size was small.

Change in GSR. Levene's test showed that the variances for GSR levels were equal, $F(1,19)$=2.72, p=0.12, but the Anderson-Darling normality test did not show a normal distribution, p=0.01. Thus, we used the Mann-Whitney U test to compare the V and N data.

Measured GSR was found to be statistically significantly different between the V group and the N group: $U(V = 11, N = 11)$=23, p =0.02; d=0.76. The effect size, (d=0.76), met Cohen's convention for a *large effect*. Figure 9 shows that, particularly after 300 second mark when the relatively slow to change GSR response has begun rising, individuals in the N group ($M = 1.84, SD = 2.53$) experienced higher GSR levels (associated with higher levels of cybersickness) than the V group ($M = 0.49, SD = 0.52$).

Change in Pupil Size. Pupil size data passed both Levene's test and the Anderson-Darling test: $F(1,20) = 0.75$, $p = 0.40$ and $p = 0.62$. Thus we used the parametric t statistic for our comparisons.

In our data, measured pupil size was not found to be statistically significantly different between the V group and the N group: $t(18.53)$=0.53, p=0.60; d=0.27. The effect size (d=0.27) met Cohen's convention for a *small effect*. Observation of Figure 10 shows that pupil size is very similar for our V group ($M = 4.25, SD = 0.68$) and N group ($M = 4.43, SD = 0.91$).

4.2 Subjective Responses

In this section, we present results of the analysis of the subjective responses for the simulator sickness questionnaire (SSQ) and the MEC-Spatial Presence Questionnaire (MEC-SPQ), as well as responses to the vibration-condition preference question (V or N). In addition to the statistical test results, we show the data as box plots for each of the sub-scales of the two questionnaires in Figure 11, and report the descriptive statistics in Table 4.

		Discomfort Dial	HR	GSR	Pupil Size
Pre	V	0.34 (0.21)	73.09 (9.08)	0.39 (0.42)	3.34 (0.53)
	N	0.35 (0.19)	68.24 (15.13)	0.93 (1.15)	3.50 (0.67)
Post	V	0.35 (0.21)	80.79 (7.40)	***0.49 (0.52)**	4.25 (0.68)
	N	0.37 (0.21)	77.39(14.78)	1.84 (2.53)	4.43 (0.91)
Difference	V	0.01 (0.21)	7.70 (5.67)	0.10 (0.24)	0.91 (0.26)
	N	**0.02 (0.20)**	**9.15 (8.85)**	**0.91 (1.47)**	**0.93 (0.32)**

Table 3. Descriptive statistics (Mean, SD) for time series data taken during the drive (post) and the difference values (post-pre). **Bold** in Post indicates a significant difference between the V group and N group. GSR had a large effect size; the other variables had trivial or small effect sizes. **Bold** in Difference indicates the larger of the two values.

	SSQ				MEC-SPQ		
	Nausea	Oculomotor	Disorientation	Total	AA	SP	SS
V	42.50 (31.75)	***35.83 (14.01)**	63.27 (33.15)	529.59 (280.20)	3.61 (0.68)	3.00 (0.98)	3.70 (0.92)
N	60.71 (24.61)	53.75 (21.02)	54.41 (35.46)	631.58 (265.86)	3.70 (0.92)	2.88 (1.04)	2.97 (1.10)

Table 4. Descriptive Results for Subjective Responses, Mean (SD). **Bold** indicates a significant difference between the V group and N group. The effect size for Oculomotor was large.

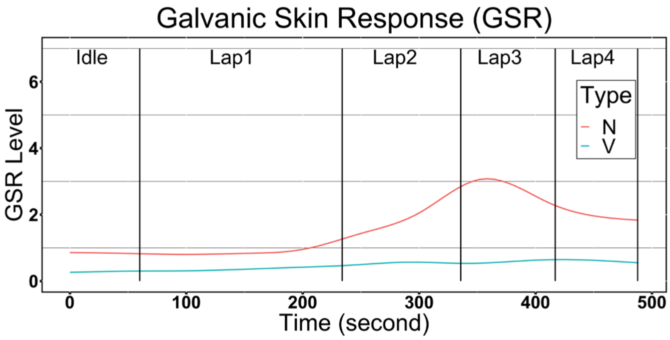

Fig. 9. The average GSR in the V group was lower than the N group and the effect size was large. The GSR value for the N group increased and reached the highest value at around 350seconds (Red line). This is consistent with the relatively slow (minutes) response of GSR to stimuli generating general arousal/stress. The GSR was almost constant in the V group (Blue line)

.

