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Postural stability predicts the likelihood of cybersickness in active HMD-based virtual reality

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ABSTRACT

Cybersickness is common during virtual reality experiences with head-mounted displays (HMDs). Previously it has been shown that individual differences in postural activity can predict which people are more likely to experience *visually*-induced motion sickness. This study examined whether such predictions also generalise to the cybersickness experienced during active HMD-based virtual reality. *Multisensory* stimulation was generated by having participants continuously turn their heads from left to right while viewing the self-motion simulations. Real-time head tracking was then used to create ecological (‘compensated’) and non-ecological (‘inversely compensated’) head-and-display motion conditions. Ten (out of 20) participants reported feeling sick after being exposed to these self-motion simulations. Cybersickness did not differ significantly between the two compensation conditions. However, individual differences in spontaneous postural instability when standing quietly were found to predict the likelihood of subsequently experiencing cybersickness. These findings support recent proposals that postural measures can help diagnose who will benefit the most/least from HMD-based virtual reality.

1. Introduction

Head Mounted Displays (HMDs) offer an efficient and cost-effective alternative to other tools used to generate virtual environments for research, training and treatment [1,2]. In recent years, a number of companies have entered the commercial HMD market and are now producing devices ranging widely in cost. These HMDs range from Google Cardboard, which uses a smartphone placed in a cardboard frame, to custom-built headsets such as the Oculus Rift and the HTC Vive. The latter HMDs have wide binocular fields of view (100° or more) and provide stereoscopic 3D content, which can enhance illusions of self-motion within the scene [3–7]. The head tracking on these HMDs also allows for real time updates of the user’s viewpoint across a 360° field of view. This can facilitate exploration, increase the perceived realism of the simulation, and produce a stronger sense of immersion [8]. However, despite the benefits of HMD-based virtual reality, there are still a number of problems associated with HMD use [9].

One commonly reported side-effect of HMDs is that they can induce sickness symptoms similar to those caused by the physical motion of the observer [10]. Common sickness symptoms induced by HMDs include nausea, dizziness, stomach awareness, disorientation and headaches [11]. Reports suggest that these symptoms can last for hours, or in some cases days, after exposure to the virtual environment [10–12]. In the past, the sickness experienced in virtual reality has been described using a variety of terms, including gaming sickness, simulator sickness, and cybersickness [10,13–19]. This study will focus on *cybersickness* as opposed to *visually induced motion sickness* (VIMS). While VIMS refers to sickness induced primarily by visual motion stimulation (such as that provided by fixed-base flight and driving simulators), we argue that HMD-based virtual reality instead induces cybersickness, because the provocative motion stimulation might be visual, non-visual or multisensory in origin [18,20].

One approach to improve the uptake of HMD-based virtual reality is to find ways to reduce cybersickness in all individuals. While head movements are often required to explore virtual environments when wearing HMDs, the multisensory stimulation they generate appears to increase the likelihood of cybersickness [21,22]. This may explain why users move their heads less when exploring virtual, compared to real world, environments [23]. Thus, we need to better understand the roles that active head-motion and head tracking play in generating HMD-

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based cybersickness; this is one goal of the present study. We also attempt to predict who might suffer the most (or benefit the least) from this type of HMD-based virtual reality. To this end, this study will also examine whether individual differences in postural stability can be used to predict which users will be more likely to experience cybersickness.

1.1. What role do head-movements play in generating HMD-based cybersickness?

There are several reasons why head movements made during HMD-based virtual reality might generate cybersickness. One reason is that there are unavoidable delays between the user making a tracked head movement and the visual scene being updated in their HMD. This system lag is not constant and depends on a number of factors, including the delay associated with the tracker, the accuracy of the position tracking, and the computational load required to generate the visual displays (as well as other background processes) [11]. Excessive/perceptible lags are thought to increase the likelihood of cybersickness, because they generate unusual patterns of multisensory stimulation [20,24,25]. For example, sensory conflict theories ([26] see also [27–29]) predict that increasing system lag will: (1) result in greater mismatches between available visual and non-visual/inertial motion information; and (2) generate patterns of multisensory stimulation that are more difficult to reconcile with expectations based on past experiences. Although some studies have found support for this proposal that cybersickness should increase with the system lag [30–32], others have reported no significant effects of display lag [25,33]. Differences in these reports might be explained by head movements either not being carefully controlled or not being encouraged across the different studies.

A second reason why head-movements might increase the likelihood of cybersickness is because they generate automatic eye-movements [34,35]. In the real world, these eye-movements normally act to stabilise the visual scene on our retinas. However, because they are driven by visual and inertial information, they are presumably much less successful in achieving a desirable outcome in HMD-based virtual reality (due to the presence of system lag and the fact that these eye-movements are typically not tracked or compensated for by the display). This might explain the common reports of a loss of perceptual stability and eyestrain made when wearing HMDs.

A third reason why head movements might increase the likelihood of experiencing cybersickness with HMDs is that there can be problems with how the consequences of these head movements are modelled. For example, software errors or errors in calibrating the HMDs could lead to either an exaggeration or a reduction in the visual consequences of the user's head motions [36]. Again, according to sensory conflict theories, these modelling errors would generate mismatches between (or within) the visual and non-visual motion senses, which should increase the likelihood of experiencing cybersickness.

1.1.1. Examining head-and-display-motions in this study

As we were interested in investigating the effects of active head movements on HMD-based cybersickness, we had users make continuous left-right oscillatory head movements in this study (an admittedly extreme/worst case scenario). We placed physical limits on the amplitudes of these head-movements and provided an auditory guide for users to control their frequency. The use of these carefully controlled head movements was a novel aspect of our approach. We also manipulated the expected level of sensory conflict and the modelling accuracy of these head movements. This manipulation was performed by using two different head-and-display-motion conditions: (1) 'compensated' and (2) 'inversely compensated'. Based on the recent findings of Palmisano, Mursic and Kim [18], an HMD-based study using a very similar manipulation, the former ecological 'compensated' condition was expected to produce less sensory conflict (and therefore less cybersickness) and the latter non-ecological 'inversely compensated' condition was expected to increase sensory conflict (and therefore produce more cybersickness). These experimental conditions are described in more detail in Section 2.2.

