CYBERSICKNESS IN VIRTUAL REALITY VERSUS AUGMENTED REALITY

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CYBERSICKNESS IN VIRTUAL REALITY VERSUS AUGMENTED REALITY

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EDITORIAL
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Editorial: Cybersickness in Virtual Reality and Augmented Reality

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Keywords: cybersickness, virtual reality, augmented reality, postural instability, vection, adverse aftereffects, simulator sickness, visual acuity in head mounted displays

Editorial on the Research Topic

Cybersickness in Virtual Reality and Augmented Reality

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INTRODUCTION

Early virtual reality (VR) systems introduced abnormal visual-vestibular integration and vergence-accommodation, causing cybersickness (McCauley and Sharkey, 1992) reminiscent of simulator sickness reported by military pilots, e.g., having some shared causes and overlapping (Lawson, 2014a) but distinguishable symptoms (Stanney et al., 1997). Improved processing, head tracking, and graphics were expected to overcome cybersickness (Rheingold, 1991), yet it persists in today's much-improved VR (Stanney et al., 2020a, 2020b). This must be resolved, because VR and Augmented Reality (AR)[1] are proliferating for training for stressful tasks, exposure therapy for post-traumatic stress, remote assistance/control, and operational situation awareness (Hale and Stanney, 2014; Beidel et al., 2019; Stanney et al., 2020b, 2021; NATO Science and Technology Office, 2021).

Experts considered the cybersickness problem recently at a *2019 Cybersickness Workshop*[2] and a 2020 *Visually-Induced Motion Sensations* meeting.[3] Military aspects were discussed during 2019–2021 meetings of a *Cybersickness Specialist Team* (NATO Science and Technology Office, 2021). The *Bárány Society's Classification Committee* just developed relevant international symptom standards for visually-induced motion sickness (VIMS; Cha et al., 2021). Finally, >40 authors produced twelve articles comprising this *Frontiers* Research Topic initiated by Dr. Stanney. Below, we summarize their work and provide recommendations.

COMMENTS ON THE 12 TOPIC ARTICLES

Three Articles Explored The Benefits Of Ambient Or Earth-Referenced Visual Cues

1) Hemmerich et al. found that an Earth-fixed visual horizon (but not a non-horizon cue) significantly reduced cybersickness.[4] 2) Shahnewaz Ferdous et al. posited that Earth-stable cues

[1]AR overlays virtual images on a partial view of the real world. While AR often causes less visual-vestibular conflict, vergence-accommodation problems may persist.

[2]https://s2019.siggraph.org/conference/programs-events/organization-events/frontiers-workshops/cybersickness-causes-and-solutions/

[3]https://ieda.ust.hk/dfaculty/so/VIMS2020/

[4]A VR was used. Our recommendations for futures studies of this type are at the end of this editorial.

introduced into VR or AR (via a partial virtual frame) should improve balance and lessen cybersickness. They discussed two small studies of balance-impaired VR/AR users. Their VR study detected a cueing difference for two balance measures and the Simulator Sickness (SSQ) Disorientation measure[5], while their AR study (which allowed sight of the room) detected a difference in one balance measure but no SSQ measures. Benefits were seen only with balance-impaired subjects. While the findings were mixed, an appropriately-designed Earth-referenced cue should aid orientation. Expanded studies of this type should compare similar VR-versus-AR fields of view. Finally, 3) Cao et al. provided VR users with Earth-stable granulated peripheral cues that allowed some peripheral vision, which improved visual target searching better than restricting field-of-view (FOV), a typical countermeasure. Could this approach also mitigate cybersickness better than FOV restriction?

Two Articles Discussed Aspects Of Tracking Latency As A Cybersickness Contributor

4) Stauffert et al. explored cybersickness implications of latency between the movement of a tracked object and its movement on a head-worn display. They provided information to assist in assessing latency, and stressed the need for comparable assessments. 5) Palmisano et al. posited that a key (and readily quantifiable) contributor to cybersickness is a large, temporally inconsistent difference between actual and virtual head position. Their findings are relevant to Moss et al. (2011), who found that varying head tracking latency was sickening. As many studies have observed that visually-moving fields elicit symptoms even when the head is still (e.g., Webb and Griffin, 2002), however, the contribution of visual field motion versus head position/motion conflict should be studied.