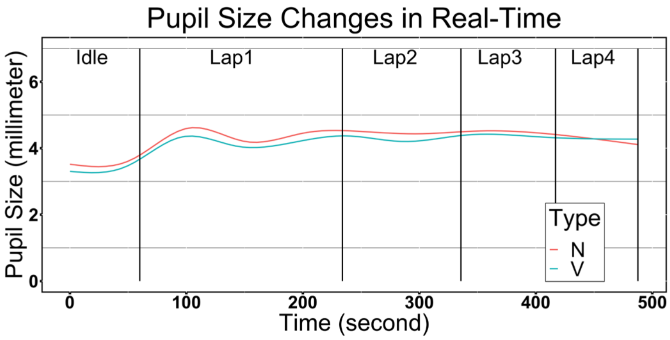

Fig. 10. The average Pupil Size in the V group (Blue line) was smaller than the N group (Red line).

4.2.1 SSQ

Change in Nausea. The independent samples t-test did not find a significant difference in the Delta-SSQ Nausea scores between the V and N groups, $t(18.83)=1.50$, $p=0.14$; $d=0.64$. The effect size, ($d=0.64$), exceeded Cohen's convention for a *large effect*. The differences visible in the blue box-plots in Figure 11 are not statistically significant.

Change in Oculomotor. The independent samples t-test did find a significant difference in the Delta-SSQ Oculomotor subscale scores between the V and N groups, $t(17.42)=2.35$, $p=0.013$; $d=1.00$. The effect size, ($d=1.00$), exceeded Cohen's convention for a *large effect*. The differences visible in the yellow box-plots in Figure 11 are statistically significant.

Change in Disorientation. The independent samples t-test did not find a significant difference the Delta-SSQ Disorientation scores between the V and N groups, $t(19.91)=-0.60$, $p=0.55$; $d=0.25$. The effect size, ($d=0.25$), met Cohen's convention for a *small effect*. The differences visible in the red box-plots in Figure 11 are not statistically significant.

Change in Total SSQ Score. The independent samples t-test did not find a significant difference for Delta-SSQ Total SSQ score between the V and N groups, $t(19.94)=0.87$, $p=0.39$; $d=0.37$. The effect size, ($d=0.37$), exceeded Cohen's convention for a *moderate effect*. The differences visible in the green box-plots in Figure 12 are not statistically significant.

4.2.2 Presence

To understand participants' sense of spatial presence after their VR experience, we had them complete the MEC-SPQ questionnaire. The data were analysed using the Mann-Whitney U test. We found no statistically significant differences in responses between the V and N group responses.

Attention Allocation. The Mann-Whitney test did not find a significant difference for the level of Attention Allocation between the V group (Mdn=4) and the N group (Mdn=4), $U(V=11, N=11)$=874, p=0.37.

Spatial Presence. The Mann-Whitney test did not find a significant difference for the level of Spatial Presence between the V group (Mdn=3) and the N group (Mdn=3), $U(V=11, N=11)$=1021.5, p=0.64.

Spatial Situation. The Mann-Whitney test did not find a significant difference for the level of Spatial Situation between the V group (Mdn=3) and the N group (Mdn=3), $U(V=11, N=11)$=1008.5, p=0.72.

4.2.3 Vibration Condition Preference

After we completed data collection for the main part of the study, we asked participants if they wanted to experience a one-lap ride around the course in the vibration condition they had not yet experienced. Our goal was to enable participants to compare the overall experience in the two conditions and report to us their preference for the V or N condition. Only one participant declined. All 21/21 of those who experienced both conditions indicated their preference for the vibration-on condition.

