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Vection and cybersickness generated by head-and-display motion in the Oculus Rift

Stephen Palmisano
University of Wollongong, stephenp@uow.edu.au

Rebecca Mursic
University of Wollongong, rm207@uowmail.edu.au

Juno Kim
University of Wollongong, juno@uow.edu.au

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Abstract

Cybersickness is often experienced when viewing virtual environments through head-mounted displays (HMDs). This study examined whether vection (i.e., illusory self-motion) and mismatches between perceived and physical head motions contribute to such adverse experiences. Observers made oscillatory yaw head rotations while viewing stereoscopic optic flow through an Oculus Rift HMD. Vection and cybersickness were measured under 3 conditions of visual compensation for physical head movements: "compensated", "uncompensated", and "inversely compensated". When a nearer aperture was simulated by the HMD, vection was found to be strongest in the "compensated" condition and weakest in the "inversely compensated" condition. However, vection was similar for all 3 conditions during full-field exposures. Cybersickness was most severe for the "inversely compensated" condition, but was not different for the other two conditions. We conclude that mismatches between perceived and physical head-movements can contribute strongly to cybersickness. The relationship between vection and cybersickness is weaker and appears complex.

Keywords

rift, generated, vection, cybersickness, oculus, motion, head-and-display

Disciplines

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Vection and Cybersickness Generated by Head-and-Display Motion in the Oculus Rift

Stephen Palmisano[1,2*], Rebecca Mursic[1,2], & Juno Kim[3]

[1]Centre for Health Initiatives, University of Wollongong, Australia

[2] School of Psychology, University of Wollongong, Australia

[3] School of Optometry and Vision Science, The University of New South Wales, Australia

RUNNING HEAD: Challenges for Vection Research

ABSTRACT (Word Count: 149)

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***Corresponding author:**
Stephen Palmisano, PhD
School of Psychology,
University of Wollongong,
NSW, Australia, 2522
Tel: (612) 4221-3640
Fax: (612) 4221-4163
Email: stephenp@uow.edu.au

Abstract (100-150 words)

Cybersickness is often experienced when viewing virtual environments through head-mounted displays (HMDs). This study examined whether vection (i.e., illusory self-motion) and mismatches between perceived and physical head motions contribute to such adverse experiences. Observers made oscillatory yaw head rotations while viewing stereoscopic optic flow through an Oculus Rift HMD. Vection and cybersickness were measured under 3 conditions of visual compensation for physical head movements: “compensated”, “uncompensated”, and “inversely compensated”. When a nearer aperture was simulated by the HMD, vection was found to be strongest in the “compensated” condition and weakest in the “inversely compensated” condition. However, vection was similar for all 3 conditions during full-field exposures. Cybersickness was most severe for the “inversely compensated” condition, but was not different for the other two conditions. We conclude that mismatches between perceived and physical head-movements can contribute strongly to cybersickness. The relationship between vection and cybersickness is weaker and appears complex.

Keywords: Head-mounted displays; Vection; Self-motion Perception; Motion Sickness; Cybersickness; Virtual reality.

1. Introduction

Head-mounted displays (HMDs) have many potential applications (including scientific visualisation, architecture and design, education and training, as well as manufacturing and medicine) [1]. In recent years, HMDs have also become increasingly popular for gaming and home entertainment. A variety of impressive low-cost HMDs are now poised to break onto the market, including the Oculus Rift, the Razer OSVR and the HTC Vive (see http://heavy.com/tech/2015/07/best-vr-virtual-reality-headset-glasses-goggles-oculus-rift-specs-review/). These high resolution and wide field-of-view devices also track the motion of the user's head [2]. With head-tracking enabled, they effectively provide a 360° field of view (over time) and can generate a compelling sense of immersion in the virtual environment (which can be further enhanced by adding 3D sound as well as tactile and force feedback). These HMDs are especially useful for simulating scenarios that require a convincing first-person perspective. This first-person perspective can be strengthened by displaying stereoscopic 3D content to induce compelling visual illusions of self-motion (see vection below [3]). Despite the benefits of HMDs, there are a number of challenges associated with their use [4].

One commonly reported side-effect of HMDs is that they are nausegenic [4-22]. The motion sickness experienced with HMDs is most appropriately referred to as 'cybersickness' [11,23]. In principle, the cybersickness experienced while wearing an HMD could be visual, non-visual or even multisensory in origin [4,22]. Based on his extensive review of research on cybersickness in virtual environments, Lawson (2015) reported that between 61% and 80% of participants experience adverse symptoms, with up to 43% experiencing nausea and up to 17% having to discontinue their participation [4].

