Unexpected Vection Exacerbates Cybersickness During HMD-Based Virtual Reality

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Visually induced illusions of self-motion (vection) are thought to cause cybersickness during head-mounted display based virtual reality (HMD VR). However, the empirical support for this widespread belief is rather mixed. Our exploratory study examined the possibility that only unexpected experiences of vection provoke cybersickness. Fifteen males and 15 females played an HMD VR game (Mission: ISS) for up to 14 min with: 1) their experiences of vection and cybersickness assessed every 2 minutes; and 2) the game being terminated whenever they reported feeling sick. Of the 30 participants tested, 17 reported feeling sick and 13 remained well. Sick and well participants did not differ in terms of the strength of their vection experiences. However, the sick participants were significantly more likely to report unexpected/uncontrolled vection. When these data were subjected to machine learning analysis, unexpected vection was found to be the most important predictor of cybersickness. These preliminary findings suggest that vection can be used to safely enhance experiences in HMD VR–as long as developers ensure that any simulated self-motions are expected and perceived to be under the user's control.

Keywords: cybersickness, motion sickness, virtual reality, head-mounted display (HMD), vection

1 INTRODUCTION

For decades, virtual reality (VR) technology has promised to transform the way in which we interact with software. Head-mounted displays (HMDs) are now both widespread and accessible, with a growing number of HMD VR apps developed for consumer entertainment, industry, military, and research applications (Bhagat et al., 2016; Liu et al., 2016; Burns et al., 2017; Lee et al., 2017; Pfandler et al., 2017). Despite these advancements, motion sickness remains a pervasive problem for HMD VR. This **cybersickness** (also known as simulator sickness, or VR sickness) continues to limit both the use and the appeal of these new HMD systems. Unfortunately, up to 67% of adult VR users experience mild to severe symptoms mirroring those of other types of motion sickness (Chang et al., 2012). These symptoms can appear quite soon after exposure (Clifton and Palmisano, 2019; Risi and Palmisano, 2019; Teixeira and Palmisano, 2021) and last up to 12 h afterwards (Kennedy et al., 1994; Kennedy et al., 1994; Merhi et al., 2007). Currently we lack a universally accepted theory of cybersickness (Lawson, 2014; Palmisano et al., 2020). Thus, in this paper we outline and explore a new hypothesis of cybersickness in HMD VR (developed in response to the criticisms of, and/or the mixed evidence found for, existing sensory conflict theories).

1.1 Sensory Conflict, Vection and Motion Sickness

Reason and Brand's (1975) *sensory conflict theory* remains the most commonly cited theory of all types of motion sickness (Keshavarz et al., 2014) – including cybersickness. According to this theory,

a multisensory pattern of motion stimulation will be more likely to induce sickness if it results in a sensory conflict or an expectancy violation. Reason and Brand (1975) originally proposed that motion sickness was caused either by: 1) intrasensory conflicts between the inner ears' otolith organs (the gravireceptors) and its semicircular canals (inertial rotation detectors), or 2) intersensory conflicts between visual and vestibular information about self-motion. Later Reason (1978) revised the theory, proposing that *expectancy violations* were the major trigger for motion sickness. According to this *sensory rearrangement theory*, during self-generated movements, people can become sick when there is a mismatch between their expected and sensed patterns of multisensory motion stimulation (referred to as a **neural mismatch**). If they are not responsible for generating their physical motion (e.g., they are being passively transported on a moving vehicle), the theory predicts that they should be even more likely to become sick (e.g., compared to driving the vehicle). This is because it will be much harder for passengers to select the appropriate expected pattern of motion stimulation under these circumstances (relative to the driver). This, in turn, should increase the likelihood of a neural mismatch and motion sickness.

According to Stoffregen and Riccio (1991), most sensory conflict theories do not generate readily testable hypotheses. However, a more recent variant of *sensory conflict theory* does allow for direct testing. According to Hettinger and others (Hettinger et al., 1990; Hettinger and Riccio, 1992), visually induced illusions of self-motion (**vection**)[1] are a necessary prerequisite for certain types of motion sickness (such as visually induced motion sickness or **VIMS**). Put simply, they argue that the key factor which differentiates sick (from well) users during VR is whether they experience an illusory self-motion (or not). If (as they propose) this vection represents a potentially provocative sensory conflict, then *sensory rearrangement theory* suggests that the severity of their sickness should also increase with the strength of the vection experience. We will discuss the support for these *vection based hypotheses* of motion sickness below.

1.1.1 Is Vection a Necessary Prerequisite for VIMS?
Consistent with this hypothesis, Hettinger et al. (1990) found that VIMS was much more likely to occur during visually induced illusions of self-motion. In their fixed-based flight simulation

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[1]Note, Palmisano et al. (2015) identified four main definitions of vection in the literature: 1) Vection is a visual illusion of self-motion in a stationary observer; 2) Vection is an illusion of self-motion; 3) Vection is a visually mediated perception of self-motion (real or illusory); 4) Vection is a conscious subjective experience of self-motion (real or illusory). In this paper, we chose to define vection as an illusion because A) that is how Hettinger and colleagues defined vection (Hettinger et al., 1990; Hettinger and Riccio, 1992) and our study aimed to explore a novel version of their hypothesis; B) that is the most commonly referred to definition of vection in the literature. However, such a definition implies that vection is an unusual error or mistake. Definition #3 provides another way to describe our participants' experiences of whole-body self-motion in the current study. By contrast to definitions #1 and #2, #3 (and #4) suggest that vection might be related to the critical processing involved in actually controlling self-motion (see Stoffregen and Bardy, 2001, as well as Palmisano et al., 2015 for further discussion).

study, 10 of their 15 participants reported experiencing vection. While 8 of these 10 participants eventually became sick (i.e., 80%), only one of the "no vection" participants experienced any sickness (i.e., 20%). Based on these findings, they concluded that VIMS is unlikely to occur without vection. Ji et al. (2009) however disagree. In one of their experiments, they presented observers with centrally and peripherally viewed patterns moving in opposite directions, but at the same speed. Even though these ambiguous motion displays were reported to completely suppress vection, they were still found to reliably generate VIMS (and optokinetic nystagmus). However, some caution should be used when interpreting the findings of this study. Nooij et al. (2017) were unable to completely suppress vection using the same display manipulation as Ji et al. (2009). Thus, it is conceivable that the VIMS observed in the Ji et al. (2009) study could still have been produced by unreported vection.

1.1.2 Does VIMS Increase With Vection Strength?
While Hettinger et al. (1990) did not explicitly propose a linear scaling relationship between vection strength and sickness severity, most VIMS studies have examined this possibility. To date, the evidence for such a relationship is mixed. Consistent with expectations based on *sensory rearrangement theory*, many studies have reported positive linear relationships between vection strength and VIMS (e.g., Hettinger et al., 1990; Flanagan et al., 2002; Smart et al., 2002; Bonato et al., 2004, 2005, 2008; Diels et al., 2007; Palmisano et al., 2007; Nooij et al., 2017, 2018; Clifton and Palmisano, 2019; Risi and Palmisano, 2019; Pöhlmann et al., 2021). However, other studies have found either non-significant or negative linear relationships between vection strength and VIMS (Webb and Griffin, 2002, 2003; Lawson, 2005; Bonato et al., 2008; Ji et al., 2009; Chen et al., 2011; Golding et al., 2012; Keshavarz et al., 2014; Riecke and Jordan, 2015; Gavgani et al., 2017; Palmisano and Riecke, 2018; Kuiper et al., 2019 – please see Keshavarz et al., 2015 for a review of this literature).