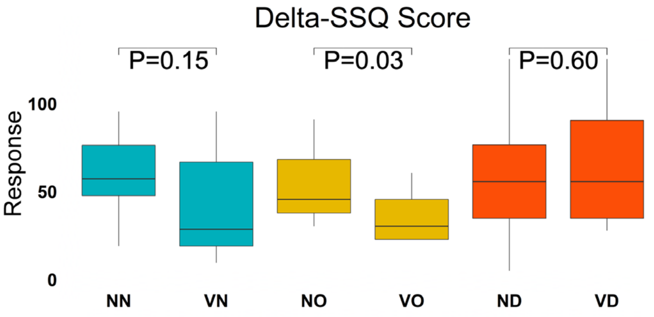

Fig. 11. There was a significant difference in Delta-SSQ Oculomotor between the two conditions (NO and VO); we did not find any significant differences for Delta-SSQ Nausea (NN and VN) or Delta-SSQ Disorientation (ND and VD).

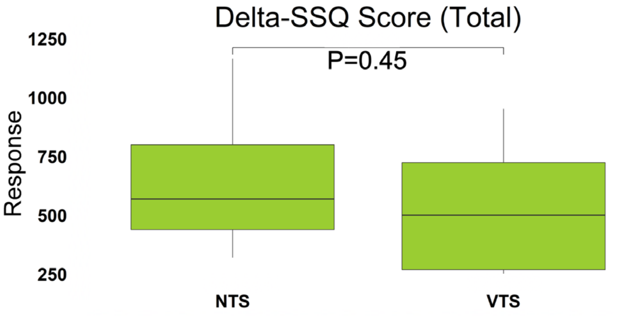

Fig. 12. We did not find any significant difference for the Delta-SSQ total score N and V.

5 DISCUSSION

When we began this work, we decided to base our work on sensory conflict theory as it is popularly considered to be a likely contributor to the occurrence of cybersickness in fully immersive virtual reality experiences. In particular, we considered conflict between the visual and vestibular senses. In the following, we discuss our results against our goals of reducing cybersickness, maintaining quality of user experience (level of presence), and understanding participant preference for vibration-on or no vibration.

5.1 Cybersickness

Our first hypothesis was:

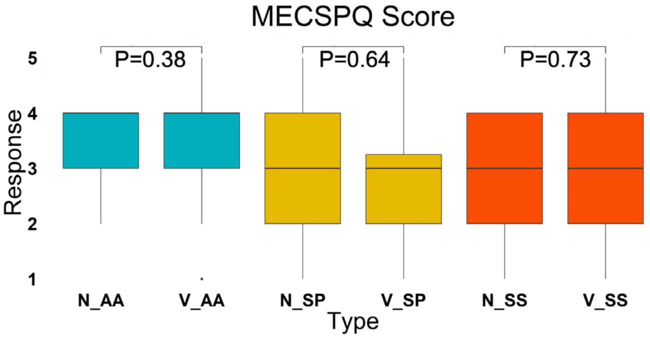

Fig. 13. There was no significant difference between the two conditions in terms of Attention Allocation (N_AA and V_AA), Spatial Presence (N_SP and V_SP) or Spatial Situation (N_SS and V_SS) subscales of the MEC-SPQ.

H_1 : Minimally matched floor vibration will reduce the level of cybersickness compared to no vibration.

In our experiment, we found partial support for this hypothesis: GSR signal levels and scores on the Delta-SSQ Oculomotor subscale differed significantly between the V and N groups in the direction of the V group having lower indications of cybersickness than the N group. This supports our first design goal, reduce cybersickness, and first hypothesis: minimally matched floor vibration will reduce level of cybersickness compared to no vibration.

Previous research has reported a positive correlation between GSR and cybersickness [26]. Our research supports the earlier results. The GSR response in the no-vibration group began to increase strikingly around the 300-second mark, consistent with GSR response times to general arousal or stress. The GSR response in the V group was mostly stable, and consistently low. We speculate that the decrease in GSR in the N group after about 350 seconds is related to how we handled the data for the participants who stopped early.