1.2. Can we predict who is more likely to experience cybersickness in HMDs?

We were also interested in whether it would be possible to predict which users would be more likely to experience cybersickness with HMDs. Research has shown that there are large individual differences in the susceptibility to, and experience of, cybersickness (e.g., [37]). It is possible that the sickness inducing effects of the factors outlined above (in Section 1.1) might vary due to individual differences in the ability to process visual motion stimuli during active head movements. Recent evidence reveals individual differences in the temporal processing of visual and auditory stimuli during such head movements [38,39]. This suggests, for example, that for the same physical display lag there could be substantial individual differences in perceived display lag during active head motion. However, while these individual differences in multisensory processing are intriguing, they have yet to be directly linked to the likelihood of experiencing cybersickness.

Postural instability theory (e.g., [40]) provides another possible (and testable) explanation for the observed individual differences in most types of motion sickness (including cybersickness). According to this theory: (1) postural instability is required for motion sickness; (2) instabilities in postural control precede the onset of motion sickness; and (3) individual differences in spontaneous postural instability should predict who is more likely to become sick (versus well). Consistent with this theory, research has shown that people who display greater postural instability (when standing quietly in stationary visual surroundings) are more likely to subsequently report "being sick" when they are exposed to visual motion stimulation [20,40–52]. These predictions have been found to hold for many different types of *visual* motion stimulation, including the visual stimulation with large moving rooms [46], handheld devices [49], console video games [43] and CAVEs [15]. However, this research has been primarily focussed on VIMS rather than on the cybersickness generated by multisensory head-and-display motion in HMD-based virtual reality. Some of these past experiments involved active participants (e.g., playing videogames and navigating through the virtual environments using different types of game controllers), but the control motions involved typically required minimal physical movement (there is however one notable exception [53] which we will discuss in detail below).

1.2.1. Research on motion sickness and postural instability with HMDs

While there is a considerable body of research linking postural instability to VIMS, there has been little research on whether this relationship also generalises to the motion sickness experienced in HMDs. The limited evidence on this particular topic appears to be mixed and is discussed below.

The first such study, by Cobb [54], failed to find a significant relationship between pre-exposure postural activity and reported sickness severity after exposure to HMD-based virtual reality. However, this null finding might have been due to the rather coarse postural measures which were used (such as how long the user could hold a Tandem Romberg or normal posture and how much hip displacement there was over a 30 s period). In this study the virtual reality game ('Zone Hunter') was viewed through an early Vissette II HMD. While head movements were tracked and incorporated into the display, the participant's control motions were also rather limited (they could only move forward and look from side-to-side at the virtual environment).

Two more recent HMD-based studies have also examined the relationship between postural instability and motion sickness [53,55]. In one of these studies, Merhi and colleagues [55] continuously recorded head and torso movements as their seated participants played an Xbox video game ('Whacked') while wearing a Visette Pro HMD for up to 50 min. They found that participants who would eventually become sick made significantly different vertical head movements to those who remained well. However, it should be noted that this study actually examined VIMS (as opposed to cybersickness), since participant head-movements were not being used to alter the display.

By contrast, the most recent HMD study by Munafo and colleagues [53] examined the relationship between postural instability and cybersickness. They first measured the pre-exposure postural stability of their participants when standing and performing two simple visual tasks (inspection and visual search). Then their participants donned an Oculus Rift DK2 HMD and played one of two publicly available video games ('Balance rift' and 'Affected') for up to 15 min. Unlike the Mehri et al. study, the participants' tracked head movements were actually used to control the game play in these experiments. Even so, their findings were still consistent with the predictions of postural instability theory. Specifically, they found that differences in pre-exposure postural sway could be used to predict who would later become sick (or remain well).

1.2.2. Examining the relationship between cybersickness and postural instability in this study

Like Munafo et al. [53], the current study will also investigate whether the predictions of postural instability theory generalise to the cybersickness experienced during *active* HMD-based virtual reality. In order to do so we will first record our participants' centre of foot pressure (CoP) data when standing quietly in a stationary room (eyes-open and eyes-closed). Unlike the Munafo et al. study, the participants will not be instructed to perform specific visual tasks during these CoP recordings. Instead, participants will simply be told to look forward (when they have their eyes open) and stand as still as possible (instructions similar to those in Palmisano et al. [37]). We will then estimate their spontaneous postural stability based on their sway area, as well as the positional variability and the temporal dynamics of their CoP data. We will then examine the relationship between these postural measures and their sickness data. Like most of the previous research in this area we will focus on eyes-open postural activity [37,47,50,53,55–57].

1.3. The current study

Here we plan to investigate the cybersickness induced when our participants' active head-movements alter their HMD-based virtual reality displays in real-time. To date, only a handful of studies have examined motion sickness in HMDs (e.g. [18,53–55]). Of these studies, almost all have: (1) used publicly/commercially available games; and (2) either not tightly controlled their participants' head movements or not incorporated the consequences of them into their displays. Via our instructions and our use of custom software, we aimed to expose all of our participants to very similar display content and head-and-display movement conditions. Specifically, the study was aimed at: (1) comparing the cybersickness generated by more ecological 'compensated' and non-ecological 'inversely compensated' head-and-display motion conditions; and (2) checking whether this cybersickness could also be predicted by individual differences in pre-exposure postural activity. Our design therefore provides us with an opportunity to test the predictions of both sensory conflict and postural instability theories. The former theory would predict that we should find greater cybersickness in the non-ecological 'inversely compensated' head-and-display movement condition (compared to the ecological 'compensated' condition). The later theory predicts that we should find significant differences in spontaneous postural activity between individuals who would later become sick and those who would remain well.