Three Articles Explored Additional Effects Of Head Motion, Head Orientation, Or Head-Mounting Of Displays

6) Kim et al. posited that linear head oscillations increase sensory conflict in VR devices that only track angular motion. While they failed to detect device-related differences in perceived scene stability, spatial presence, or cybersickness, this was a creative pilot study exploring implications of different tracking devices. 7) Wang et al. confirmed that vection (the illusion of self-motion) elicited by viewing a rotating dot pattern was stronger when concordant with expected graviceptive cues. VR/AR designers should know that when vection is desired, its direction should not contradict somatosensory/vestibular cues that would be present during real motion. Also, specific motion/orientation perceptions will tend to be altered to minimize sensory conflict (Young et al., 1975; Lackner and Teixeira, 1977; Dizio and Lackner, 1986; Howard et al., 1987; Golding, 1996; Tanahashi et al., 2012). The notion that vection can reduce sickening conflict is better supported than vection as a cause of sickness (Lawson, 2014a; Stanney et al., 2020b). Finally, 8) Hughes et al. evaluated head-worn versus tablet-based AR during tactical combat casualty training. They observed greater sickness with head-worn AR, but symptoms for both devices were mostly limited to the Oculomotor cluster of the SSQ, with little Nausea. Moreover, while subjects in the head-worn condition completed fewer training scenarios in the time allotted, they had more correct responses in completed scenarios. AR could be a less-sickening training approach, and solutions to mitigate oculomotor disturbances would make it even better.

Three Articles Explored The Role Of Active Sensorimotor Engagement Or Maintenance Of Postural Equilibrium

9) Curry et al. evaluated participants in a head-worn racing game. They did not detect main differences in cybersickness between active drivers versus passengers. The reasons for this should be explored, as a difference has been observed in other contexts (Rolnick and Lubow, 1991; Stanney and Hash, 1998; Seay et al., 2002; Sharples et al., 2008). 10) Weech et al. found a correlation between visually-influenced body sway (reflected by the center-of- pressure [COP] ratio)[6] and SSQ Disorientation and Oculomotor sub-scores in a VR. It makes sense for the Disorientation score to be related to sway; expanded studies should determine if COP ratio correlates with SSQ Total Sickness or Nausea scores, as these are likely to predict quitting a training session. Finally, 11) Jasper et al. evaluated the efficacy of different cybersickness recovery strategies. Their study elicited sufficient cybersickness (Stanney et al., 2003). Greatest recovery was observed for resting with the VR off (real natural decay), while doing a virtual hand-eye task yielded the least recovery. We agree with the authors' implication that administration of the SSQ during VR/AR should be explored further.

Three Studies Addressed The Role Of Individual Cybersickness Susceptibility (Two Of Which Were Mentioned Immediately Above)

12) Golding et al. found that sickness severity in a moving visual surround is predicted by history of susceptibility to motion sickness, migraine, and fainting. They did not detect a relationship between sickness and vection, adding to the

[5]Four measures are yielded by SSQ (Total Sickness Score, Disorientation score, Nausea Score, and Oculomotor score) (Kennedy et al., 1993). Five within-device balance-related measures were tried (two sway measures, one sway-driven dodgeball task, and one questionnaire).

[6]Defined as the amount of sway associated with visual scene oscillation, where a high ratio implies an inability to down-weigh visual information and is a hypothesized cybersickness contributor.

TABLE 1 | Twelve Research Topic Publications (by Number), and their Links to Etiological Hypotheses.