Responses to the SSQ showed that the Delta-SSQ Oculomotor subscale score was significantly lower in the V group than in the N group, with large effect size. An interesting avenue of future research might focus on similarities and differences in how vibration (or not) and head-bobbing (or not) effect participant comfort. It is interesting to note that the V results meet the *virtual environment sickness* profile order described by Kennedy *et al.* [51] of D>N>O, while N is more similar to a *seasickness* or *airsickness* profile order N>D>O.

We observed no other significant differences on any measure. As our number of participants was about half of what the *a priori* power analysis recommended, N=22 rather than N=40, we are not surprised at these results.

Summary. Overall, we conclude that floor vibration that is at least minimally matched the scenario can mitigate some indicators of cybersickness. This conclusion is based on our findings of significant differences for V and N groups for the variables change in Delta-SSQ Oculomotor score and change in GSR.

5.2 Presence and Preference

In this work we found support for our second and third hypotheses:

H_2 : The use of floor vibration will not influence the level of presence.

H_3 : Minimally matched floor vibration will be preferred over no vibration.

Our data from the MEC-SPQ revealed no significant differences between V and N groups on its three presence-related subscales. All 21 participants who experienced both vibration conditions responded that they preferred the VR experience with floor vibration compared to the no-vibration condition.

Presence. Our results did not find that the level of presence differed between the V and H conditions. We acknowledge that this does not prove there are no differences. Regardless of whether there was vibration feedback or not, our simulator delivered a high level of place illusion and plausibility through the realistic virtual representation of off-road driving. We were not surprised that participants in both conditions reported a high level of presence [50]. We believe the actual level of presence might have been higher than the reported scores if we had been able to account for the negative effect of cybersickness on the user experience [56]. These presence results support our second hypothesis: floor vibration will not influence level of presence, and second design goal: preserve presence.

Preference. We were pleasantly surprised that 21 out of 21 participants who experienced riding through the park in both vibration conditions preferred the V experience over the N experience. (The remaining participant did not try the extra experience because their cybersickness symptoms from the first condition were too severe.) The major reason participants gave for preferring the vibration-on condition was the *realism* of the system. The participant comments contained no mention of anything related to cybersickness, positive or negative.

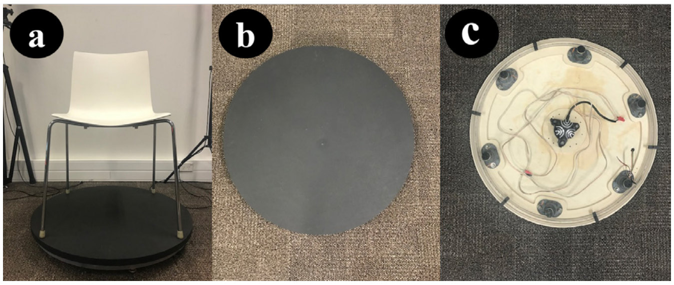

Fig. 14. The mini version of the floor vibration platform. We created is at 1/6 scale of the original floor. It is a fitted size with the same chair that used in the study (a) and (b). We attached only one transducer in the middle (c).

These results for Preference support our third hypothesis: minimally matched floor vibration will be preferred over no vibration.

5.2.1 Deployability

Although our platform requires some resources (space, cost, and time to setup), technically, it is a simple device. We built a "mini" version of the floor vibration platform as an example of a simple and cost-effective solution. The Buttkicker audio transducer we used in the "mini" could easily be attached underneath the seat of a chair or a sofa as Sawada *et al.* [48] did in their study. The small platform size of the "mini" and the flexibility in mounting the transducer extend the utility of the system. The "mini" supports our third design goal, deployability.

5.3 Observations and Implications

Two participants in the N group confessed that they tried to mitigate cybersickness with their own strategies, such as fixing their gaze on the dashboard of the vehicle, or moving their head in the direction opposite to the vehicle's turning direction. At the end of the study, most of the participants mentioned that horizontal (yaw) rotation at high vehicle speeds elicited stronger cybersickness symptoms than vertical movement (pitching up and down). Because our floor produces only vertical vibration, we conjecture that the floor vibration may compensate only for the elements of the missing vestibular stimulation that map to the vertical direction, while delivering less or no stimulation in yaw. This is an interesting avenue for future work.