1.1 Relationship between Vection and Cybersickness in HMDs

One factor often associated with the occurrence of cybersickness when wearing HMDs is vection [11,24-29]. However, there has been surprisingly little systematic examination of vection using HMDs (and even less research examining both vection and motion sickness with HMDs). Vection was traditionally defined as a visual illusion of self-motion induced in a stationary observer [30]. Early findings (using fixed-based simulators rather than HMDs) suggested that traditional vection might be a prerequisite for visually induced motion sickness in stationary observers [25]. However, while fixed-base simulator studies have often reported positive correlations between vection and visually induced motion sickness [14, 31-33], other studies appeared to suggest negative relationships between the two phenomena [34], and still others failed to find significant relationships between them [4,28,35-37].

The research reviewed above was all conducted with stationary observers (hence the terms "traditional vection" and "visually induced motion sickness"). However, HMDs allow (and even encourage) observer motion. Thus, the vection experienced while wearing an HMD is more appropriately defined as "visually-mediated self-motion perception" [38]. While visual motion should still be primarily responsible for inducing vection when wearing HMDs, head and body movements are also likely to contribute to this experience – both directly by stimulating the inertial self-motion senses (such as the vestibular system of the inner ear, the proprioceptive neck receptors, etc.) and indirectly by altering the visual scene. For example, in recent research (simulating active pursuit of a target over a ground plane) Riecke and Jordan (2015) found that most subjects reported vection was greater through an HMD than on a 3D tv [37]. Interestingly, the HMD did not appear to be more provocative in terms of generating motion sickness. However there was also some anecdotal evidence that head motion and tracking might have been responsible for increasing vection more with the HMD (e.g., one subject reported that the vection benefits of the HMD were greatest when they moved their head from side-to-side).

Thus vection with HMDs is likely to depend not only on visual display parameters (such as field of view, binocular overlap, display resolution and luminance, the visually simulated speed and path of self-motion, the visually simulated environmental depth, occlusion of real visual surroundings, etc.) [37,39], but also on how ecological/compatible the available multisensory self-motion information is perceived to be. Consistent with this notion, Kim and colleagues [3] have shown that vection in HMDs depends on the nature of the head-and-display motion. They had observers either sit still or make continuous oscillatory yaw head movements while viewing optic flow simulating self-motion in depth. When observers moved their heads while looking at the optic flow, vection was strongest when compatible visual motion stimulation accompanied the head-motion ("compensated"), and weakest when this additional display motion was applied in the wrong direction ("inversely compensated"). Interestingly, vection was always stronger when the flow generated by active head motion was later played back to now head stationary observers. Unfortunately, cybersickness was not examined in that study. So how this vection might relate to experiences of cybersickness is currently unknown.

1.2 Relationship between Head-movements and Cybersickness in HMDs

While head movements are often necessary to explore virtual worlds when wearing HMDs, they have also been linked to cybersickness [5]. One HMD study by Howarth and Finch (1999) found that exploring virtual environments via head movements produced significantly more cybersickness than keeping one's head still and using a hand control [40]. Another study by Regan and Price (1993) found that participants who were instructed to make more pronounced and rapid head-movements experienced significantly more cybersickness than those who moved their heads naturally [19]. An observational study by Walker and colleagues (2010) also reported that (1) participants moved their heads more in a real world task than in an HMD version of the task; and (2) those who experienced greater cybersickness moved their heads less during the virtual task (possibly as a strategy to avoid exacerbating their cybersickness symptoms) [41]. So if head-movements are nausogenic what might the source/s of the problem be? Several possibilities are discussed below.

One popular explanation is based on the fact that head-movements made with HMDs generate asynchronies between the user's visual and inertial sensory inputs [14,22,26]. In any virtual reality system, there are unavoidable delays between the user's physical motion and the computer responding to this tracked motion by updating the visual scene. The screens of HMDs move with the observer's head, so the visual scenery depicted on them must be moved in the opposite direction in order to compensate for head motion. Conceivably display lag might lead to cybersickness by increasing visual-inertial sensory conflicts [42], or generating postural instability if one is standing [43], or even by altering compensatory eye-movements [44]. Currently the evidence about whether display lag contributes to cybersickness in HMDs appears to be mixed. While some researchers have found that increasing display lag also increases cybersickness [45,46], others have found no significant change [8,14]. However, these apparently discrepant findings might reflect study-based differences in the detectability of lag[1] – since baseline system lag, additional display lag, and the types of head movements studied, often varied markedly from study-to-study. While it did not examine cybersickness, one recent study found that increasing baseline display lag (from 113 to 163 ms) impaired vection during active head oscillation [50]. However, these authors concluded that beyond this critical level of lag, the visual system appeared to downplay the sensory conflict.