1.1.3 Is There a Relationship Between Vection and Cybersickness During HMD VR?
Only a few studies have examined possible relationships between vection and cybersickness during HMD-based VR. In one of the earlier studies, Palmisano et al. (2017) had HMD users make continuous left-right head-movements with their virtual environment being updated in either an ecological or non-ecological direction based on these tracked movements. Under the latter (maximum sensory conflict) condition, the authors reported a *negative* relationship between vection strength and cybersickness (i.e., stronger vection in their study was associated with reduced cybersickness). By contrast, Risi and Palmisano (2019) reported that stronger vection in their study was associated with increased cybersickness, whereas Teixeira and Palmisano (2021) failed to find a significant association between vection strength and cybersickness severity. While the experimental conditions and activities were quite different in each of these studies, their conflicting findings clearly demonstrate that cybersickness severity does not always

increase with the reported strength of vection. Instead, they suggest that if there is a relationship between vection and cybersickness, then it clearly must be a complex one.

1.2 Unexpected Vection and Cybersickness

Experiences of vection were likely to have been quite different in the VIMS/cybersickness studies described above. Not only would they have differed in terms of the types of self-motion being simulated (e.g., linear or rotary, accelerating or constant velocity, self-generated *via* controller motions or passively viewed, etc.), but also in terms of the strength of the vection that they induced (ranging from weak/intermittent to strong/fully saturated) (Palmisano et al., 2015). However, reviews of this research have not taken these likely differences in vection type and strength into account. That could potentially explain why such different (including null) relationships have been reported between vection and VIMS/cybersickness in past studies.

One aspect of vection that has thus far been neglected, is whether the experience of self-motion is *expected* (or not). Past research has shown that vection is more likely, and more compelling, when the illusory self-motion is expected, anticipated, or primed (e.g., Andersen and Braunstien, 1985; Palmisano and Chan, 2004; Palmisano and Riecke, 2018). Since discrepancies between expected and sensed self-motion are thought to be provocative for motion sickness (Reason, 1978), this suggests that *unexpected experiences of vection* should be particularly provocative for cybersickness. However, to date, the specific effects of unexpected vection on HMD-induced cybersickness have not been examined.

1.2.1 Expectancy and Motion Sickness

According to Reason's (1978) *sensory rearrangement theory*, motion sickness is caused by neural mismatches between expected and currently sensed motion (see also Oman, 1982, 1990; Bles et al., 1998). However, only a few studies have *directly* examined the possible link between expectations and motion sickness (Griffin and Newman, 2004; Perrin et al., 2013; Wada et al., 2018). For example, Kuiper et al. (2020) found that auditory cues about future motion direction significantly reduced the sickness induced by a physically moving sled. They also found that this sickness was reduced during more (as opposed to less) predictable sled motion conditions. Another study by Feenstra et al. (2011) found that motion sickness could be reduced in a 6 degrees of freedom motion simulator, when participants were provided with anticipatory visual cues about the physical motion. These findings suggest that being able to anticipate upcoming motion does provide some benefits in terms of reducing the likelihood of motion sickness and/or its symptom severity.

1.2.2 Control and Motion Sickness/Cybersickness

A number of studies have *indirectly* assessed the role of expectations in motion sickness by studying the driver/passenger effect. Passengers are significantly more likely than drivers to become sick during actual vehicular motion (e.g., Turner and Griffin, 1999). Such effects are particularly apparent on public transport (e.g., bus travel). Passengers who cannot see the road ahead experience greater sickness, likely due to their reduced capacity for predicting the consequences of their self-motion in the absence of optic flow (Turner and Griffin, 1999). The driver/passenger effect has also been reported in driving simulation studies (Rolnick and Lubow, 1991; Dong et al., 2011). When both drivers and passengers only experience simulated movement, those who are in control of the visual simulation are less likely to become sick. Such differences in sickness cannot be explained based on visual motion alone (as this should be very similar–see Chang et al., 2021). To date, virtual driver/passenger effects have been reported both in large screen fixed-base driving simulator studies and (more recently) in HMD-VR studies (e.g., Rolnick and Lubow, 1991; Stanney and Hash, 1998; Seay et al., 2002; Sharples et al., 2008; Dong et al., 2011; Curry et al., 2020).

According to Reason's (1978) *sensory rearrangement theory*, driver/passenger effects occur because it is harder for passengers to select the appropriate expected pattern of motion stimulation - since they are not responsible for generating the (real/simulated) vehicular motion (speeding it up, slowing it down and turning). The theory therefore predicts that they should be more likely to become sick compared to drivers (who are in active control of both the vehicle's motion and their multisensory stimulation - Oman, 1982; Chang et al., 2021). However, it should be noted that driver/passenger effects could also be explained by the *postural instability theory* of motion sickness. As they control their vehicular motion, drivers are able to anticipate the forces that will act on their body and plan the postural adjustments needed to maintain stability (Dong et al., 2011; Stoffregen et al., 2017). Passengers will, however, have a reduced ability to anticipate such changes in motion, and as a result (in the real world) their postural adjustments will be less tuned to situational changes in the vehicle's motion. This will place them at a greater risk of developing motion sickness (Dong et al., 2011).[2]

1.3 The Current Study

In this exploratory study, we will (repeatedly) assess the vection and cybersickness experienced by our participants as they actively control their self-motions during HMD VR. To our knowledge, no previous study has examined the effects of *unexpected* vection on cybersickness during HMD VR. Vection was not even checked in most simulation studies examining the effects of expectancy and control on motion sickness. However, as these studies presented first person driving games on large screens (Dong et al., 2011; Chang et al., 2021), or used HMD VR (Curry et al., 2020), they should have induced compelling experiences of vection (since global patterns of optical flow were used to simulate the vehicular movement). As such, we aim to provide the first exploratory study assessing the impact of the nature of the

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[2]In a recent simulation study, Stoffregen et al. (2017) found that individuals with real-world driving experience became sick more rapidly than those without any experience when "driving" in Forza Motosport 3 (as expected based on *sensory rearrangement theory*). However, no group differences in sickness incidence or severity were found. Driving experience did affect head and torso movements just before sickness. Such movements also differed between "sick" and "well" participants. These findings appear to favor a *postural instability* explanation of motion sickness (at least for this study).