Two participants in the V condition reported that riding in the virtual park with vibration-on was almost the same as if they rode in a real vehicle on similar terrain in the real world. One of these two participants said, "By chance, I drove a Ute (pickup truck) in the morning before I came here for the study, and this experience surprised me since the realism is very similar". Though most of the participants raised realism as a "Wow!" factor in V, one participant stated that high realism induced anxiety during the vehicle ride; the anxiety may have contributed to cybersickness.

It is expected that a cybersickness mitigation solution can be made more robust by combining matched vibration with other techniques, such as head-bobbing, and FOV changes. We leave these as future work.

Based on the results and observations, we believe that introducing floor vibration to our system not only mitigated cybersickness, but also increased the level of realism.

Lastly, we suggest that our passive driving simulation scenario could be valuable in similar research in the future: Our driving course is well designed to induce an observable level of cybersickness while providing a high level of realism. We will make this system available to other researchers.

5.4 Limitations

Even though we accept that the vibration we provided was only a minimal approximation of the missing sensory input to the vestibular system, there is actually no real way to know for sure if the vibration we supplied actually stimulated the vestibular system in the "right" way. We need to further monitor and assess reactions to vibration generated directly as vestibular noise.

Lastly, two of the participants in the N condition came up with their own mitigation strategies against cybersickness, and we estimate their strategy worked for reducing cybersickness. Thus, there is a chance that this led to lower overall cybersickness in the N group. Nevertheless, we still showed the advantages of floor vibration, but there may still exist some hidden negative impacts in the data. In future work, researchers should consider preventing such a strategy that can be confounding.

6 CONCLUSION

Based on sensory conflict theory, we investigated the impact of floor vibration on cybersickness using a virtual vehicle driving system in a highly realistic and complex off-road drive through a virtual park. Due to the timing of the COVID lockdown in New Zealand, we were able to recruit just over half of the number of participants recommended by our *a priori* power analysis. This lowered the statistical power of our analyses. Our platform induced an observable level of cybersickness, while evokingc a similar level of sense of presence in both vibration-on and no vibration conditions. The significant changes in SSQ Oculomotor scale and the physiological signal GSR suggest that floor vibration in VR experience can mitigate cybersickness compared to experiences without floor vibration. Floor vibration-on was also overwhelmingly the preferred to no-vibration by all of our participants who experienced both.

For our experiment we chose a vibration fidelity point between purely random vibration and total fidelity. We and others have now shown proof-of-concept that artificial stimulation of the vestibular through a vibrating floor can reduce cybersickness. There is clear value in continuing research into how to best use vibration to mitigate cybersickness and to understand the mechanisms which make it work. If total vibration fidelity is unachievable, how much fidelity is good enough?

ACKNOWLEDGMENTS

We would like to thank the participants of our user studies for their help and feedback on our work. We would also like to thank the reviewers of our submission for their detailed and constructive feedback on earlier drafts.

REFERENCES

[1] H. Akiduki, S. Nishiike, H. Watanabe, K. Matsuoka, T. Kubo, and N. Takeda. Visual-vestibular conflict induced by virtual reality in humans. *Neuroscience letters*, 340(3):197–200, 2003.

[2] I. M. Arafat, S. M. S. Ferdous, and J. Quarles. The effects of cybersickness on persons with multiple sclerosis. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*, VRST '16, p. 51–59. Association for Computing Machinery, New York, NY, USA, 2016. doi: 10.1145/2993369.2993383

[3] B. Aykent, F. Merienne, C. Guillet, D. Paillot, and A. Kemeny. Motion sickness evaluation and comparison for a static driving simulator and a dynamic driving simulator. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 228(7):818–829, 2014.

[4] P. Budhiraja, M. R. Miller, A. K. Modi, and D. Forsyth. Rotation blurring: use of artificial blurring to reduce cybersickness in virtual reality first person shooters. *arXiv preprint arXiv:1710.02599*, 2017.

[5] B. Cebeci, U. Celikcan, and T. K. Capin. A comprehensive study of the affective and physiological responses induced by dynamic virtual reality environments. *Computer Animation and Virtual Worlds*, 30(3-4):e1893, 2019.