2. Material and methods

2.1. Participants

The 21 participants tested in this study were drawn from University of Wollongong (UOW) School of Psychology staff and students as well as external volunteers. However, the data of one participant was excluded from analysis after testing (as his responses to the pre-exposure items of the Simulator Sickness Questionnaire indicated moderate sickness before the actual experiment). The remaining 14 females and 6 males ($M = 28.4$ years, $SD = 10.1$ years) all had normal corrected vision (i.e. 20/20 or better) and stereoacuities of 60 arcsecs or better (16 of them had stereoacuities of 40 arcsecs or better). These participants varied in height ($M = 169.33$ cm, $SD = 8.96$ cm), weight ($M = 78.23$ kg, $SD = 4.21$ kg), and in terms of their inter-pupillary distances ($M = 63.15$ mm, $SD = 0.73$ mm). They did not report any visual, vestibular, neurological, or gastrointestinal abnormalities at the time of testing. The study was approved by the UOW Ethics Committee in advance (HE16/086), and each participant provided informed written consent before participating.

2.2. Design

The study had a fully within-subjects design. Prior to exposure to the self-motion simulations in the HMD, participants were measured on a number of physical factors, including their height, weight and inter-pupillary distance. Their stereo acuity and visual acuity were also measured, as well as their spontaneous postural instability when standing quietly with their eyes open and closed. The experiment examined whether individual differences in spontaneous postural instability could predict cybersickness after exposure to two different multisensory self-motion simulation conditions. In the ecological 'compensated' condition, the visual scene moved in the *opposite* direction to, and at the same speed as, the head motion (mimicking the visual motion that would occur when viewing real scenes). By contrast, in the 'inversely compensated' condition the visual scene moved in the *same* direction as the head motion, but at twice the rate of the head motion. These two conditions were tested over two separate days. Testing was conducted at least 12 h apart in order to limit any residual motion sickness effects [58].

2.3. Materials

Before testing, each participant's static stereoacuity was measured using the Random Dot Stereo Butterfly Test (Stereo Optical Co., Inc.), and their interocular separation was measured using a digital pupillary distance (PD) meter (PD-NH-L8; http://www.iconic-us.com). The visual acuity of each of their eyes was also checked using an online test (http://www.prokerala.com/health/eye-care/eye-test/e-test.php), which was viewed at the recommended testing distance of 30 cm. Their weight was measured via a Bertec balance Plate (http://bertec.com/products/balance-plates.html). Importantly, this balance plate was also used to record any changes to the location of the participant's centre of foot pressure (CoP) when standing quietly (before and after exposure to the HMD simulations).

Experimental displays were presented on the Oculus Developer's Kit Version 1.0 headset (weighing approximately 380 g; see Fig. 1). This

Fig. 1. Participant wearing the Oculus Rift DK1.

HMD had a binocular field of view of 110° diagonal, as well as a resolution of 1280 × 800 (640 × 800 per eye) and a refresh rate of 60 Hz. Internal head tracking was provided by a gyroscope, an accelerometer and a magnetometer.[1] The HMD was connected to a Dell PC with an Intel® Core™ i5-4570 CPU @3.20Ghz, 8 GB Ram, with a 64-bit OS. This HMD came with 3 different pairs of viewing lenses, which were used to correct for the refractive errors of each participant. Participants were instructed to rotate their heads (from left to right and back) in time with a computer generated metronome (TempoPerfect; http://www.nch.com.au/metronome/) to produce regular oscillation.

A 36 × 36 cm cardboard document storage box was used to create the motion limiters for the participants' head movements. Internal cardboard support was added to reduce the total area to 31 cm from the left to right sides, and the front of the box removed to allow participants to easily enter the space. This box was raised by two steel supports at the rear of the device relative to the participant. Participants were seated and moved forward to enter the box while wearing the headset. They were centred within the box so that on each oscillation they would turn to make the HMD contact the cardboard as a stopping point for their range of motion.

Motion sickness susceptibility was assessed in two different ways. Firstly, participants were asked "Do you feel sick?" directly after each self-motion simulation. Secondly, we had participants complete the Simulator Sickness Questionnaire (SSQ; see [60]) before and after each testing session on both days. The SSQ consists of 16 items (each was rated either 0 = 'none', 1 = 'slight', 2 = 'moderate' or 3 = 'severe') about the participant's symptoms, including their general discomfort, fatigue, headache, eye strain, difficulty focussing, increased salivation, sweating, nausea, difficulty concentrating, fullness of head, blurred vision, dizziness with eyes open and with eyes closed, vertigo, stomach awareness and burping. When scored according to published guidelines, the SSQ yields a total sickness score, as well as three sub scores for Nausea, Oculomotor symptoms and Disorientation.

2.4. Displays

Custom software for this experiment was developed in Visual C+ + utilising OpenGL and the Microsoft Visual Studio 2010 version of the Oculus Rift SDK. These computer generated displays simulated the forwards self-motion in depth of an observer inside a 3D spherical cloud (radius approximately 6 m). While viewing these displays participants continuously rotated their heads in yaw (i.e., from left to right and back), in time with a computer metronome set at 30 beats per minute. Since the participant's tracked head movements were used to update the simulated viewpoint in the display, this resulted in a horizontally oscillating self-motion display. The 3-D cloud consisted of 32,768 blue circles (only a subset of which were visible per eye on any given frame). These objects optically increased in size (from 0.25 to 5° in diameter) as they approached the observer. Total delays from head rotation to display update were on average 81 ms for both the 'compensated' and the 'inversely compensated' conditions. Unlike our earlier study [18], displays in this experiment also included a stationary fixation target. Unlike the optic flow, the visual location of this target remained directly in front of the participant during their head motions.