vection experience in active HMD-VR and its relation to cybersickness. Specifically, we aim to see whether experiences of unexpected vection and/or a perceived loss of control are more likely to precede cybersickness than expected/controlled motion in a naturalistic VR gameplay setting. Based on the findings of these past studies, and the widely held belief that vection contributes to motion sickness, we predict that *unexpected* vection might be particularly provocative for cybersickness. We hypothesise that the participants in our study who become sick will be more likely to report *unexpected* vection and a perceived loss of control of their self-motion (compared to those who remained well). For these sick participants, we also predict that there will be a significant positive relationship between the strength of their *unexpected* vection and the severity of their cybersickness.
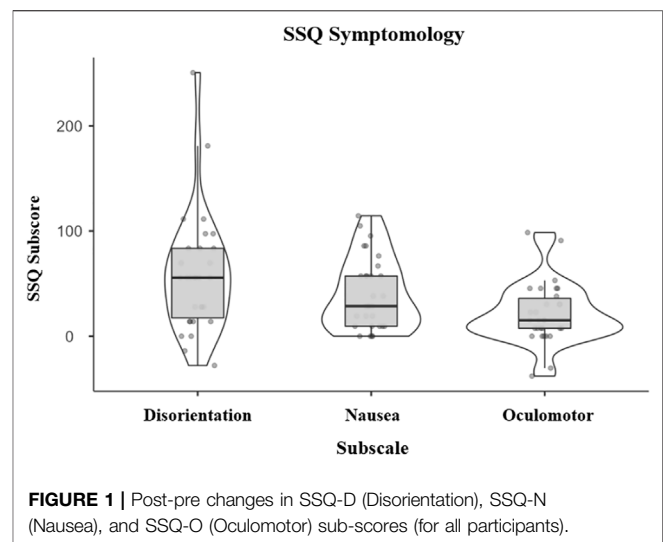
2. MATERIALS AND METHODS

2.1 Participants

The study examined 30 participants (15 males and 15 females; Age = 25.9 years ± 6.5 years), who were recruited from the University of Wollongong (UOW) and the general population. These participants all had normal or corrected-to-normal vision and no self-reported visual, vestibular, or neurological impairments. All reported feeling well at the start of the experiment. The study was approved in advance by the UOW Ethics Committee, and each participant provided informed written consent prior to participating in the study.

2.2 Materials

2.2.1 Hardware and Software

Exposure to the virtual environment was delivered *via* an Oculus Rift CV1 head-mounted display (HMD), two Oculus Touch (hand) controllers, and two infrared tracking cameras (for monitoring head and hand positions). The HMD had a resolution of 1,080 × 1,200 pixels for each eye and a refresh rate of 90 Hz using organic light-emitting diode (OLED) technology. The virtual environment was generated by a Microsoft Windows 10 Dell Precision 5820 computer, which contained an NVidia GeForce GTX1080 graphics card with the latest stable driver software installed and an Intel 7th generation CPU. The game software used in this study was "*Mission: ISS*" (https://www.oculus.com/experiences/rift/1178419975552187/?locale=en_US). Participants were exposed to the game's tutorial section, which simulated first-person exposure to micro-gravity inside a virtual model of the International Space Station. Within the parameters of the tutorial participants learned to move through the space station *via* "thrusting" (pushing the left joystick in the direction of their desired body movement and then accelerating in that direction) and by pulling themselves along the space station's interior (using the Oculus Touch hand controllers to first grab, and then release, handles and other protrusions). As the experience and control of micro-gravity locomotion was alien to participants, it was expected that this software might be more likely to induce unexpected vection and cause participants to perceive a loss of control in their self-motion.

FIGURE 1 | Post-pre changes in SSQ-D (Disorientation), SSQ-N (Nausea), and SSQ-O (Oculomotor) sub-scores (for all participants).

2.2.2 Cybersickness Severity and Symptom Profiling

Directly before and after HMD VR exposure, cybersickness symptomology was measured using a 16-item version of Kennedy et al.'s (1993) Simulator Sickness Questionnaire (SSQ). Verbal ratings of cybersickness severity were also measured every 2 minutes during HMD VR exposure using the Fast Motion Sickness (FMS) Scale (from 0 = "no sickness" to 20 = "frank sickness" — see Keshavarz and Hecht, 2011).[3]
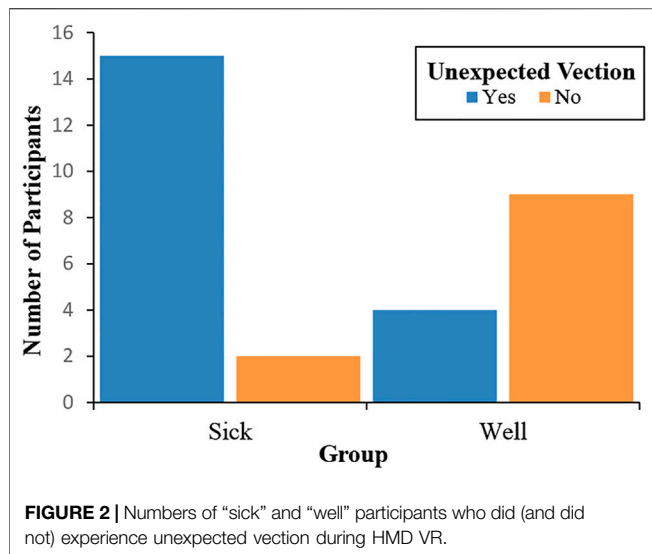
2.2.3 Vection Type and Strength

Vection strength was rated verbally on a scale (from 0 = "no vection" to 10 = "strong vection") every 2 minutes during exposure: "How strong *is* your feeling of whole body movement relative to the virtual environment on a scale of 0–10?" We also obtained an overall vection strength rating at the end of the trial ("How strong *was* your feeling of whole body movement relative to the virtual environment?" on the same 0–10 scale). In addition, at the end of their exposure to HMD VR, participants were also quizzed about the nature of their experience of vection. If they had reported experiencing sickness, they were asked:

1. "Did your feelings of being in control of your perceived body movement change prior to sickness?"
2. "Was your perceived body movement more or less expected/anticipated prior to sickness?"
3. "Is there anything else you wanted to add? Do you have any insights about why you think you became sick?"

Alternatively, if they reported remaining well throughout the HMD VR session, they were instead asked:

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[3]It was possible that repeatedly asking these questions might have modestly reduced our participant's sense of presence.

FIGURE 2 | Numbers of "sick" and "well" participants who did (and did not) experience unexpected vection during HMD VR.

1. "Did you feel in control of your perceived body movement during the simulation?"
2. "Was your perceived body movement expected/anticipated during the simulation?"
3. "Is there anything else you wanted to add?"

Participants' responses about their perceived body movement were double-checked during debriefing at the end of the experiment. This was to see whether participants were referring to whole body self-motions relative to the virtual environment (rather than the motions of their various limbs or their postural sway while standing in place during HMD VR).

2.3 Procedure

Participants first completed a demographics, VR and Gaming History sheet. They were next given an information sheet that described the experiment, which they were asked to sign to indicate their consent. Visually induced illusions of self-motion were verbally described to participants before the study by the experimenter with reference to both the "train illusion" and the "traffic light illusion". Linear and circular vection in standing and seated observers were also described in the information sheet. In addition, both types of vection were also quickly demonstrated to participants at the beginning of the experiment (when they were instructed on how to use the controls).