Hypotheses	I. Sensory conflict (and variants)	II. Postural instability	III. Eye movement	IV. Evolutionary (and variants)
Publication	#1–5; 7; 9–11	#7, 9–10	#6–8; 10	#9, 11, 12
Comment	Relevant variants: frame-of-reference (#1–3), neural mismatch (#4–5[9]; 7, 11), reweighting/ development (#9–10)	Possible or direct relevance	Possible relevance during certain self/ scene motions, oculomotor reactions	Possible relevance for individual differences; partially related to evolution

many studies failing to find this relation (Lawson, 2014a; Stanney et al., 2021).[7] Consistent with the literature (Lawson, 2014a; Stanney et al., 2020a), the aforementioned article #11 by Jasper et al. and #9 by Curry et al. observed mixed findings concerning sex as a factor in cybersickness susceptibility. Jasper et al. observed that women reported more cybersickness, but this was confounded by women having less experience with video games. The sex difference detected in Curry et al. was solely among the subset of subjects who discontinued participation early, wherein women quit earlier when driving, but not when passengers. Future studies of individual cybersickness differences should estimate variance accounted for by experience with motion sickness, driving, video games, and head-worn displays.

CAUSAL HYPOTHESES RELEVANT TO THE 12 TOPIC ARTICLES

While the explanatory capabilities of a complete motion/ simulator/cybersickness theory have been described (Lawson, 2014a), there is no universally accepted theory. Six hypotheses were discussed by Stanney et al. (2021) and ten by Keshavarz et al. (2014). Most of these can be grouped into four established categories (Table 26.1, Keshavarz et al.), which in **Table 1** are linked to the 12 articles in this Research Topic. This taxonomy may aid further literature inquiries concerning theoretical implications.[8]

CONCLUDING RECOMMENDATIONS TO THE RESEARCH COMMUNITY

We thank the authors for contributing many provocative studies. As is common in research, as many questions were raised as were answered. Answering the key cybersickness questions requires controlled, labor-intensive research entailing:

1. Assessment of relevant stimulus experiences (Jasper et al.) and past susceptibility (Golding et al.): This is vital to interpretation and such measures can be used as covariates to improve analyses.
2. Larger samples (e.g., Moss and Muth, 2011) than have commonly been employed (e.g., Kim et al.; Shahnewaz Ferdous et al.), in order to deal with high individual variability in susceptibility (Lawson, 2014a).
3. Stimuli that elicit functionally relevant cybersickness (Stanney et al., 2014[10]), to avoid basement effects or detection of statistical differences lacking clear functional significance (e.g., Hemmerich et al.).
4. Managing sessions and session intervals to reduce carry-over effects which may confound studies with many cybersickness sessions held closely together (e.g., Hemmerich et al.; Kim et al.). Sickening VR or simulator studies should ideally limit the number of sessions to three (Lawson et al., 2009[11]) and allow 1 week of recovery between sessions, to reduce visual-vestibular and vergence-accommodation carry-over effects due to adaptation (Dai et al., 2011) or sensitization (Dizio and Lackner, 2000), as well as learning, fatigue, classical conditioning, subject attrition, and ultradian variation (Lawson et al., 2009; Lawson, 2014a) (Comparable session guidelines need to be established for AR studies.)
5. Careful establishment of measures, e.g., whenever "objective" indicators of cybersickness are considered (Stauffert et al.; Shahnewaz Ferdous et al.; Hemmerich et al.); researchers should realize that specificity needs more emphasis (Bos and Lawson, 2021), and an established symptom scale is required for validation (Lawson, 2014b).

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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[7]Curry et al. (#9) also posit that their findings are (indirectly) inconsistent with a causal cybersickness role for vection.

[8]Stanney et al. and Keshavarz et al. provide (and evaluate) the source materials.

[9]Palmisano et al. (#5) hypothesize a new conflict between virtual versus physical head pose.

[10]Moderate-to-medium cybersickness severity occurs at 20–28 SSQ points (Table 31.3), and 20 points is where some subjects would quit (personal communication, Dr. Stanney, 1 May 2020).

[11]See p. 16–17.