Another possible reason why head-movements are problematic could be the eye-movements generated in HMDs [44,50]. Normally when we move our heads, the resulting visual and inertial stimulation generates eye-movements that act to stabilize the images on our retinas. However, eye-movement based image stabilization is less successful during head motion with HMDs – either due to detectable asynchronies between visual and inertial inputs (when head tracking is on) or the absence of corresponding visual inputs (when head tracking is off). Research has shown that eye-movements in HMDs can result in a loss of perceptual stability, and even oscillopsia in extreme cases [48,51]. Extrapolating from Ebenholtz's research, inappropriate eye-movements might generate cybersickness symptoms in their own right, such as increased eye strain, difficulty focussing and blurred vision [52].

A third factor that is seldom discussed is how accurately/ecologically the consequences of the user's head movements are modelled by the displays. In principle, incorrect display calibration and software based projection errors could both increase the likelihood of cybersickness (since, as a consequence, the visually simulated world will not look or behave like the real world). HMD calibration tolerances are more challenging than those for 3D TVs or CAVEs. Because their screens are small and close to the eyes, screen positions and orientations relative to the eyes become important (e.g., incorrect interocular separations and/or HMD alignment on the head can lead to visual display artefacts). Different types of software projection errors are also possible, such as exaggerating/minimising the visual consequences of the tracked head motions [53], applying the compensatory visual motion along the wrong axis [54] or in the wrong direction [3,55], and accidently switching the left and the right eyes views of a stereo 3D simulation [56]. All of these display calibration and software errors would be more salient when the head is moving – and thus their potential for inducing cybersickness would also be expected to increase.

1.3 The current study

Vection and head movements have both been proposed to contribute to experiences of cybersickness when wearing HMDs. Barrett (2014) notes that "head movements made during immersion in a VE [virtual environment] providing strong self-motion cues would be

[1] Further complicating this issue, lag detection thresholds have ranged quite widely in the literature from as little as 14 ms [47] to as much as 322 ms [48].

nauseogenic" [5] (pp. 23). However, there is little empirical data on how vection and cybersickness interact when head movements are made. In a recent HMD study, we examined vection induced under 3 conditions of visual compensation for head movements: "compensated", "uncompensated", and "inversely compensated" [3]. We found that vection was not simply determined by the properties of the optic flow, but instead varied significantly depending on the nature of the visual-inertial stimulation. The current study builds upon this earlier research investigating: (1) the likelihood of cybersickness during head movements in these three different visual compensation conditions, as well as (2) the relationship between vection strength and cybersickness symptomology.

2. Material and Methods

2.1 Observers

Thirteen naïve adult students and staff from the University of Wollongong (7 males and 6 females) participated in this study (mean age 25.5 years; standard deviation 7.0 years). All had normal or corrected-to-normal vision, were clear of any visual or vestibular impairment, and presented no obvious signs of oculomotor or neurological pathology. The Wollongong University Ethics Committee approved the study in advance (HE10/120). Each observer provided written informed consent before participating in the study.

2.2 Visual displays

Our custom software was developed in Visual C++ utilising OpenGL and the Microsoft Visual Studio 2010 version of the Oculus Rift SDK. Computer-generated stereoscopic self-motion displays simulated constant velocity forward locomotion either with or without simulated yaw head rotations. The observer was simulated to lie inside a 3D spherical cloud (radius of approximately 3 m) of 40,960 blue circular objects. These objects ranged in optical size from 0.25 to 2.5 degrees in diameter depending on their simulated proximity to the observer. Approximately 5,120 or 4,019 objects were visible per each eye on any given frame - depending on whether the observer had full-field exposure to the optic flow (the "full-field exposure" condition) or instead viewed this optic flow through two simulated nearby circular apertures which were 74 degrees in diameter (the "simulated aperture" condition). Yaw, pitch, and roll changes in head orientation were recorded for all trials. However, this head tracking data was only used to update the orientation of the virtual camera in two of the three visual compensation conditions tested. Total delays from head rotation to display update were held constant at ~72 ms for both the "compensated" and "inversely compensated" conditions (delays were effectively infinite for the "uncompensated" condition).

2.3 Materials

These optic flow displays were viewed via the Oculus Rift (Version 1.0) with head tracking enabled. It had a binocular field of view of approximately 110 degrees diagonal during "full-field exposure" conditions, and approximately 86 degrees when a near circular aperture was also simulated. This display had a refresh rate of 60 Hz and a resolution of 640 x 800 per eye. This version of the Oculus Rift also came with 3 different pairs of viewing lenses which were used to correct for the specific refractive errors of each observer. The observer's angular changes in head orientation were recorded using the Oculus Rift's in-built accelerometers and gyros. This HMD also contained a three-axis rate sensor which was used to measure yaw, pitch and roll head rotations (sampled at 10Hz). Observer head rotations were timed according to a computer generated metronome (TempoPerfect by NCH software) set at 35 beats per minute.