Directly before their exposure to HMD VR, participants completed the pre-exposure sections of the SSQ to provide a baseline measure of their current sickness levels. They then donned the Oculus CV1 HMD and ran through the tutorial section of "*Mission: ISS*" either for 14 min, or until they responded "yes" to the question: "Do you feel sick?" During the tutorial, participants actively explored the space station *via* "thrusting" (pushing the joystick in the direction of the desired locomotion and then accelerating in space) and by pulling themselves *via* the hand controllers along the space station's interior while instructed to physically stand in place (in relation to the laboratory floor). Cybersickness severity (FMS) and vection

strength measures were taken every 2 minutes during each trial. Directly after leaving HMD VR, their post-exposure cybersickness symptomology was then assessed using the SSQ and participants also provided an overall rating of vection strength for the trial. Finally, they verbally responded to our three exploratory questions about the nature of their experiences of vection during HMD VR.
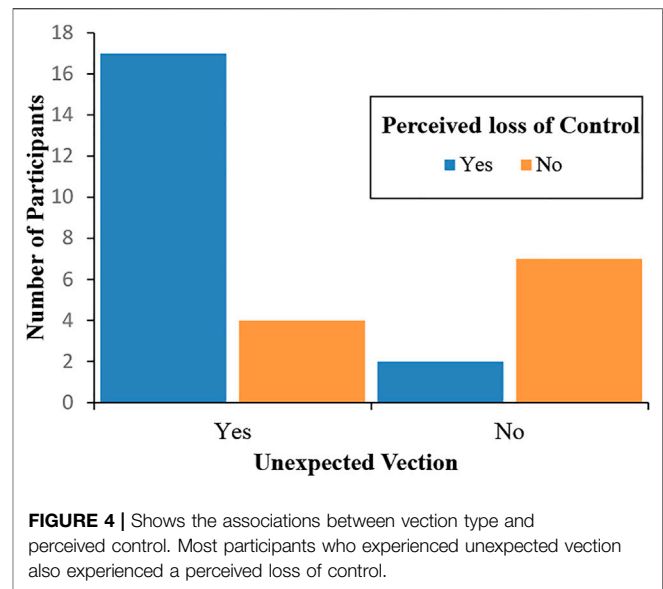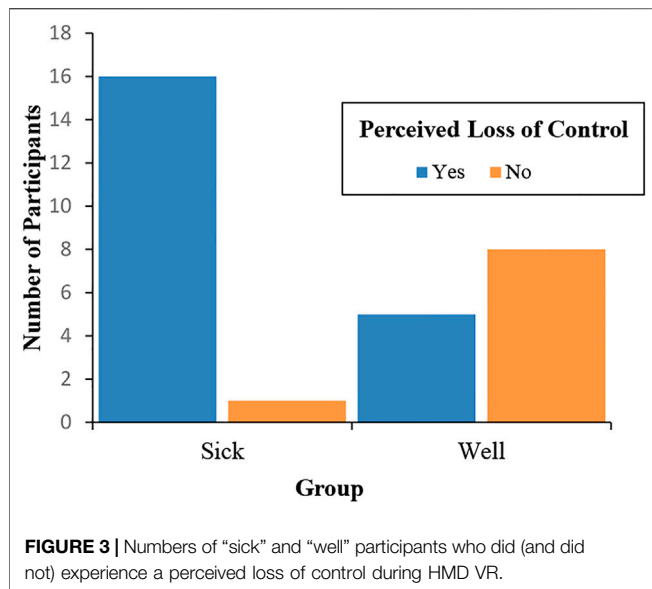
2.4 Data Analysis

Data from all 30 participants (15 females, 15 males) are included in the analyses below. Assumption testing was performed as appropriate for all analyses[4] and post-hoc power estimations are included throughout the results section.[5]

To check on the success of our classification of participants into sick and well groups, we conducted an independent samples *t*-test on the average FMS scores for these two groups (one of our two sickness severity measures). As the assumption of normality was violated for our other sickness severity measure (the SSQ Total scores), a Yuen's trimmed means test was conducted (bootstrapped at 1,000 samples) to assess the difference between sick and well groups on these post-pre SSQ-T scores.

We explored the possible relationships between vection and sickness a number of different ways. We initially used a Pearson's chi-square test of contingencies to assess whether experiences of perceived loss of control/unexpected vection were related to the likelihood of developing cybersickness [Analyses were conducted with IBM SPSS Statistics, with significance level set at alpha = 0.05]. We also performed an independent samples *t*-test to compare the average vection strength ratings for sick and well participants. Then a linear mixed model (jamovi 1.6.23, GAMLj package) was used to test our hypothesis that there would be a positive linear relationship between vection strength and cybersickness severity for sick participants. To investigate whether a non-linear model might provide more predictive power, we also used a Pascal distribution model (jamovi 1.6.23, GAMLj package) in our follow up analysis. Finally, we

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[4]The exploratory nature of this study warranted a large number of statistical analyses (9). While the *p*-values reported in this paper were not corrected for multiple comparisons, all that were interpreted as significant ranged from 0.001 to 0.002. Thus, they would have remained significant even if stringent Bonferroni correction had been applied. The only exceptions were: 1) the linear relationship between VectionSTR and cybersickness severity for the well group (linear-mixed model) with *p* = 0.42. However, we demonstrated that a non-linear model was more appropriate for our data; and 2) the Pearson correlation between vection change and drop out times with *p* = 0.009. For this test, we indicated that the finding needed to be interpreted with caution (note after stringent correction this test still indicated a tendency with *p* = 0.08).

[5]Power analysis is notoriously challenging for generalised mixed models and requires simulations that are beyond the scope of this study (which currently includes several sophisticated analysis methods). To increase the robustness of our mixed-model analyses, we used bootstrapping with 1,000 re-samples. Based on our sample size, a conventional *t*-test should be able to detect effect sizes of 0.94 or larger (with α = 0.05, 1-β = 0.8). However, mixed-effects analyses are more powerful than analyses based on conventional t and F tests (Judd et al., 2017; Brysbaert and Stevens, 2018) or chi-square analyses (Miller, Roe, Hu & Bell, 2020). Thus, our mixed models analyses should have been able to detect effect sizes less than 0.9.

FIGURE 3 | Numbers of "sick" and "well" participants who did (and did not) experience a perceived loss of control during HMD VR.

FIGURE 4 | Shows the associations between vection type and perceived control. Most participants who experienced unexpected vection also experienced a perceived loss of control.

used random forest classification with JASP 0.14.1 (see the r package randomForest for more details: https://cran.r-project. org/web/packages/randomForest/randomForest.pdf) to determine whether machine learning methods would allow us to predict a participant's Sick/Well group status based only on their vection type (expected/unexpected) and their maximum vection strength rating.[6]

Finally, we ran generalised mixed model analyses (jamovi 1.6.23, GAMLj package) to explore how vection strength and cybersickness severity ratings changed over time. We also used a Pearson correlation to look for possible relationships between vection strength and premature dropout times (due to sickness).

3 RESULTS

3.1 Cybersickness Data
3.1.1 Cybersickness Incidence and Symptomology
Participants were classified as either being "sick" or "well" based on their answers to the question: "Do you feel sick?" Seventeen of them responded "yes" to this question and the remaining 13 responded "no". The SSQ's three sub-scores were used to assess their nausea (SSQ-N), disorientation (SSQ-D) and oculomotor (SSQ-O) symptoms. To examine the changes in each of these symptoms over the course of the HMD VR exposure, we subtracted each participant's pre-exposure sub-scores from their post-exposure sub-scores (**Figure 1**). As expected for HMD VR, we found that these post-pre scores were higher on average for the SSQ-D ($M = 68.21$, $SD = 54.51$) than for the SSQ-N ($M = 48.65$, $SD = 33.27$) and the SSQ-O ($M = 37.142$, $SD = 29.14$).