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ORIGINAL RESEARCH
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Sensory Down-Weighting in Visual-Postural Coupling Is Linked With Lower Cybersickness

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Sensory dynamics can be re-shaped by environmental interaction, allowing adaptation to altered or unfamiliar conditions that would otherwise provoke challenges for the central nervous system. One such condition occurs in virtual reality, where sensory conflict is thought to induce cybersickness. Although the sensory re-weighting process is likely to underlie adaptation to cybersickness, evidence of a link between sensory re-weighting dynamics and cybersickness is rare. Here, we characterize the relationship between sensory re-weighting in a balance control task and cybersickness. Participants were exposed to visual oscillation while standing in tandem stance. The sway path length of the center of pressure (COP) was measured and averaged for each level of visual oscillation, and a ratio was computed between high and low oscillation magnitudes to reflect the relative contributions of multiple sensory sources of information concerning balance control. Results showed a significant relationship between the magnitude dependency of sway and common sub-scales of cybersickness: disorientation [$r_{(21)} = 0.45$, $p = 0.028$] and oculomotor discomfort [$r_{(21)} = 0.45$, $p = 0.033$]. We conclude that participants who reported less cybersickness were better-able to down-weight visual information at high magnitude oscillations, thus demonstrating a lower dependency between sway and visual magnitude. The results confirm the utility of balance control as an indicator of cybersickness, and support the role of multisensory re-weighting in determining an individual's tolerance to VR applications.

Keywords: sensory re-weighting, vection, self-motion perception, motion sickness, virtual reality

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INTRODUCTION

Motion sickness is often experienced in conditions where abnormal relationships exist between sensory cues (Money, 1970; Reason and Brand, 1975; Reason, 1978; Oman, 1990). Habituation to motion sickness due to continued exposure to the novel conditions is thought to reflect sensorimotor learning or re-weighting, whereby the internal models linking prior expectations, motor output, and sensory feedback are updated (Oman, 1990; Oman and Cullen, 2014). Adapting internal models of sensory dynamics usually depends upon environmental interaction, whereby the statistics of a novel environment are repeatedly exposed to the central nervous system (Harris and Wolpert, 1998; Lackner and DiZio, 2005). Findings from neurophysiology suggest a highly-dispersed network of cortical and sub-cortical regions that underlie the re-weighting process (Wolpert et al., 1998; Andersen and Buneo, 2003; Block and Bastian, 2012; Medendorp et al., 2018), and specific neural units that encode and integrate unexpected multisensory cues have been identified in animal models (Brooks and Cullen, 2013; Oman and Cullen, 2014).

There is considerable evidence that sensory re-weighting occurs after exposure to conditions where the normal relationships between sensory cues are disrupted experimentally. Kitazaki and Kimura (2010) reported down-weighting of vestibular cues in postural stabilization when the cues were rendered irrelevant for estimating spatial orientation of the body. Others have shown similar effects over a period of weeks (Dilda et al., 2014). Experimental derivations of sensory weights in spatial orientation tasks reveal that patients with bilateral vestibulopathy weight vision two to three times higher than control participants, consistent with long-term adaptation effects (Alberts et al., 2017).

It has been proposed that individual variability in the speed and extent to which sensory re-weighting occurs may explain a portion of the heterogeneity in cybersickness in virtual environments (e.g., Weech and Troje, 2017; Weech et al., 2018a,b, 2019). Successful habituation to the novel conditions occurs if the internal models of sensory interactions are adapted to account for conflicts between efferent and afferent signals, or between sensory cues across channels. Such changes can occur extremely rapidly, especially when postural stability is threatened by a failure to re-weight cues (Carver et al., 2006; Jeka et al., 2010).