2.5. Procedure

The testing for this experiment was conducted over two different days. Participants were exposed only to one of the experimental self-motion simulation conditions on each day (e.g., 'compensated' only on day 1 and 'inversely compensated' only on day 2 or vice versa for counterbalancing across participants). On the first day of testing, participants first had their age, sex, height, weight and inter-pupillary distance recorded. In addition, their visual acuity and stereoacuity were assessed. From this point on the testing protocol was similar on both days. First, participants had their spontaneous postural instability measured with their eyes open and eyes closed. Specifically, their centre of foot pressure (CoP) displacement was measured as they stood on a Bertec balance plate (sampled at 1000 Hz) for one minute with their eyes open (while viewing the actual, stationary laboratory scene), and again for one minute with eyes closed. They then completed a pre-exposure Simulator Sickness Questionnaire (SSQ). Participants next donned the HMD and adjusted the headset for a comfortable fit. They were given practice making oscillatory head movements in time with the metronome (wearing the Oculus Rift HMD without any visual stimulation). They were instructed to turn their heads (from left-to-right and back) lightly tapping the cardboard limiters with the headset in time with the metronome beats. Next, participants were shown a display which simulated self-motion in depth while sitting perfectly still and with their heads stationary (head tracking was also turned off for this practice display). Five experimental self-motion simulation trials then followed. Each of these trials consisted of a 60 s presentation of the visual self-motion display viewed during head motion. At the end of each display participants answered the following Yes/No question: "Do you feel sick?" Participants completed five of these experimental trials, then directly afterwards, they completed the post-exposure items of the SSQ.

3. Results

3.1. Angular head oscillation

We first checked to see whether head movements were similar in the two different compensation conditions. Fig. 2 shows time-series plots of yaw head orientation for a representative participant in the 'compensated' and 'inversely compensated' conditions respectively. Prior to the analyses, the amplitudes and frequencies of these yaw head movements were averaged across the five trials for each of the compensation conditions. One participant's data was excluded from these analyses due to data recording error. Average yaw head amplitudes were not significantly different for the 'compensated' ($M = 21.11°$, $SD = 3.65°$) and 'inversely compensated' ($M = 20.91°$, $SD = 4.29°$) conditions, t

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[1] In addition to the DK1 there are now two more recent versions of the Oculus Rift, the DK2 (resolution: 960 x 1080 pixels per eye; refresh rate: 60–75 Hz) and the CV1 (resolution: 2160 x 1200 pixels per eye; refresh rate: 90 Hz). Field of view is similar across all three HMDs (110°-100°) and all have similar rotational head tracking based on their inertial measuring units. Recently Zhao et al. [59] provided motion-to-photon lag estimates for 60° (1.05 ± 0.48 ms), 75° (4.83 ± 1.05 ms) and 90° (9.83 ± 0.98 ms) head turns at 0.7 Hz with the DK2. These small baseline lags should be quite similar to those for the DK1. However, it should be noted that Zhao et al. did not use a virtual scene when estimating this lag. In this study, our estimate of the lag also included the virtual (optic flow) simulation (81 ms – using a technique described in detail in [1] and [18]). This empirically determined end-to-end system lag could therefore be used to reproduce our head-and-display conditions with more modern headsets.

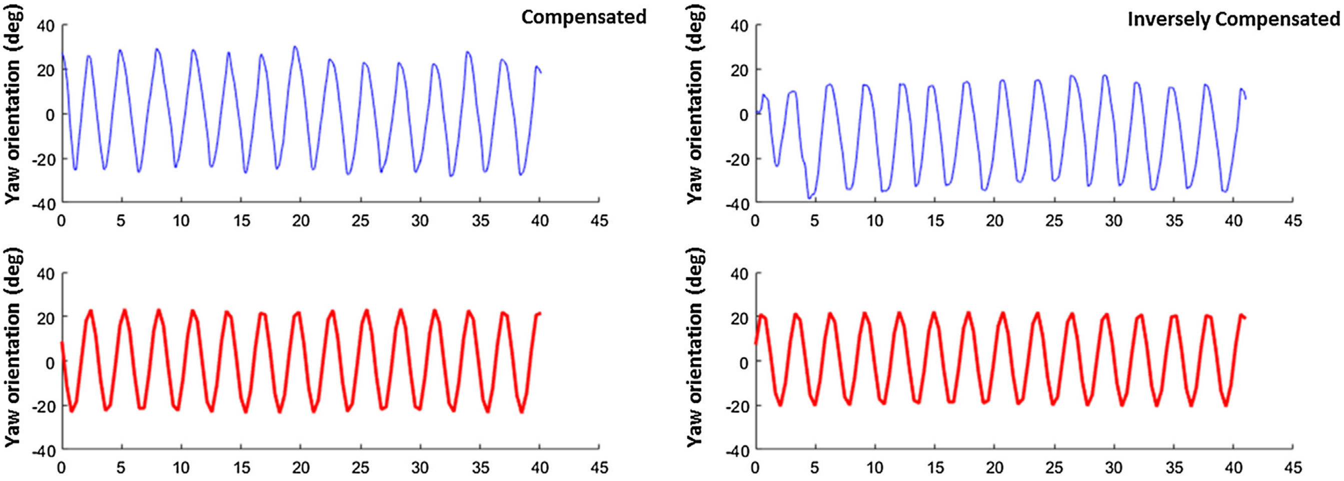

Fig. 2. Raw traces of yaw head orientation in the 'compensated' (upper left) and 'inversely compensated' (upper right) conditions (measured as Euler angles in degrees) over time (for representative participant P1). Sinusoidal fits for this data are provided in red in the two lower plots.

(18) = 0.29, $p > 0.05$, $d = 0.05$. Similarly, average yaw head movement frequencies were also not significantly different for the 'compensated' ($M = 6.08$ Hz, $SD = 1.39$ Hz) and the 'inversely compensated' ($M = 6.64$ Hz, $SD = 0.11$ Hz) conditions, t (18) = −1.56, $p > 0.05$, $d = -0.45$.