[6] C.-H. Chang, W.-W. Pan, L.-Y. Tseng, and T. A. Stoffregen. Postural activity and motion sickness during video game play in children and adults. *Experimental Brain Research*, 217(2):299–309, Mar. 2012. doi: 10.1007/s00221-011-2993-4

[7] R. M. S. Clifford, S. Jung, S. Hoermann, M. Billinghurst, and R. W. Lindeman. Creating a stressful decision making environment for aerial firefighter training in virtual reality. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 181–189, 2019.

[8] S. Cobb, S. Nichols, and J. Wilson. Health and safety implications of virtual reality: In search of an experimental methodology. In *Proceedings of FIVE*, vol. 95, pp. 227–242, 1995.

[9] C. Curry, R. Li, N. Peterson, and T. Stoffregen. Cybersickness in virtual reality head-mounted displays: Examining the influence of sex differences and vehicle control. *International Journal of Human-Computer Interaction*, 36(12):1161–1167, July 2020. doi: 10.1080/10447318.2020.1726108

[10] R. Curry, B. Artz, L. Cathey, P. Grant, and J. Greenberg. Kennedy SSQ results: fixed-vs motion-based ford simulators. In *Proceedings of DSC*, pp. 289–300, 2002.

[11] M. S. Dennison, A. Z. Wisti, and M. D'Zmura. Use of physiological signals to predict cybersickness. *Displays*, 44:42–52, 2016.

[12] C. Donalek, S. Djorgovski, S. Davidoff, A. Cioc, A. Wang, G. Longo, J. Norris, J. Zhang, E. Lawler, S. Yeh, A. Mahabal, M. Graham, and A. Drake. Immersive and collaborative data visualization using virtual reality platforms. *2014 IEEE International Conference on Big Data (Big Data)*, pp. 609–614, 2014.

[13] X. Dong, K. Yoshida, and T. Stoffregen. Control of a virtual vehicle influences postural activity and motion sickness. *Journal of experimental psychology. Applied*, 17 2:128–38, 2011.

[14] Ł. Dziuda, M. P. Biernacki, P. M. Baran, and O. E. Truszczyński. The effects of simulated fog and motion on simulator sickness in a driving simulator and the duration of after-effects. *Applied ergonomics*, 45(3):406–412, 2014.

[15] J. P. Ehsani, F. O'Brien, and B. Simmons-Morton. Comparing g-force measurement between a smartphone app and an in-vehicle accelerometer. In *Proceedings of the Ninth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, pp. 221–227, 2017.

[16] A. S. Fernandes and S. K. Feiner. Combating vr sickness through subtle dynamic field-of-view modification. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 201–210, 2016.

[17] F. Franz, E. Edgar, L. Albert-Georg, and B. Axel. G*power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, 39(175–191), 2007.

[18] S. Grassini and K. Laumann. Questionnaire measures and physiological correlates of presence: A systematic review. *Frontiers in Psychology*, 11:349, 2020. doi: 10.3389/fpsyg.2020.00349

[19] J. Hvass, O. Larsen, K. Vendelbo, N. Nilsson, R. Nordahl, and S. Serafin. Visual realism and presence in a virtual reality game. In *2017 3DTV Conference: The True Vision - Capture, Transmission and Display of 3D Video (3DTV-CON)*, pp. 1–4, 2017.

[20] S. Jung and C. E. Hughes. The effects of indirect real body cues of irrelevant parts on virtual body ownership and presence. In *ICAT-EGVE 2016 - International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments*, pp. 107–114, 2016.

[21] S. Jung, C. Sandor, P. J. Wisniewski, and C. E. Hughes. Realme: The influence of body and hand representations on body ownership and presence. In *Proceedings of the 5th Symposium on Spatial User Interaction, ACM SUI 2017*, pp. 3–11, 2017.

[22] S. Jung, P. J. Wisniewski, and C. E. Hughes. In limbo: The effect of gradual visual transition between real and virtual on virtual body ownership illusion and presence. In *Proceedings of the 25th IEEE Conference on Virtual Reality and 3D User Interfaces, IEEE VR 2018*, 2018.