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[6]To be consistent with the previous analysis, and to minimise the BIC and AIC, we used generalised mixed models with Pascal distributions and random intercepts to investigate how vection and cybersickness both developed/evolved over time.

3.1.2 Checking Cybersickness Severity in "Sick" and "Well" Groups
To check on the success of our classification of participants into "sick" and "well" groups, we conducted an independent samples *t*-test on the average FMS ratings for the two groups. As expected, average FMS ratings were significantly higher for the 17 "sick" participants ($M = 6.42$, $SD = 3.78$) compared to the 13 "well" participants ($M = 2.12$, $SD = 1.71$, $t(29) = 3.81$, $p < 0.001$, $d = 1.40$, $1-\beta = 0.96$). As the assumption of normality in our sample was violated, Yuen's trimmed means test was conducted bootstrapped at 1,000 samples to assess the difference between "sick" and "well" groups' post-pre SSQ-T scores. The "sick" participants were found to have significantly higher post-pre SSQ-T scores ($M = 76.12$, $SD = 39.73$) compared to the "well" participants ($M = 29.06$, $SD = 18.83$, $t(17.6) = 3.64$, $p = 0.001$, $\xi = 7.16$, $1-\beta = 0.97$).

3.2 Group Differences in Vection Type and Perceived Control
3.2.1 Incidence of Unexpected Vection in "Sick" and "Well" Groups
Of our 17 "sick" participants, 15 indicated that they had also experienced unexpected vection during HMD VR. By contrast, of our 13 "well" participants, only 4 indicated that they had experienced unexpected vection. We used a Pearson's chi-square test of contingencies (with $\alpha = 0.05$) to assess whether experiences of unexpected vection were related to the likelihood of developing cybersickness. This test was found to be statistically significant ($\chi^2 (1) = 30) = 10.48$, $p = 0.001$, $1-\beta = 0.90$) – with the association between unexpected vection and the incidence of cybersickness being large ($\phi = 0.59$). As illustrated in **Figure 2**, participants who reported unexpected vection were significantly more likely to also report becoming sick (compared to participants who always reported that their vection was expected).
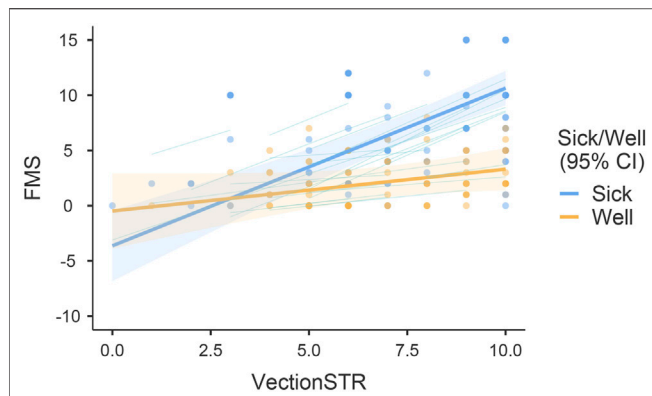
FIGURE 5 | Modelled linear relationships between vection strength (VectionSTR) and cybersickness severity (FMS) for the "sick" and "well" groups.
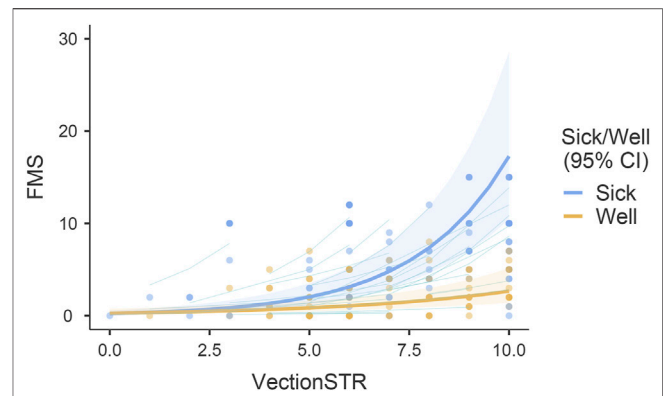

FIGURE 6 | Modelled non-linear (exponential) relationships between vection strength (VectionSTR) and cybersickness severity (FMS) as a function of sick/well grouping.

3.2.2 Likelihood of Experiencing a Perceived Loss of Control in "Sick" and "Well" Groups

Of our 17 "sick" participants, 16 reported they had also experienced a perceived loss of control prior to sickness during HMD VR. By contrast, of our 13 "well" participants, only 5 reported that they had experienced a perceived loss of control. We used a Pearson's chi-square test of contingencies (with $\alpha = 0.05$) to assess whether such experiences were related to the likelihood of developing cybersickness. This test was found to be statistically significant ($\chi^2 (1) = 10.87, p = 0.001, 1\text{-}\beta = 0.90$) – with the association between perceived loss of control and cybersickness being large ($\phi = 0.6$). As illustrated in **Figure 3**, participants who reported a perceived loss of control were significantly more likely to also report becoming sick (compared to participants who always felt that they were in control of their perceived movement).

3.2.3 Associations Between Vection Type and Perceived Control

We used Pearson's chi square test of contingencies (with $\alpha = 0.05$) to assess whether experiences of unexpected vection were related to participant perceptions of control. This test was found to be statistically significant ($\chi^2 (1) = 9.34, p = 0.002, 1\text{-}\beta = 0.87$) – with the association between unexpected vection and perceived loss of control being large ($\phi = 0.56$). As illustrated in **Figure 4**, participants who reported unexpected vection were significantly more likely to also report a perceived loss of control (compared to participants who always reported their vection was expected).

3.3 Relationship Between Vection Strength and Cybersickness Severity

We initially performed an independent samples *t*-test to compare the average vection strength ratings of our "sick" and "well" participants. The 17 "sick" participants ($M = 7.39, SD = 2.13$) did not report significantly stronger experiences of vection compared to the 13 "well" participants ($M = 6.79, SD = 1.73$), $t(29) = 0.83$, $p = 0.41, d = 0.31$. Thus, these groups did not appear to differ in terms of the average strength of their vection. Rather, they differed primarily in terms of types of vection that they

experienced (whether it was expected or unexpected - see **Section 3.2.1**).

3.3.1 Testing for Linear Relationships Between Vection Strength and Cybersickness Severity

We next used a linear mixed model to test our hypothesis that there would be a positive relationship between vection strength and cybersickness severity for the "sick" participants. Cybersickness severity (as measured by the FMS) was modelled in terms of the reported vection strength (VectionSTR), the participants' sickness grouping (Sick/Well) and their interaction as fixed effects (with random intercepts across participants):

$$\text{FMS} \sim 1 + \text{VectionSTR} + \text{Sick/Well} + \text{Sick/Well: VectionSTR} + (1\text{ID})$$

Compared to models with random slopes, the above model had lower Akaike's Information Criteria (AIC) and Bayesian Information Criteria (BIC). This revealed a significant interaction between VectionSTR and Sick/Well, $F(1,195) = 18.32, p < 0.001$. Thus, the main effects of Sick/Well and VectionSTR on cybersickness severity were not investigated further. Simple effects confirmed that there was a stronger positive linear relationship between VectionSTR and cybersickness severity for those in the "sick" group ($F(1,204) = 90.81, p < 0.001$, coefficient = 1.368) compared to the "well" group (where the relationship only just reached significance - $F(1,204) = 4.18, p = 0.042$, coefficient = 0.383, note: this relationship would not have reached significance with Bonferroni correction) (**Figure 5**). Indeed, the coefficients indicate that the estimated influence of vection strength on cybersickness was 3.57 times larger in the "sick" group than in the "well" group.