3.2. Sickness data

We next examined the incidence and the severity of the cybersickness induced in this experiment.

3.2.1. Identifying sick and well groups

Based on their responses to the question "do you feel sick?" at the end of each trial, participants were assigned into "well" (those who never responded that they felt sick) and "sick" groups (those who responded that they felt sick in at least one trial). Sickness was reported by 10 of our participants. The remaining 10 participants reported that they were not sick after each and every experimental trial. Nine of the participants (45%) reported sickness in the 'compensated' condition and 8 of them (40%) reported sickness in the 'inversely compensated' condition. Sickness was reported by 3 males (50% of the male participants) and 7 females (50% of the female participants).

3.2.2. Sickness severity and type

The sickness induced by the 'compensated' and 'inversely compensated' self-motion conditions was further examined using the SSQ data[2] (see Fig. 3). Even though the 'inversely compensated' condition was expected to generate more sensory conflict than the 'compensated' condition, a paired samples t-test revealed that the SSQ total scores for these two conditions were not significantly different, t (19) = 0.82, $p > 0.05$.

In terms of the types of sickness symptoms induced, the highest absolute sub-scores were found for disorientation in both of the conditions tested ('Compensated' disorientation: $M = 28$; $SD = 37$; 'Inverse' disorientation: $M = 31$; $SD = 30$). The sub-scores found for nausea and oculomotor were considerably lower than those for disorientation ('Compensated' Nausea $M = 19$ and $SD = 20$; 'Inverse' Nausea $M = 20$ and $SD = 18$; 'Compensated' Oculomotor $M = 19$; $SD = 14$; 'Inverse' Oculomotor $M = 22$; $SD = 19$). Paired samples t-tests confirmed that there were no significant differences between the 'compensated' and 'inversely compensated' conditions on any of the three SSQ sub-scores ($p > 0.05$ in all 3 cases).

3.2.3. Relationships between the yes/no and SSQ-based sickness measures

Independent-samples t-tests were conducted with group ("well" or "sick") as the independent variable and the average SSQ scores as the dependent variables. As expected, SSQ total scores were significantly greater for the "sick" ($M = 34.97$, $SD = 22.84$) compared to the "well" ($M = 16.64$, $SD = 12.36$) participants, t (18) = 2.23, $p = 0.04$, $d = 1.00$. Nausea sub-scores were also significantly greater for the "sick" ($M = 29.10$, $SD = 17.63$) compared to the "well" ($M = 10.02$, $SD = 8.55$) participants, t (18) = 3.08, $p < 0.01$, $d = 1.45$. However, the oculomotor and disorientation sub-scores were not found to differ significantly between these two groups ((t (18) = 1.32, $p = 0.20$, $d = 0.62$ and t (18) = 1.95, $p = 0.07$, $d = 0.92$ respectively).

3.3. Postural activity data

Several postural stability measures were calculated for each eyes open quiet stance trial (see Table 1). The CoP data recorded for each trial were first smoothed, using a low-pass order-5 Butterworth filter with a cut-off frequency of 10 Hz, to remove unwanted high-frequency artefacts. Then the participant's sway area (Area) for that trial was computed as a 95% confidence ellipse around the area covered by their CoP (principal component analysis was used to fit the ellipse's semi-axes as per Apthorp, Nagle & Palmisano, [62]; see also [63,64]). We also calculated the standard deviations of their CoP fluctuations along the anterior-posterior and medial-lateral axes ($STDEV_{A/P}$ and $STDEV_{M/L}$). We also examined the temporal dynamics of their postural activity by conducting a detrended fluctuation analysis (DFA) on their A/P and M/L CoP data [65,66]. DFA reveals the relative distribution of the variance in the CoP data across the different timescales. The scaling component of the DFA (i.e., α) is an index of the long-range autocorrelation in the time series data.[3] DFAα values were here used as measures of the extent to which CoP positions were self-similar over these different timescales along each axis ($DFA\alpha_{A/P}$ and $DFA\alpha_{M/L}$).

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[2] To rule out order/day of presentation effects, a paired samples t-test was also conducted to compare overall cybersickness on day 1 and day 2 of testing. This analysis ignored which condition (i.e. 'compensated' or 'inversely compensated') was tested on each of these two days. No significant difference was found between the SSQ total scores based on this order/day of presentation (t (19) = 0.10, $p > 0.05$). This was unexpected as a recent simulator sickness study by Keshavarz et al. [61] reported significantly reduced VIMS was seen on day 2 compared to day 1.

[3] DFA α values > 0.5 indicate that an autocorrelation occurred at some timescale in the data. α = 1 represents the maximum possible self-similarity, whereas white noise generates an α = 0.5. As α increases above 1 a greater proportion of fluctuations occur at longer time scales [67]. As α values decrease the system becomes increasingly random.

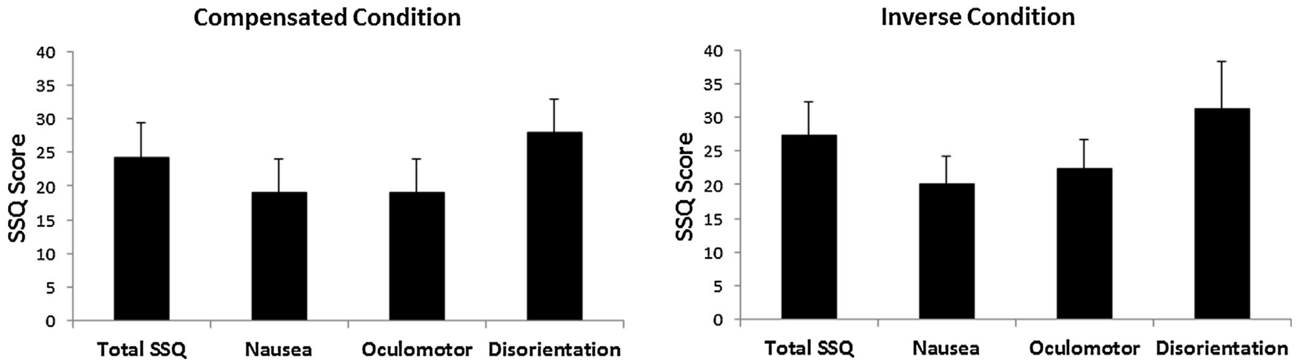

Fig. 3. Effects of visual compensation condition (‘compensated’ and ‘inversely compensated’) on participants’ Total, Nausea, Oculomotor and Disorientation SSQ scores. Error bars represent standard errors of the mean (SEMs).