Motion sickness symptoms were measured using the Simulator Sickness Questionnaire (SSQ) at the beginning and end of each testing session. The SSQ assessed the simulator sickness symptoms produced by each of the three visual compensation conditions. When scored according to published guidelines [52], the SSQ yields four scores: a total SSQ score, a nausea sub-score, an oculomotor sub-score and a disorientation sub-score. Sixteen questionnaire items contribute to these SSQ scores: "general discomfort", "fatigue", "headache", "eye strain", "difficulty focusing", "increased salivation", "sweating", "nausea", "difficulty concentrating", "fullness of the head", "blurred vision", "dizziness with eyes open", "dizziness with eyes closed", "vertigo", "stomach awareness", and "burping". For each testing session, observers indicated the degree to which each symptom was experienced both pre- and post-treatment by circling one of four choices (0 = "none", 1 = "slight", 2 = "moderate", or 3 = "severe").

2.4 Procedure

Three conditions of visual compensation for physical head movements were examined. The "compensated" condition adjusted the simulated viewpoint of the observer in the HMD in an ecological fashion based on his/her tracked head motions (i.e., the simulated viewpoint was rotated in a contralateral direction relative to the head motion). The "inversely compensated" condition had the opposite effect in yaw (rotating the simulated viewpoint in the ipsilateral direction relative to the head motion). In the "uncompensated" condition (pure radial flow control), the focus of expansion of the optic flow was always aligned with the yaw orientation of the observer's nose irrespective of the head motion. Each visual compensation type condition was tested on a different day (They were separated by approximately 24 hours in order to allow any residual sickness symptoms from the previous days testing to subside). In order to minimise the possible influence of postural instability on cybersickness, observers always remained seated throughout each testing session.

Each day consisted of testing two blocks of trials (i.e., the "simulated aperture" and "full-field exposure" versions of the visual compensation condition that was under examination). Both blocks of trials required observers to make continuous yaw-plane head movements (at around 0.6 Hz and ±30°; initially demonstrated to observers by guiding their heads). The second block of trials was identical to the first – except that the simulated apertures (visible in all trials during the first block) were removed, resulting in a larger area of visual motion stimulation. Each observer was exposed ten times to each visual compensation condition (first 5 times viewing the flow through the simulated aperture and then 5 times without the aperture). In order to control for possible order effects, the three different visual compensation conditions ("compensated", "inversely compensated" and "uncompensated") were presented in different random orders for each observer.

On each testing day, the session began with a description of the tasks which would be performed prior to and directly following exposure to the experimental displays. Observers were told that they would see displays of moving objects and that "sometimes the objects may appear to be moving towards you; other times you may feel as if you are moving. Your tasks are to rate the strength of your feeling of self-motion and any symptoms of motion sickness directly after each display presentation". Observers then completed the pre-exposure sections of the SSQ (Pre-Exposure Background; Pre-Exposure Physiological Status; Baseline (Pre) Exposure Symptoms checklist). They then put on the Oculus Rift headset while sitting on a height-adjustable chair that maintained their legs comfortably at close to right angles. Observers initially stared ahead with their head erect in darkness. The experimenter executed the simulation application, after instructing the observer to fixate at the green central target prior to each trial and to reset their gaze position back to the centre of the display directly afterwards (i.e. before the start of the next optic flow display).

The first optic flow display in each block was viewed with the head held stationary and head tracking turned off – it presented a purely radial (i.e. non oscillating) pattern of optic flow (the standard stimulus). Observers were asked if they felt that they were moving or not. If they responded that they felt that they were moving, they were told that the strength of this vection experience was "50" (the modulus for their magnitude estimates). The five experimental trials were presented next. Observers viewed each display and provided a vection strength rating (relative to "50") at the conclusion of each trial. After completing both blocks of trials for the particular visual compensation condition, observers immediately completed the post-exposure symptom checklist of the SSQ.