Evidence supports the theory that a change in sensory weights over time is associated with a change in the severity of motion sickness. Seasickness is associated with atypical sensory weights for vision, proprioception, and the vestibular sense, as measured by computerized dynamic posturography (Shahal et al., 1999). Successful habituation to seasickness following extended sea travel was associated with a reduction in vestibular weighting after 6 months that had disappeared after 12 months (Tal et al., 2010). This suggests an initial reduction in vestibular weights due to the conflict between vestibular and visual cues on-board, followed by a restoration of normal vestibular weights once habituation has occurred. On the other hand, Tal et al. (2010) also found that individuals who did not habituate to seasickness by 12 months demonstrated a linear increase in vestibular weights, indicating that a failure to down-weight vestibular cues prevents seasickness adaptation. Extended spaceflight has also been shown to lead to down-weighting of vestibular cues due to a central reinterpretation of spatial orientation cues conveyed by the vestibular system in a zero-gravity environment (Black et al., 1995; Black and Paloski, 1998). Specifically concerning cybersickness, evidence suggests a reduction in cybersickness when the sensory re-weighting process is facilitated by adding noise to a sensory channel. Results of experiments using bone-conducted vibration of the vestibular system (Weech et al., 2018a) and noisy galvanic vestibular stimulation (Weech et al., 2020b) reveal that exposure to a tonic or phasic noise stimulus leads to improved comfort in VR applications. These results are considered to reflect an optimal integration of sensory cues in conditions of uncertainty, according to statistical (Bayesian) principles of cue combination (Ernst and Banks, 2002; Ernst and Bülthoff, 2004; Butler et al., 2010).

Here we asked if the short-term dynamics of sensory re-weighting predict the experience of cybersickness in virtual reality. We characterized sensory re-weighting effects in terms of the extent to which participants' postures were affected by visual information in a balance control task. Given the dynamic nature of posture-related feedback cues, the maintenance of stable posture requires adjustments to sensory feedback cue weights from the visual, proprioceptive, and vestibular senses (Nashner and Berthoz, 1978; Bronstein et al., 1990; Horak and MacPherson, 1996; Peterka, 2002). Non-linear response properties of the balance control system suggest a role for sensory re-weighting in maintaining stability: small magnitude visual oscillations produce oscillatory postural responses with gains of $\sim$1, but increasing visual oscillation magnitude leads to lower sway with gains of $<$1 (Kiemel et al., 2006).

Using an established paradigm for assessing sensory re-weighting in the control of balance (e.g., Oie et al., 2002, 2005; Allison et al., 2006; Jeka et al., 2008), we measured the extent to which visually-induced sway was modulated at different amplitudes of visual field oscillation. To this end, we derived the ratio between body sway at low- and high-amplitudes of visual field oscillation, and used this measure as an index of sensory re-weighting (Peterka, 2002). Following the balance control task, we collected measures of cybersickness produced by exposure to virtual reality content, and assessed the relationship between sensory re-weighting and cybersickness severity. Given our focus on short-term sensory re-weighting dynamics (as opposed to long-term adaptation), we examined the cybersickness response for a single bout of VR.

Our main outcome measures were twofold. First, we measured the non-linear response properties of the balance control system across visual oscillation magnitudes (small magnitude visual oscillations produce oscillatory postural responses with gains of $\sim$1, but increasing visual oscillation magnitude leads to lower sway with gains of $<$1; Kiemel et al., 2006). Second, we asked participants to report subjective linear vection strength while they were exposed to radially-expanding optic flow. Vection has been implicated as a strong predictor for cybersickness (Keshavarz et al., 2015; Weech et al., 2018b; but c.f. Webb and Griffin, 2002) and as such, we assessed vection and its association with cybersickness and indices of sensory re-weighting.

METHODS

Participants

Twenty-three adults (15 women, age $= 21.04$ (M) $\pm$ 2.74 (SD) yrs, range 18–29) participated in the study. We screened participants for exclusion criteria using a self-report questionnaire that was completed by individual participants prior to the study. Exclusion criteria for the study included any musculoskeletal disorders, balance/vestibular disorders, uncorrected hearing/visual deficits, or previous/ongoing neurological conditions (e.g., stroke). Participants were informed of all procedures and apparatuses and provided written consent. All participants provided informed written consent prior to taking part in the study. Remuneration was provided to each participant ($10 per hr). All procedures were carried out with the approval of the institutional ethics board and in accordance with the Declaration of Helsinki.