Table 1
Sway area, STDEV and DFAα values prior to testing the ‘compensated’ and ‘inversely compensated’ conditions.

		Compensated	Inversely Compensated
Area (cm^2)			
	Mean	1.62	1.31
	SD	0.94	1.71
$STDEV_{M/L}$ (cm)			
	Mean	0.20	0.16
	SD	0.08	0.14
$STDEV_{A/P}$ (cm)			
	Mean	0.45	0.30
	SD	0.15	0.24
$DFA\alpha_{M/L}$			
	Mean	1.41	1.38
	SD	0.10	0.13
$DFA\alpha_{A/P}$			
	Mean	1.51	1.52
	SD	0.07	0.08

The spontaneous postural stability of our participants (i.e., prior to HMD testing) was found to be similar on both testing days. Paired samples *t*-tests confirmed that there were no significant differences in either sway area ($t\ (19) = -0.69$, $p = 0.50$, $d = -0.15$), $\text{STDEV}_{\text{A/P}}$ ($t\ (19) = -0.21$, $p = 0.84$, $d = -0.05$), $\text{STDEV}_{\text{M/L}}$ ($t\ (19) = -0.89$, $p = 0.39$, $d = -0.23$), $\text{DFA}\alpha_{\text{A/P}}$ ($t\ (19) = -0.65$, $p = 0.53$, $d = -0.15$) or $\text{DFA}\alpha_{\text{M/L}}$ ($t\ (19) = 1.04$, $p = 0.31$, $d = 0.24$). Thus, these postural measures were averaged across the two testing days for the subsequent analyses discussed below.

3.3.1. Predicting “sick” versus “well” groups from spontaneous postural instability

We first checked that participants in the “sick” and “well” groups did not differ significantly in terms of their age, weight, height, stereoacuity and interpupillary distance (all of the *t*-tests conducted had uncorrected *p* values that were greater than 0.2). We next investigated whether the “sick” participants displayed greater postural instability prior to their exposure to HMD-based motion stimulation (compared to the “well” participants). Independent *t*-tests were conducted on their average sway areas (standard deviations and DFAα values) with sickness group as the independent variable.

We found significantly larger sway areas for the “sick” ($M = 2.07\ \text{cm}^2$, $SD = 0.91\ \text{cm}^2$) compared to the “well” ($M = 1.30\ \text{cm}^2$, $SD = 0.49\ \text{cm}^2$) group, $t\ (18) = 2.35$, $p = 0.02$, $d = 1.05$ (see Fig. 4). $\text{STDEV}_{\text{A/P}}$ values were also significantly greater for the “sick” ($M = 0.50\ \text{cm}$, $SD = 0.16\ \text{cm}$) compared to the “well” ($M = 0.41\ \text{cm}$, $SD = 0.10\ \text{cm}$) group, $t\ (18) = 1.47$, $p = 0.04$, $d = 0.66$ (see Fig. 4). However, $\text{STDEV}_{\text{M/L}}$ values were not significantly different for “sick” ($M = 0.24\ \text{cm}$, $SD = 0.07\ \text{cm}$) and “well” ($M = 0.18\ \text{cm}$, $SD = 0.05\ \text{cm}$) groups, $t\ (18) = 2.22$, $p = 0.17$, $d = 0.99$.

$\text{DFA}\alpha_{\text{M/L}}$ values were greater on average for the “sick” group ($M = 1.44$, $SD = 0.09$) compared to the “well” group ($M = 1.36$, $SD = 0.10$); however, they were not significantly different, $t\ (18) = 1.89$, $p = 0.08$, $d = 0.85$. $\text{DFA}\alpha_{\text{A/P}}$ values were also not significantly different for the “sick” ($M = 1.53$, $SD = 0.06$) and “well” groups ($M = 1.50$, $SD = 0.07$), $t\ (18) = 1.04$, $p > 0.05$, $d = 0.46$.

3.3.2. Relationships between spontaneous postural instability and sickness severity

Based on the findings reported above in section 3.3.1, we decided to perform an exploratory correlational analysis to investigate whether individual differences in spontaneous postural instability were also related to the severity of the cybersickness. This analysis included averaged sway area, positional variability ($\text{STDEV}_{\text{A/P}}$ and $\text{STDEV}_{\text{M/L}}$), and temporal dynamics measures (DFAα for A/P and M/L CoP), as well as the averaged total SSQ scores as the dependent variable (see Table 2). Although several of the postural measures were found to correlate significantly with each other, only $\text{STDEV}_{\text{A/P}}$ was found to correlate significantly with the total SSQ scores. We have plotted this significant relationship in Fig. 5.

4. Discussion

Previously, it has been shown that individual differences in postural activity can be used to predict who will be more likely to experience *visually*-induced motion sickness (VIMS). This study examined whether susceptibility to cybersickness (induced by multisensory HMD-based stimulation) could also be predicted based on similar measures of postural instability. Consistent with the findings of a recent study by Munafo et al. [53], we found evidence that it could.

We first checked whether other physical and demographic measures might account for our cybersickness findings. Age, weight and height did not differ significantly between our “sick” and “well” groups – ruling out the possible influence of these non-specific physiological effects. As the HMD used was stereoscopic, we also examined whether cybersickness varied as a function of stereoacuity and interpupillary distance. Having also ruled out their possible contributions, we examined the relationships between our postural measures and the incidence and severity of cybersickness.