[23] S. Jung, A. L. Wood, S. Hoermann, P. L. Abhayawardhana, and R. W. Lindeman. The impact of multi-sensory stimuli on confidence levels for perceptual-cognitive tasks in vr. In *Proceedings of the 27th IEEE Conference on Virtual Reality and 3D User Interfaces, IEEE VR 2020*, 2020.

[24] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3):203–220, 1993.

[25] B. Keshavarz and H. Hecht. Validating an efficient method to quantify motion sickness. *Human factors*, 53(4):415–426, 2011.

[26] Y. Y. Kim, H. J. Kim, E. N. Kim, H. D. Ko, and H. T. Kim. Characteristic changes in the physiological components of cybersickness. *Psychophysiology*, aug 2005.

[27] M. Klüver, C. Herrigel, S. Preuß, H.-P. Schöner, and H. Hecht. Comparing the incidence of simulator sickness in five different driving simulators. In *Proceedings of Driving Simulation Conference*, 2015.

[28] S. Laborde, E. Mosley, and J. F. Thayer. Heart rate variability and cardiac vagal tone in psychophysiological research – recommendations for experiment planning, data analysis, and data reporting. *Frontiers in Psychology*, 8:213, 2017. doi: 10.3389/fpsyg.2017.00213

[29] J. J. LaViola Jr. A discussion of cybersickness in virtual environments. *ACM SIGCHI Bulletin*, 32(1):47–56, 2000.

[30] C. Lee, G. A. Rincon, G. Meyer, T. Höllerer, and D. A. Bowman. The effects of visual realism on search tasks in mixed reality simulation. *IEEE Transactions on Visualization and Computer Graphics*, 19(4):547–556, 2013.

[31] J. J.-W. Lin, H. B. L. Duh, H. Abi-Rached, D. E. Parker, and T. A. F. Iii. Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. In *Proceedings of the IEEE Virtual Reality Conference 2002*, VR '02, p. 164. IEEE Computer Society, USA, 2002.

[32] S. Liu, N. Yu, L. Chan, Y. Peng, W. Sun, and M. Y. Chen. Phantomlegs: Reducing virtual reality sickness using head-worn haptic devices. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 817–826, 2019.

[33] T. Louis, J. Troccaz, A. Rochet-Capellan, and F. Bérard. Is it real? measuring the effect of resolution, latency, frame rate and jitter on the presence of virtual entities. ISS '19, p. 5–16. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3343055.3359710

[34] N. McHugh, S. Jung, S. Hoermann, and R. W. Lindeman. Investigating a physical dial as a measurement tool for cybersickness in virtual reality. In *25th ACM Symposium on Virtual Reality Software and Technology*, VRST '19. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3359996.3364259

[35] O. Merhi, E. Faugloire, M. Flanagan, and T. Stoffregen. Motion sickness, console video games, and head-mounted displays. *Human Factors*, 49(5):920–934, Oct. 2007. doi: 10.1518/001872007X230262

[36] J. Munafo, M. Diedrick, and T. A. Stoffregen. The virtual reality head-mounted display oculus rift induces motion sickness and is sexist in its effects. *Experimental brain research*, 235(3):889—901, March 2017. doi: 10.1007/s00221-016-4846-7

[37] Y.-H. Peng, C. Yu, S.-H. Liu, C.-W. Wang, P. Taele, N.-H. Yu, and M. Y. Chen. Walkingvibe: Reducing virtual reality sickness and improving realism while walking in vr using unobtrusive head-mounted vibrotactile feedback. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3313831.3376847

[38] J. Plouzeau, J.-R. Chardonnet, and F. MÉRIENNE. Dynamic Platform for Virtual Reality Applications. In *EuroVR conference 2017*, pp. 2–5. Laval, France, Dec. 2017.

[39] J. Plouzeau, D. Paillot, B. AYKENT, and F. Merienne. Vibrations in dynamic driving simulator: Study and implementation. In *CONFERE 2013*, pp. 1–8. CONFERE 2013, France, July 2013.