3.3.2 Testing for Non-linear Relationships Between Vection Strength and Cybersickness Severity

To investigate whether a non-linear model might provide more predictive power, we used a Pascal distribution model in our follow up analysis. Cybersickness severity (as measured by the

TABLE 1 | Evaluation metrics.

	Precision	Recall	F1 Score	Support	AUC
Sick	0.778	0.875	0.824	8	0.857
Well	0.833	0.714	0.769	7	0.857
Average/Total	0.804	0.800	0.798	15	0.857

Note. Precision is the number of correctly identified members of a class divided by all the times the model predicted that class. Recall is the number of members of a class that the classifier identified correctly divided by the total number of members in that class. The F1 score combines precision and recall into one metric. Support is the number of class observations in the test set. Area Under Curve (AUC) is calculated for every class against all other classes.

FMS) was again modelled in terms of the reported vection strength (VectionSTR), the participants' sickness grouping (Sick/Well) and their interaction as fixed effects (with random intercepts across participants):

$$FMS \sim 1 + VectionSTR + Sick/Well + Sick/Well: VectionSTR + (1ID)$$

Based on the Bayesian information criterion, this non-linear model was superior to the linear model described in **Section 3.3.1** (with a BIC of 907.092 as opposed to 1,027.058). As illustrated in **Figure 6**, this revealed a significant interaction between VectionSTR and Sick/Well grouping, $\chi^2 (1) = 6.967$, $p = 0.008$. Thus, the main effects of Sick/Well grouping and vectionSTR on FMS were not investigated further. The simple effects of vectionSTR, and their effect sizes, confirmed a stronger positive relationship between VectionSTR and cybersickness severity for those in the "sick" group ($\chi^2 (1) = 89.2$, $p < 0.001$, estimate = 0.427, very large effect size $\varphi = 0.89$) compared to the "well" group ($\chi^2 (1) = 13.9$, $p < 0.001$, estimate = 0.227, medium effect size $\varphi = 0.39$).

3.3.3 Predicting Sick/Well Grouping Based on Vection Strength and Vection Type (Expected/Unexpected)

Finally, we used random forest classification to assess whether machine learning methods would allow us to predict a participant's Sick/Well group status based only on their vection type (expected/unexpected) and their maximum vection strength rating (training set 50%, test set 50%, 50 trees). The evaluation metrics revealed that our model performed strongly (**Table 1**). Its prediction accuracy was found to be very high at 80% (AUC = 0.857) – based solely on these two vection-based predictor variables. Accuracy and

node purity indicated that unexpected vection was much more important than vection strength in predicting the Sick/Well group membership (**Table 2**). Please see additional details about the model's performance in **Table 3** and **Figure 7**.

3.4 Exploring Changes in Vection and Cybersickness Over Time

After investigating the effects of vection type and strength on cybersickness for "sick" and "well" participants, we wanted to further understand how vection and cybersickness both developed/evolved over time. We were especially interested in understanding how changes in vection strength over the VR exposure were related to participant dropout times. To be consistent with the previous analysis, and to minimise the BIC and AIC, we used generalised mixed models with Pascal distributions and random intercepts.

3.4.1 Changes in Vection Strength Over Time

We ran a generalised mixed model to investigate how vection strength (vectionSTR) changed over time. In this model, time in trial (Time), participants' sickness grouping (Sick/Well) and their interaction were entered as fixed effects (with a random intercept per participant):

$$VectionSTR \sim 1 + Sick/Well + Time + Sick/Well: Time + (1ID)$$

As can be seen in **Figure 8** there was a significant effect of Time on vection strength, $\chi^2 (1) = 17.2132$, $p < 0.001$. Consistent with the statistical analyses reported above, the effect of Sick/Well grouping on (general) vection strength was again not significant.

3.4.2 Changes in Cybersickness Severity Over Time

We also ran a generalised mixed model to investigate how cybersickness severity (FMS) changed over time. In this model, time in trial (Time), participants' sickness grouping (Sick/Well) and their interaction were entered as fixed effects (with a random intercept per participant):

$$FMS \sim 1 + Sick/Well + Time + Sick/Well: Time + (1ID)$$

As illustrated in **Figure 9**, we observed a significant interaction between Time and Sick/Well grouping on cybersickness severity, $\chi^2 (1) = 5.05$, $p < 0.025$. Simple effects confirmed that there was a much stronger positive relationship between Time and cybersickness severity for the "sick" group ($\chi^2 (1) = 154.5$, $p <$

TABLE 2 | Variable importance.

	Mean decrease in accuracy	Total increase in node purity
Vection Type (expected/unexpected)	0.120	0.255
Vection Strength (Maximum Rating)	−0.017	0.081

Note. Larger values in accuracy decrease (% increase in mean squared error when the variable is excluded) and node purity increase (decrease in Gini impurity when a variable is chosen to split a node in the forest) indicate a larger importance of the variable.

TABLE 3 | Confusion matrix between predicted and observed group in the test set.

	Predicted	
	Sick	**Well**
Observed	7	1
Well	2	5

Note. This confusion matrix includes only the 15 participants of the test set (i.e., 50% of the overall data) on which the random forest predictions were assessed. The other 15 participants' data was used to train the model.
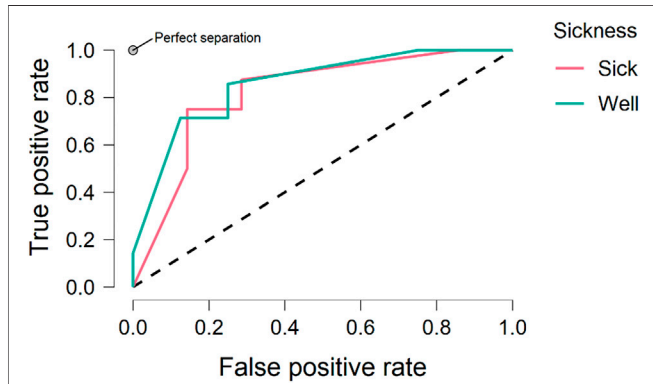

FIGURE 7 | Receiver operating curve (ROC) plots showing the performance of our vection-based model at all classification thresholds in terms of predicting Sick/Well group membership.
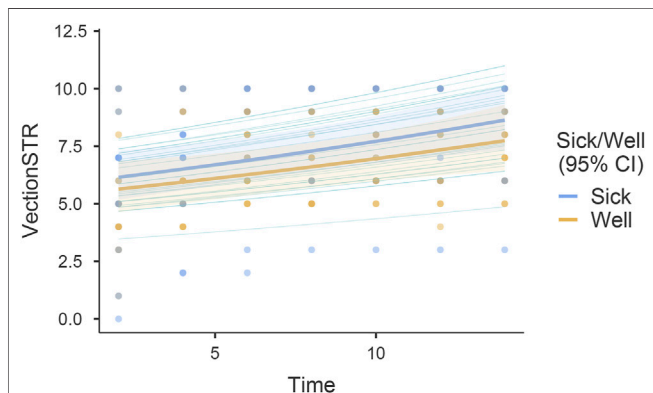

FIGURE 8 | Shows vection strength ratings (VectionSTR) as a function of time in trial (Time) and participant Sick/Well grouping.