From our quiet stance CoP data, we calculated each participant’s sway area, as well as their positional variability and DFAα values for sway along each axis. Participants who had greater positional variability in their CoP were significantly more likely to report being sick following active exposures to HMD-based motion stimulation. Thus postural instability appears to not only predict the likelihood of sickness being induced by purely visual motion stimulation, but also the likelihood of cybersickness being produced by multisensory self-motion

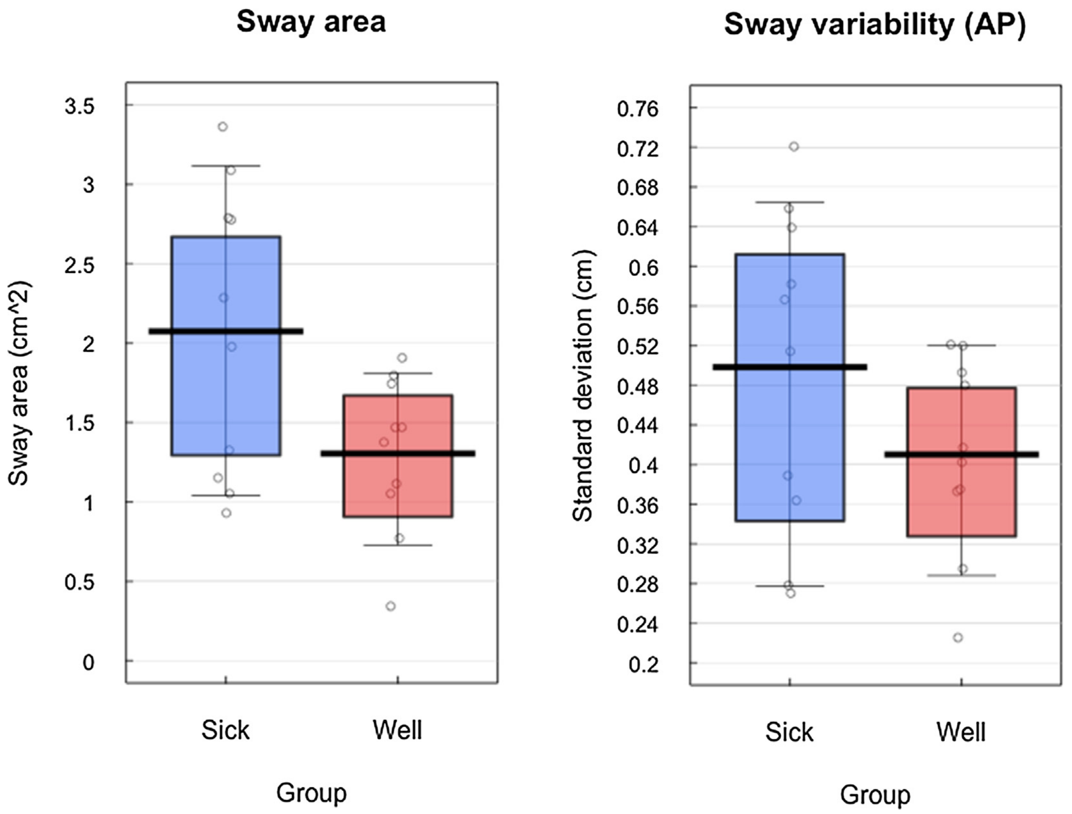

Fig. 4. Spontaneous postural sway prior to HMD exposure. This figure shows the sway areas (left panel) and sway variability in the A/P axis (right panel) for the "sick" versus "well" groups. Error bars in each case represent the 95% confidence interval. Black circles are individual data points (jittered for display purposes).

Table 2
Kendall's Tau-b correlation matrix of postural measures and total SSQ scores.

	AREA	$STDEV_{A/P}$	$STDEV_{M/L}$	$DFA\alpha_{A/P}$	$DFA\alpha_{M/L}$	Total SSQ
AREA	1	0.63**	0.59**	0.31	0.37*	0.26
$STDEV_{A/P}$		1	0.26	0.21	0.30	0.36*
$STDEV_{M/L}$			1	0.42*	0.27	0.09
$DFA\alpha_{A/P}$				1	0.33*	0.28
$DFA\alpha_{M/L}$					1	0.13
Total SSQ						1

** Correlation is significant at the $p < 0.01$ level (2-tailed).
* Correlation is significant at the $p < 0.05$ level (2-tailed).

stimulation.

However, the relationship between our postural measures and the severity of this cybersickness was less clear. We did find a significant correlation between positional variability along the A/P axis and sickness severity (as indexed by the total SSQ scores). This result, and a similar but non-significant trend observed for sway area, appears promising. Particularly in the light of recent findings by Stoffregen and colleagues [67] that terrestrial measures of postural activity can predict the severity of subsequently experienced sea-sickness (like our HMD-based cybersickness, this sea-sickness is also the result of multisensory, as opposed to purely visual, motion stimulation).

This study also manipulated the expected level of sensory conflict, as well as the accuracy of modelling the participant's tracked head movements, by testing two different head-and-display-motion conditions ('compensated' and 'inversely compensated'). Since Palmisano et al. [18] had previously reported that their 'inversely compensated' condition induced greater cybersickness than their ecological 'compensated' condition, we had expected similar findings in the current study. However, we did not find significant differences between either the types or the severity of the cybersickness induced by these two conditions. Not only did the current findings appear to be inconsistent with these previous findings, but they also appeared to be inconsistent with the predictions of sensory conflict theory and ecology. The average post-exposure SSQ total score was 27.30 for the 'inversely compensated condition' and 24.30 for the 'compensated' condition in the current study (as opposed to 58.70 and 22.20 respectively in the Palmisano et al. study [18]). Thus it appears that one or more of the stimulus features in our displays must have considerably weakened the effects of the 'inverse compensation' manipulation on sickness induction.