3. Results

3.1 Vection strength ratings

As expected, full-field exposure display conditions (M = 67.2) produced significantly stronger vection ratings than the simulated aperture conditions (M = 56.2), $t(12) = 5.46$, $p = 0.0001$. Figure 1 shows the mean vection strength ratings across all observers in the three visual compensation conditions. Separate repeated-measures analyses of variance (ANOVAs) were run on the data obtained in the "simulated aperture" and "full-field exposure" blocks. For the "simulated aperture" displays, we found a main effect of *visual compensation type* ($F_{2,24} = 3.56$, $p < 0.05$). Bonferroni corrected post-hoc contrasts revealed that (i) "compensated" conditions produced significantly stronger vection ratings than the "uncompensated" control ($p < 0.05$); (ii) "inversely compensated" conditions did not produce significantly different vection ratings to the "uncompensated" control ($p > 0.05$). For the "full-field exposure" displays, the main effect of *visual compensation type* failed to reach significance for vection strength ratings ($F_{2,24} = 0.50$, $p > 0.05$).

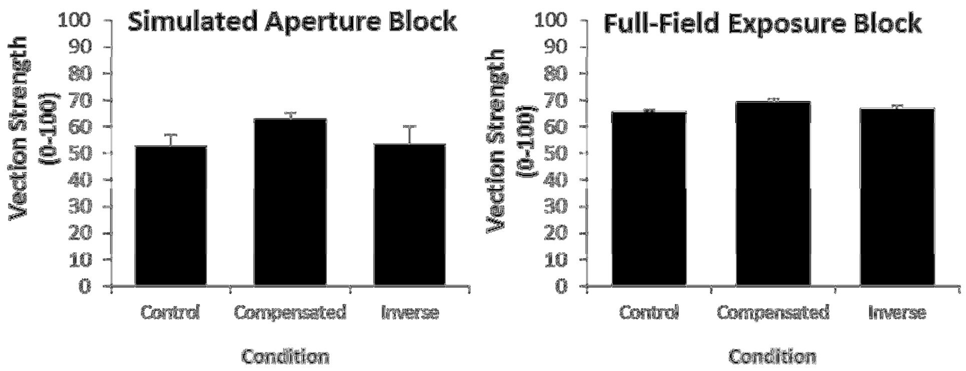

Figure 1. *Vection strength ratings for the 3 different visual compensation conditions (Control/Uncompensated, Compensated and Inversely Compensated) presented seperatedly for the simulated aperature (Left) and full-field (Right) exposure blocks.*

3.2 Cybersickness

Four SSQ scores were calculated for each subject using methods and weighting factors outlined in [53]: a total SSQ score and three sub-scores (nausea, oculomotor symptoms, and disorientation). In each case pre-scores were subtracted from the post-scores. We found significant main effects of visual compensation type for the total SSQ scores [$F(1.26,15.10) = 9.06$, $p = 0.006$], as well as the oculomotor [$F(1.29,15.52) = 8.55$, $p = 0.007$], nausea [$F(1.29,15.49) = 8.96$, $p = 0.006$] and disorientation sub-scores [$F(1.36,16.28) = 5.17$, $p = 0.03$]. Bonferroni-corrected post-hoc contrasts revealed that: (i) “inversely compensated” conditions produced significantly higher scores than “compensated” conditions on all four SSQ measures ($p < 0.05$ for total, nausea, oculomotor and disorientation symptoms); (ii) “inversely compensated” conditions produced significantly higher ratings than the “uncompensated” controls on three of the four SSQ measures ($p < 0.05$ for total, nausea, and oculomotor symptoms); and (iii) “compensated” conditions did not produce significantly different ratings to “uncompensated” control conditions on all four of the SSQ measures ($p < 0.05$ for total, nausea, disorientation and oculomotor symptoms).