[40] M. Pouke, A. Tiiro, S. M. LaValle, and T. Ojala. Effects of visual realism and moving detail on cybersickness. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 665–666, 2018.

[41] J. D. Prothero, H. G. Hoffman, D. E. Parker, I. Thomas A. Furness, and M. J. Wells. Foreground/background manipulations affect presence. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 39(21):1410–1414, 1995. doi: 10.1177/154193129503902111

[42] J. T. Reason and J. J. Brand. *Motion sickness.* Academic press, 1975.

[43] L. R. Rebenitsch. *Cybersickness prioritization and modeling*. Michigan State University, 2015.

[44] G. Riccio and T. Stoffregen. An ecological theory of motion sickness and postural instability. *Ecological Psychology*, 3(3):195–240, 1991. doi: 10.1207/s15326969eco0303_2

[45] J. Roettl and R. Terlutter. The same video game in 2d, 3d or virtual reality – how does technology impact game evaluation and brand placements? *PLOS ONE*, 13(7):1–24, 07 2018. doi: 10.1371/journal.pone.0200724

[46] M. Roussou and G. Drettakis. Photorealism and non-photorealism in virtual heritage representation. VAST'03, p. 51–60. Eurographics Association, Goslar, DEU, 2003.

[47] D. Saredakis, A. Szpak, B. Birckhead, H. A. D. Keage, A. Rizzo, and T. Loetscher. Factors associated with virtual reality sickness in head-mounted displays: A systematic review and meta-analysis. *Frontiers in Human Neuroscience*, 14:96, 2020. doi: 10.3389/fnhum.2020.00096

[48] Y. Sawada, Y. Itaguchi, M. Hayashi, K. Aigo, T. Miyagi, M. Miki, T. Kimura, and M. Miyazaki. Effects of synchronised engine sound and vibration presentation on visually induced motion sickness. *Scientific reports*, 10(7553):203–220, 2020. doi: doi.org/10.1038/s41598-020-64302-y

[49] V. Schwind, P. Knierim, N. Haas, and N. Henze. Using presence questionnaires in virtual reality. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3290605.3300590

[50] M. Slater. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1535):3549–3557, Dec. 2009. doi: 10.1098/rstb.2009.0138

[51] K. M. Stanney and R. S. Kennedy. The psychometrics of cybersickness. *Commun. ACM*, 40(8):66–68, Aug. 1997. doi: 10.1145/257874.257889

[52] T. A. Stoffregen, E. Faugloire, K. Yoshida, M. B. Flanagan, and O. Merhi. Motion sickness and postural sway in console video games. *Human Factors*, 50(2):322–331, 2008. PMID: 18516842. doi: 10.1518/001872008X250755

[53] M. Treisman. Motion sickness: an evolutionary hypothesis. *Science*, 197(4302):493–495, 1977. doi: 10.1126/science.301659

[54] I. P. Tussyadiah, D. Wang, T. Jung, and M. T. Dieck. Virtual reality, presence, and attitude change: Empirical evidence from tourism. *Tourism Management*, 66:140–154, 2018.

[55] M. van Gisbergen, M. Kovacs, F. Campos, M. van der Heeft, and V. Vugts. What we don't know. the effect of realism in virtual reality on experience and behaviour. In *Augmented Reality and Virtual Reality*, pp. 45–57. Springer, 2019.

[56] S. Weech, S. Kenny, and M. Barnett-Cowan. Presence and cybersickness in virtual reality are negatively related: A review. *Frontiers in Psychology*, 10:158, 2019. doi: 10.3389/fpsyg.2019.00158

[57] S. Weech, J. Moon, and N. F. Troje. Influence of bone-conducted vibration on simulator sickness in virtual reality. *PLOS ONE*, 13(3):1–21, 03 2018. doi: 10.1371/journal.pone.0194137

[58] Y. Wu, Y. Wang, S. Jung, S. Hoermann, and R. W. Lindeman. Exploring the use of a robust depth-sensor-based avatar control system and its effects on communication behaviors. In *25th ACM Symposium on Virtual Reality Software and Technology*, VRST '19. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3359996.3364267