0.001, estimate = 0.1158) compared to the "well" group (χ^2 (1) = 14.6, p < 0.001, estimate = 0.0698).

3.4.3 Relationship Between Vection Change and Drop out Times

As an additional exploratory analysis, we used a Pearson correlation to examine the possible relationship between vection strength and premature dropout times (due to sickness). We first calculated the change in vection strength
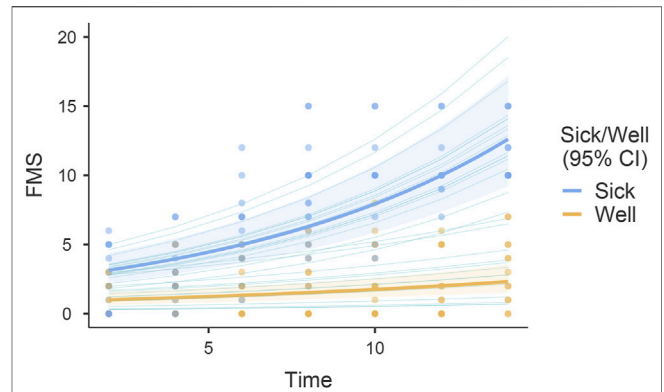

FIGURE 9 | Shows cybersickness severity (FMS) as a function of time in trial (Time) and participant Sick/Well grouping.

across the entire HMD VR exposure (until premature dropout due to sickness). We found a significant positive correlation between our "sick" participants' vection change scores and their premature dropout times (r(13) = 0.62, p = 0.009, 1-β = 0.62). Specifically, we found that "sick" participants who dropped out later in the session were more likely to experience larger changes in vection over the course of their HMD VR exposure. However, with the very stringent Bonferroni correction, the p-value would be 0.08 so this finding needs to be interpreted with caution.

4 DISCUSSION

This study examined the following hypotheses: 1) unexpected vection is a necessary prerequisite for cybersickness; and 2) cybersickness severity increases with the strength of this unexpected vection. Below we review the empirical support for each hypothesis. We also discuss additional exploratory analyses which examined how vection strength and cybersickness severity evolved together over time.

4.1 Could Unexpected Vection Be a Prerequisite for Cybersickness?

Consistent with the first hypothesis, we found that participants who became sick were significantly more likely to experience unexpected vection compared to those who remained well. Unexpected vection was reported by 88% of our "sick" participants, but only by 31% of our "well" participants. In addition, when our current data were subjected to machine learning analysis (random forest classification), we found that unexpected vection was the most important variable in predicting participant sickness status.

These results also appear to be highly compatible with the driver/passenger effects on motion sickness reported in past studies (with drivers–who have more knowledge about future self-motions, as they are in control of their self-motion–being less likely to report becoming sick). This led us to also check on

whether our "sick" participants were more likely to report a perceived loss of control during HMD VR in the current study. A perceived loss of control was reported by 94% of our "sick" participants, but only by 38% of our "well" participants. These findings suggest that experiences of unexpected vection are highly likely to be accompanied by a perceived loss of control.

4.2 Does Cybersickness Severity Increase With the Strength of Unexpected Vection?

Consistent with our second hypothesis, we found evidence of significant positive relationships between vection strength and cybersickness severity. Many studies have searched for linear scaling relationships between vection and VIMS/cybersickness. Despite the mixed findings in the past literature, we found evidence of a significant positive linear relationships between vection strength and cybersickness severity in both our "sick" and "well" participants, with a much stronger effects seen for the "sick" participants. However, while there were monotonic relationships between vection strength and cybersickness severity, the best model fits for these relationships were found to be non-linear/exponential (as opposed to linear) in nature. Using non-linear (Pascal distribution) based fits in our models, we confirmed significant positive relationships between vection strength and cybersickness severity for both "sick" and "well" participants. Critically, the effect of vection strength was still substantially stronger for our "sick" (compared to our "well") group participants.

As noted above (and shown in our chi squared analysis), participants who reported becoming sick almost exclusively experienced unexpected vection. This suggests a strong, but non-linear relationship between the strength of their (unexpected) vection and the severity of their cybersickness. While a significant relationship between vection strength and cybersickness severity was also found for our "well" participants–these effects appear to have been driven primarily by the 4 of these 13 participants who reported unexpected vection. As can be seen in **Figure 6**, cybersickness severity appeared to jump quite markedly after vection ratings exceed 5 out of 10. This suggests that the strength of the participant's (unexpected) vection needed to reach a critical value before their sickness levels became problematic.

4.2.1 What Types and Strengths of Vection Might Cause Significant Cybersickness?

Interestingly, average vection strength did not differ significantly between the "sick" and "well" participant groups. This shows that it is not vection strength alone that determines the severity of the cybersickness experienced in HMD VR. The nature/type of vection experienced also appears to be important: that is, whether it is expected/unexpected and perceived to be under the user's control or not. Crucially, this suggests that not all experiences of compelling vection should be provocative of cybersickness. However, increasing the strength of more provocative types of vection may increase the severity of cybersickness.

Machine learning classification using random forests showed that vection type and vection strength alone reliably predicted

sick/well group status with a high level of accuracy. Moreover, this analysis revealed that vection type (expected/unexpected) was more important for correct predictions than reported vection strength. This finding opens exciting applications for predicting cybersickness during HMD VR. However, given the small size of our sample, we need to use caution and these findings would need to be corroborated with a larger dataset.

4.2.2 Reconciling Current Findings With Vection Conflict Theory and Other Findings

Proponents of the *vection conflict theory* often assume that: 1) vection is a necessary pre-requisite of cybersickness (Hettinger et al.'s, 1990 original hypothesis), or 2) there is a scaling relationship between vection strength and cybersickness severity (a modified variant of the vection conflict hypothesis, which has been tested by most studies examining VIMS and cybersickness). In the past, consistent support for these proposals has been difficult to find. The current findings provide potential explanations for how those mixed findings could have arisen. Past studies looked for positive linear relationships between vection strength and cybersickness severity. However, our results revealed positive monotonic relationships between vection strength and cybersickness severity that were best described by non-linear/exponential model fits. Furthermore, they showed evidence of a thresholding process–whereby the participants' vection strength had to reach a certain critical level before significant increases in cybersickness severity were seen. Finally, our results showed that the type of vection (expected/unexpected) experienced also matters. That is, we found that unexpected vection appears to be particularly provocative for cybersickness. When taken together, these findings suggest that a certain critical amount of unexpected vection might be required to cause problematic levels of sickness (i.e., sufficient to cause them to leave/drop out of HMD VR). The existence of such a critical threshold appears to be somewhat compatible with Hettinger et al.'s (1990) original *vection conflict theory*.