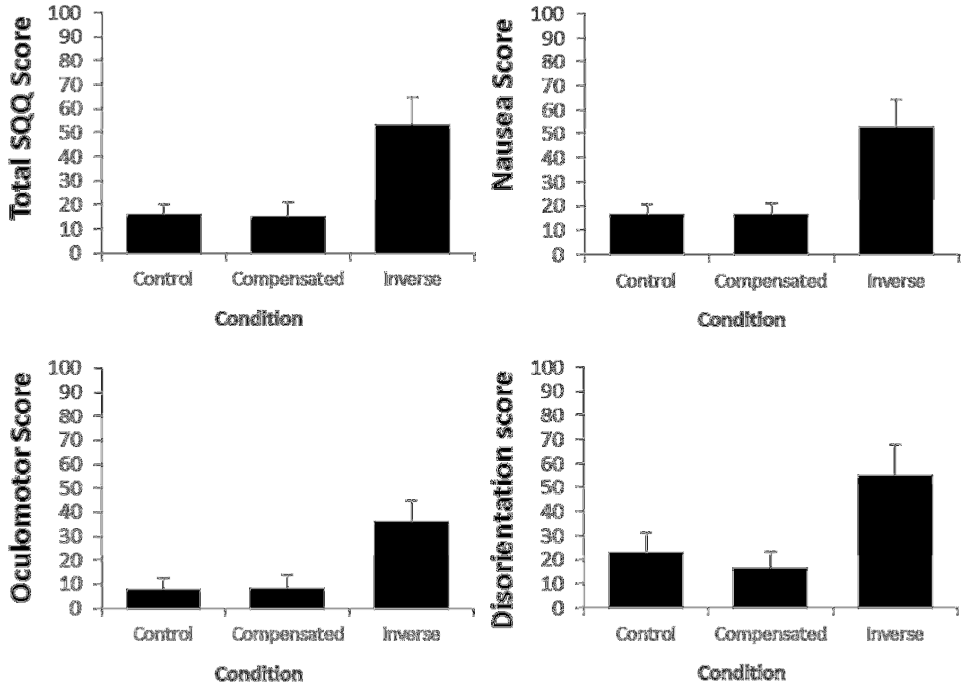

Figure 2. *Effect of visual compensation condition (Control/Uncompensated, Compensated, Inversely Compensated) on the 4 SSQ scores: Total (Top Left), Nausea (Top Right), Oculomotor (Bottom Left) and Disorientation (Bottom Right).*

3.3 Angular head oscillation

Figure 3 shows time-series plots of yaw head orientation for a representative observer in each of the visual compensation conditions. Consistent with instructions, head movements occurred primarily in the yaw plane. As can be seen in Figure 3, yaw head amplitudes were considerably larger in the "uncompensated" control condition (M = 55.37° ± 7.76°) compared with the other visual compensation conditions. However, head amplitudes in the "compensated" (M = 43.96° ± 3.04°) and "inversely compensated" (M = 45.5° ± 5.65°) conditions were very similar. Yaw head movement frequencies were also similar across all three different visual compensation conditions ("Uncompensated" M = 1.67 ± 0.05 s; "Compensated" M = 1.69 ± 0.02 s; "Inversely Compensated" M = 1.71 ± 0.09 s).

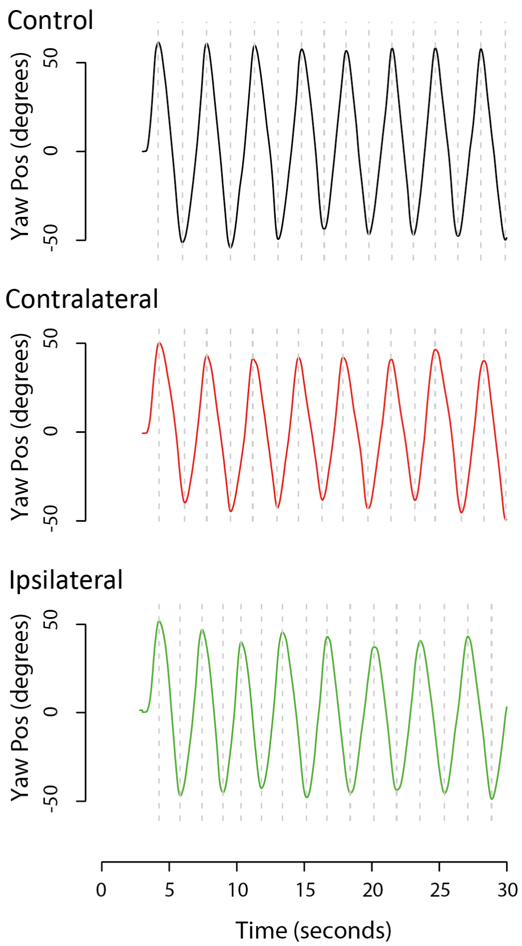

Figure 3. *Raw traces of yaw head orientation for the 3 visual compensation conditions (Control/Uncompensated, Compensated, Inversely Compensated) measured as Euler angles in degrees over time (for representative observer SS). Vertical solid and dashed lines indicate estimated troughs and peaks in the positional amplitude of yaw head rotation.*

3.4 Relationship between Vection and Cybersickness

To investigate possible relationships between vection and cybersickness, we had planned to perform two linear regression analyses with rated vection strength as the predictor and total SSQ scores as the dependent variable (Values for each measure were averaged across the 3 different visual compensation conditions, producing paired data for each of the 13 observers). The first regression used “simulated aperture” vection as the predictor, whereas the second regression used full-field vection as the predictor. We found that the negative relationship between aperture vection strength and total SSQ scores was significant, R^2 = 0.34, t_{11} = -2.38, p < 0.03 (see Figure 4 left). However, the equivalent relationship did not reach significance for full-field vection, R^2 = 0.15, t_{11} = -1.37, p > 0.05 (see Figure 4 right). The regression lines in Figure 4 suggest that cybersickness decreased as vection strength increased.