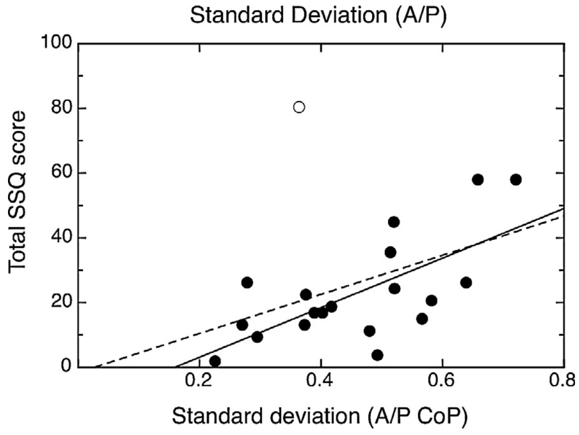

Fig. 5. Relationship between positional variability along the A/P axis and the averaged total SSQ scores. One notable outlier (the participant who had the largest SSQ score) has been highlighted (indicated here by a hollow circle). The dashed trendline indicates the significant relationship based on the entire dataset ($y = 9.25x + 10.18$, $R^2 = 0.14$), while the solid trendline indicates the relationship based on the data less this outlier ($y = 11.02x + 4.10$, $R^2 = 0.33$).

The 'compensated' and 'inversely compensated' conditions tested in our study shared many similarities to those examined by Palmisano et al. [18]. However, there were also several notable stimulus differences that we outline below. First, the end-to-end system lag in the current study (81 ms) was slightly longer on average than that in the earlier Palmisano et al. study (72 ms). Since an increase in the system lag would be expected to increase (not reduce) cybersickness, this is unlikely to explain the differences in sickness findings between the two studies. Second, the virtual environment in the present experiment was twice as deep and 1/10th as sparse as that used in the earlier study. These stimulus differences might explain why the overall sickness ratings were less (on average) than those in the Palmisano et al. study (i.e., because there was less visual motion in our displays). Third, head movement amplitudes and frequencies in the current experiment (21.0° and 6.4 Hz) were markedly different to those in the Palmisano et al. study (44.7° and 1.7 Hz). Fourth, our displays were presented for twice as long as those in the Palmisano et al. study (i.e., 60 s as opposed to 30 s). It is therefore possible that differences in cybersickness between the 'inversely compensated' and 'compensated' conditions might have been obscured by the longer trial length used in this current study (i.e., obvious differences between these conditions 30 s after stimulus onset might have disappeared by the 60 s mark). Finally, in this study we superimposed a user stationary fixation target onto the virtual environment (there was no such fixation target in the previous Palmisano et al., study [18]). This head-fixed target was the most likely reason for why the 'inverse compensation' condition was not more sickness provoking in the current study. We have previously shown that such fixation targets are highly successful at reducing observer eye-movements [68–71]. Similarly, Bonato, Bubka and Krueger [72] have also recently shown that a see-through display with this type of fixation target significantly reduced the motion sickness induced by their optokinetic drum. Our current failure to find significant differences between the two different compensation conditions may therefore provide support for the importance of visually and vestibularly driven eye-movements in the generation of cybersickness [34,35]. The likely suppression of the vestibulo-ocular reflex by the head-fixed target used in this study would appear to be the most likely explanation of its cybersickness findings.

According to Rebenitsch and Owen [10], cybersickness tends to produce disorientation ratings that are higher than nausea ratings, which in turn tend to be higher than ratings of oculomotor symptoms (i.e., SSQ-D > SSQ-N > SSQ-0). This cybersickness profile appears quite different from the profiles for other types of sickness (e.g., sickness in military simulators, sea sickness and space sickness). Although Rebenitsch and Owen did note that studies by So et al. [73], Cobb [55] and Roberts and Gallimore [74] appear to be exceptions. The current findings confirm the importance of disorientation-based symptoms in multisensory cybersickness. However, in our study, the participants' nausea and oculomotor responses appeared to be quite similar both in terms of their mean scores and their standard deviations. On average, our participants (post) sub-scores on the SSQ were 29.60 (disorientation), 20.04 (oculomotor) and 19.60 (nausea). It is possible that oculomotor symptoms were greater than usual in our study because the participants had to make continuous head-movements throughout each self-motion simulation. These head-movements were both more frequent and on average larger in amplitude than those which would normally have been made during HMD-based gaming or in past studies of cybersickness.

5. Conclusions

The findings reported here support postural instability theory and its proposals that spontaneous postural instability can be used to diagnose who will benefit the most/least from HMD-based virtual reality. Cybersickness in our study was induced via multisensory combined head-and-display motion (as opposed to the visual motion stimulation typically used in most previous sickness studies). On different trials, the participants' oscillatory head movements were either updated in the display in an ecological (compensated) or non-ecological (inversely compensated) fashion. This manipulation appeared to have little effect on the cybersickness induced in our study. We attributed the surprising resilience of our participants to the expected sensory conflicts in the inversely compensated condition to the presence of a user stationary fixation target (previously shown to alleviate motion sickness symptoms [72]).

Typical user interactions with virtual reality often involve both head and body motions. However, only head motion was examined in our study. Participants made continuous head movements which were quite different to the free head movements normally made in virtual reality. These oscillatory head movements (controlled in terms of their amplitude and frequency) were deliberately chosen to: (1) increase the likelihood of our participants experiencing cybersickness; and (2) provide them all with highly similar (i.e. more comparable) virtual reality experiences. These design features should increase the likelihood that our findings will be replicated by future laboratory experiments. However, research is also required into the cybersickness induced in more typical, applied settings. This future research will be required to determine whether our findings also generalise to the cybersickness induced by typical head and body interactions in gaming spaces.

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