4.3 Vection Change and Dropout Times

While we have provided evidence of general relationships between vection strength and cybersickness severity, it is also important to understand how these user experiences change/develop over time. As expected (based on the findings of past studies - e.g., Seno et al., 2018), vection strength was found to increase with longer exposures to HMD VR. These increases in vection strength as a function of time were found to be similar in both "sick" and "well" participants (no interaction). Cybersickness severity was also found to increase in a similar fashion with time in trial–but more so for the "sick", compared to the "well", participants (note: these findings are compatible with those of several recent HMD VR studies - e.g., Risi and Palmisano, 2019; Clifton and Palmisano, 2019; Teixeira and Palmisano, 2021). The simplest interpretation of these findings is that the longer "sick" participants experienced (predominately) unexpected vection, the stronger this vection became and the more severe the cybersickness it caused. By contrast, our "well" group participants mostly experienced expected vection.

Although the strength of this expected vection also increased over time, it had less effect on experiences of cybersickness.

An exploratory correlational analysis found that participants who dropped out later were more likely to experience larger changes in vection across their HMD VR exposure (compared to those who dropped out earlier). This finding may simply indicate that longer exposures to HMD VR allowed the participant's vection strength to build up more. However, it may also reflect individual differences in their vection responding. Vection onset latencies can vary considerably across individuals, and in addition to this, the rate at which this vection builds can differ markedly (even when observers are presented with exactly the same vection stimulus - see Seno et al., 2017). "Sick" participants who dropped out later in our study could have had longer vection onsets and slower rates of vection increase (compared to "sick" participants who dropped out earlier in the session). These participants might have required much larger changes in (unexpected) vection strength to result in problematic levels of cybersickness. Even though some of our "well" participants also experienced large changes in vection, it appears that these changes were usually expected, and not linked to a perceived loss of control. As such, they appeared to have no significant bearing on the levels of cybersickness experienced–and therefore rarely led to participant dropouts.

4.4 Implications and Relevance of Findings

Compelling vection is a common experience during HMD VR. While these illusions of self-motion have traditionally been seen as a problem to be avoided (in both theory and practice), they can often dramatically improve user experiences in HMD VR. For example, research suggests that vection can lead to greater feelings of presence and immersion within virtual environments (Riecke et al., 2006; Keshavarz et al., 2019). Indeed, compelling vection is often essential for effective first-person vehicle simulation during HMD VR. Thus, understanding the effects of vection on HMD user experiences is clearly of great importance for the further development of VR systems and applications.

The findings of the current study challenge the belief that compelling vection should be avoided in HMD VR. While they do provide evidence that certain *types* of vection are more strongly associated with incidence of cybersickness (namely *unexpected vection* and vection that results in a perceived *loss of control*), they also show that compelling vection can be induced in some individuals with no unpleasant consequences. As such, we propose that only *unexpected vection* should be avoided to minimise incidence of cybersickness. In practical terms, the findings of this study suggest that software designers should attempt to avoid inducing unexpected vection and aim to minimise perceived losses of control in self-motion situations.

The current findings also suggest that caution should be exercised when interpreting relationships between cybersickness and vection. Previously, support for a positive scaling relationship between vection strength and cybersickness severity has been inconsistent. However, these studies generally assumed that relationships between these two variables would be linear in nature. Instead, our findings suggest

that non-linear models might be better at capturing the actual relationships between vection strength and cybersickness severity. This would also explain the mixed findings of previous studies. Future studies are therefore needed to rigorously examine the relationships between these two variables. If a clear link between specific vection types/experiences and cybersickness can be found, this will allow designers to freely explore the use of vection as a tool in future programming and design, opening further avenues to enhance presence, as well as the fidelity, realism and the quality of the sensory stimulation provided by HMD VR.

4.5 Limitations

While the current findings appear promising, this was an exploratory study, and our findings were correlational in nature. We acknowledge that with our design there was a risk that expected/unexpected and perceived loss of control responses might have been influenced by demand characteristics. Vection type (expected or unexpected) was only assessed at the end of the VR exposure (either after 14 min or when they dropped out). Asking such questions then (as opposed to earlier) was aimed at reducing the influence of demand characteristics. However, this decision may have placed more demands on participant memory for this dependent measure.[7] Studies are therefore still needed to test our hypotheses about the effects of unexpected and uncontrolled vection on cybersickness using deliberate experimental manipulations. For example, future studies could experimentally manipulate controller gain during simulated HMD VR driving, or verbally prime participants to expect a direction of self-motion either consistent/inconsistent with the visual simulation, or alter the velocity of the user's vection at pre-determined and timestamped intervals [to examine the effects of unexpected (versus expected) vection on cybersickness directly]. It may also be the case that our findings (of relationships between vection strength and type and sickness) are restricted to HMD VR simulations of self-motion in microgravity. As such, their generalizability to other HMD VR simulations also needs to be demonstrated in future studies.

In the current study, participants who reported unexpected vection were significantly more likely to also report a perceived loss of control (compared to participants who always reported that their vection was expected). While there is likely a relationship between these two experiences/perceptions, future studies should try to tease apart their independent contributions to cybersickness. Previously, there have been reported differences in cybersickness during active and passive VR exposures to the same applications/optic flow (Rebenitsch and Owen, 2016). Importantly, such differences in sickness cannot be explained based on visual motion alone.

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[7]Debriefing indicated that experiences of unexpected vection were often very salient (hard to forget). For example, it was common for participants reporting unexpected vection to say they had "stopped thrusting [or pulling] to avoid hitting a looming wall [ceiling or floor]", but despite this, they were still on a collision course towards the surface (as they were simulated to be moving in a microgravity environment).

Finally, if cybersickness is exacerbated by unexpected vection and/or a perceived loss of control (as the current data points towards), we would also expect physiological reactions to these events. Thus, we recommend future studies also try to obtain independent objective evidence that the vection was indeed unexpected (e.g., using physiological indices such as skin conductance, eye movements, heart rate variability or even EEG) or indices of postural sway to indicate perceived loss of control. Ideally, some or all of these proposed objective vection indicators should be obtained in future studies (although traditional subjective vection measures will still be required for confirmation). While we only examined hypotheses related to *vection conflict theory*, our results could conceivably also be explained based on *postural instability theory*. It was possible that reports of vection/unexpected vection in our study were actually the conscious experiences associated with changes in postural activity. Thus, the sickness experienced might have actually been caused by increases in participant postural instability. However, since their postural responses were not recorded during these HMD VR exposures, this possibility will need to be assessed in a future study.

5 CONCLUSION

This study is the first to investigate the effects of unexpected vection on cybersickness when playing a commercially available HMD VR game. We found that: 1) "sick" participants were significantly more likely to experience both unexpected vection and a perceived loss of control (compared to participants who reported that they remained well); and 2) our vection strength and vection type predictors were able to explain cybersickness incidence with an accuracy of 83.3%. While average vection strength was not found to differ significantly for "sick" and "well" groups, cybersickness severity was found to scale with

vection strength–especially for the "sick" group. These findings show that compelling vection alone is not sufficient as a prerequisite of cybersickness. We conclude that unexpected vection and a perceived loss of control increase the likelihood and severity of cybersickness. Since vection is a prevalent (and in many cases a desirable) aspect of HMD-VR, further research is needed to explore this *unexpected vection hypothesis* in greater depth.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Wollongong Human Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JT, SM and SP formed the original conceptualization for the study. JT collected the data. JT, SM and SP analysed the data, interpreted the results and wrote the article.

FUNDING

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