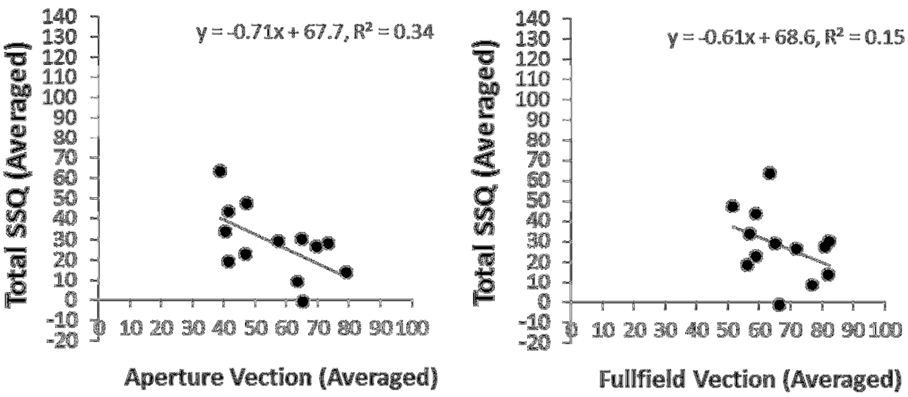

Figure 4. *Relationship between Cybersickness (as indexed by Total SSQ scores) and the strength of Aperture (Left) and Full-field (Right) Vection. Both vection and total SSQ datasets were averaged across the 3 different visual compensation conditions.*

Correlational analyses were subsequently performed to examine the nature of the relationship between aperture vection and cybersickness for each of the three visual compensation conditions. As these additional analyses were unplanned and regarded as exploratory, no corrections were made for multiple testing. Under these particular conditions, correlations between aperture vection and total SSQ were only found to reach significance for the "inversely compensated" condition, r = -.53, n = 13, p = 0.03. Correlations for the "uncompensated" control and the "compensated" conditions were r = -0.162, n = 13, p > 0.05 and r = -0.34, n = 13, p > 0.05 respectively.

4. Discussion

Traditionally popular "sensory conflict" accounts of self-motion perception and motion sickness [42,57] predict that vection in HMDs should be reduced, and motion sickness should be increased, by more visual-inertial conflict. Of the three visual compensation conditions tested, the most ecological "compensated" condition was expected to generate the least visual-inertial conflict (since inertial inputs arising from head motion were accompanied – after a finite delay – by compatible visual motion). By contrast, the two other conditions were both expected to generate significant and sustained visual-inertial conflicts. While head movements in the "uncompensated" condition generated inertial stimulation, the visual motion stimulation that normally accompanies these inertial inputs was absent. Similarly, while head movements were accompanied by combined visual-inertial stimulation in the “inversely compensated” condition, the available visual and inertial self-motion information was (by definition) inconsistent/non-ecological[2].

In the “simulated aperture” conditions, we found that vection was strongest in the “compensated” condition. However, there was no difference in the vection induced in “uncompensated” and “inversely compensated” conditions. These findings appear (at first glance) to be consistent with both sensory conflict and ecological accounts of self-motion perception – since conditions that should have been more ecological, and were expected to generate less sensory conflict, produced superior vection. However, similar vection effects were not observed during “full-field exposure” conditions. This failure to observe significant differences in vection for these three conditions under full-field conditions may reflect (near) ceiling effects. This general improvement in vection during “full-field exposure” compared to the “simulated aperture”, conditions was likely due to the increase in the area of visual motion stimulation [30]. However it might also have arisen because the “full-field exposure” conditions were always tested after the “simulated aperture” conditions, as recent research appears to show that rated vection strength tends to increase from trial-to-trial [58].

This study also examined the cybersickness generated by viewing these “compensated”, “uncompensated” and “inversely compensated” conditions through an HMD. Cybersickness is generally thought to be reflected by more disorientation and less nausea than the sickness generated by driving/flight simulators [28]. However, there appeared to be little support for this notion when we examined the nausea, disorientation and oculomotor sub-scores obtained using the displays in the current study. Of the three visual compensation conditions tested, the greatest cybersickness was found for the “inversely compensated” condition. This particular condition was similar to the consequences of moving one’s head with an ~290 ms display lag. The reported cybersickness in this “inversely compensated” condition was high compared to past studies [7] – with the average post-pre sub-scores on the SSQ being 52.8 (nausea), 36.2 (oculomotor) and 55.0 (disorientation). While some researchers have suggested that the use of the SSQ both pre- and post- exposure (as we did here) can inflate reported symptomology (via demand characteristics in the questionnaire) [59], it should be noted the symptom ratings were considerably reduced for the two other visual compensation conditions. Compared to the “inversely compensated” condition, total post-pre SSQ scores for the “uncompensated” and “compensated” conditions were each reduced by approximately 70%. Thus, even if one assumes that the absolute scores for the “inversely compensated” condition were inflated, it was still clearly very provocative for cybersickness – probably due to its unusual multisensory stimulation and the high degree of visual-inertial conflict it was expected to generate.

We had also expected that cybersickness to be elevated in the “uncompensated” condition – since we assumed it would generate considerably more visual-inertial conflict than the “compensated” condition. However, very little support was found for this proposal – other

[2] While it might have been possible to create a condition that was similar to “inverse compensation” by increasing the baseline lag, this would have initially contained an extended period of visual only stimulation. Display lag was equivalent in the current “compensated” and “inversely compensated” conditions. So any effects were not due to differences in synchronising the display with the head motion.

than perhaps the finding that disorientation scores were somewhat elevated for the "uncompensated" condition (which had a mean post-pre SSQ disorientation score of 22.8 compared to a mean score of 16.5 for the "compensated" condition). Despite this trend, cybersickness in the "uncompensated" condition was not significantly different to the "compensated" condition on *any* SSQ score (i.e., total SSQ, nausea, disorientation and oculomotor). One explanation, based on spontaneous subject reports during debriefing, was that the optic flow appeared to be easier to look at during these "uncompensated" conditions (which appears consistent with the lower oculomotor scores obtained for this condition). Presumably, this was because there was a constant focus of expansion that did not change in location relative to the centre of the display.

As discussed in the introduction, there has been much debate about whether vection is important, or indeed necessary, for experiencing visually induced motion sickness [4,28]. Although full-field vection ratings did not significantly predict individual differences in cybersickness, we did find a significant (negative) relationship between vection strength ratings and cybersickness in the "simulated aperture" conditions (i.e., subjects who experienced stronger vection in these conditions typically experienced less cybersickness). One possible explanation for this significant relationship between aperture vection and cybersickness (but not between full-field vection and cybersickness) was that the aperture appeared to impair vection more for the "uncompensated" control and "inversely compensated" conditions than for the "compensated" condition. The presence of the simulated aperture reduced the mean vection scores (and also increased their variability) across the three display compensation conditions. As apertures and masks have previously been found to reduce cybersickness [60], it is possible the simulated aperture enhanced this particular relationship by jointly reducing both vection and the cybersickness.

Taken together with the current literature, these findings support the notion that the relationship between vection and motion sickness is complex. Past studies have often found positive relationships between vection and motion sickness (i.e., stronger vection is accompanied by greater motion sickness) [28]. Instead we found evidence of a negative relationship – whereby stronger vection was accompanied by reduced cybersickness (a seemingly desirable result). However, the negative valence of this relationship might have been generated by the particular conditions examined in our experiment (i.e., continuous oscillatory head movements with 3 possible modes of visual HMD compensation). Indeed, the exploratory correlational analyses we conducted suggest that this relationship was driven primarily by the most provocative "inversely compensated" condition. However, future research with a larger sample size would be required to confirm this preliminary finding.

5. Conclusions

The current findings support the notion that vection and cybersickness both depend on complex interactions between visual and inertial inputs. Vection strength was found to depend not only the area of visual motion stimulation ("simulated aperture" versus "full-field" stimulation), but also on how the observer's tracked head-movements were represented in the visual display. While the amount of cybersickness generated was also found to vary significantly based on the type of visual compensation applied, these visual compensation effects were quite different to those observed for vection. Although the "inversely compensated" condition was the most provocative, the "uncompensated" condition was not significantly different on any sickness measure to the more ecological "compensated" condition. The later null findings suggest that (if practicable) turning the head tracking feature off might alleviate some cybersickness symptoms.

Cybersickness scores in the "inversely compensated" condition were particularly high in the current study. While this condition (i.e., the user making continuous head movements while presented with an unusual software-based display error: reversed head tracking) is likely to represent an extreme case, the sickness levels reported would limit the usability and possibly the safety of HMD use. These findings suggest that software developers should be careful to accurately represent the consequences of the users head movements in HMDs. This "inversely compensated" condition was also superficially similar to the effects of a constant excessive display lag. If the cybersickness generated by this condition was due to it mimicking the effects of display lag[3], then this might well pose limits in terms of simulation fidelity (due to the typical trade-off between simulation fidelity and display lag). It is however noted that the occurrence and severity of cybersickness experienced with HMDs is likely to depend on a variety of factors – only a subset of which have been investigated in the current study.

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[3] Although it should be noted that it has been previously proposed that temporal visuomotor adaptation may reduce cybersickness during stationary display based self-motion simulations [61].

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