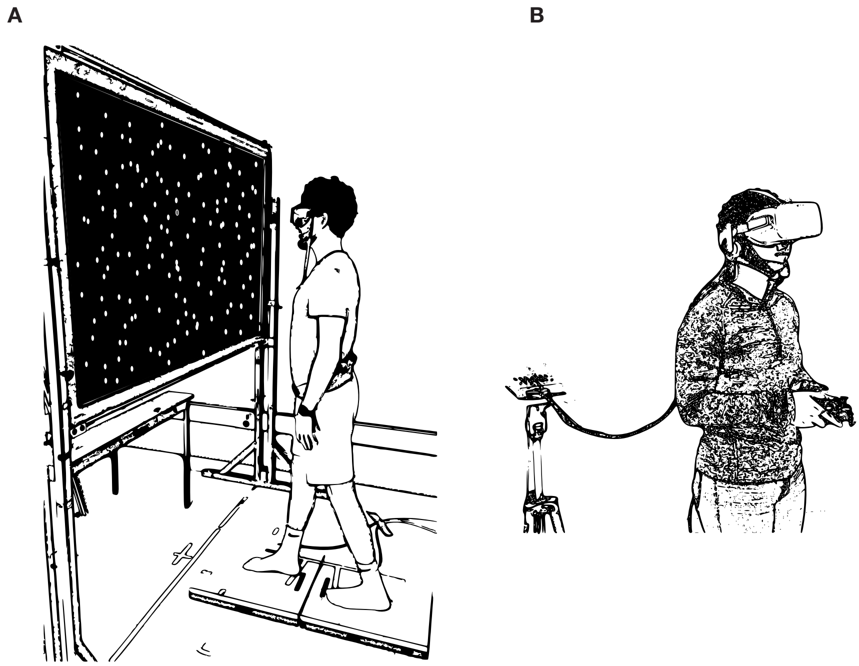

FIGURE 1 | (A) Depiction of the balance control task. Participants stood in a modified tandem stance with hands by their sides while observing the moving visual stimulus on the screen. **(B)** Depiction of the VR task. Participants held a gamepad while exposed to the VR application with the head-mounted display.

Procedure

Balance Control

In the first part of the study, we collected balance control data using a set of two force plates (4060-05; Bertec, Columbus, OH) arranged in a fore-aft layout and separated by ∼1 cm. Vertical ground reaction force and moments of force were recorded using a custom-built LabVIEW program (National Instruments, Austin, TX) over a 120 s period for each trial. Force plate data were amplified online using an internal digital pre-amplifier, sampled at a rate of 1,000 Hz, and stored for off-line analysis. The force plates were calibrated before data collection for each participant. Once collected, the force plate data were low-pass filtered (6 Hz, dual-pass 2nd-order Butterworth filter), and the COP parameter (sway path length) was extracted using a custom-made LabVIEW program.

Participants were instructed to stand unshod in a "tandem" stance with one foot on each of the force plates and with the left foot behind the right foot, with the arms rested at their sides in a comfortable posture (**Figure 1A**). A projection screen (1 × 1.8 m; 1.3 m lens to screen distance) was positioned at a distance of 0.57 m from the participant, and we back-projected images onto the screen using a projector (1920 × 1080 resolution; PROPixx DLP, VPixx Technologies). Each participant wore a pair of goggles (80 × 50 deg visual field) to prevent their ability to see the frame of the projection screen, which would diminish visual-postural coupling and vection.

In each trial, a field of 500 randomly-located dots (blue, 3° visual angle) populated the background (black). In addition, a fixation dot (purple) appeared at the participant's individually measured eye-height. Participants were asked to fixate on this purple fixation dot, and to maintain their posture throughout the task. The field of dots (and the fixation dot) always adhered to a coherent sinusoidal global motion (left-right linear translation, 0.2 Hz frequency), but the motion amplitude differed in each trial. The amplitude of oscillation for each trial was administered in a randomized order according to the method of constant stimuli, selected from four levels (4, 8, 12, and 16 mm) that were repeated three times each, resulting in 12 trials. Each trial lasted for 2 min. A further three trials of 30 s duration were conducted in the same stance, where participants viewed a vection-inducing optic flow stimulus. This consisted of 250 white dots on a black background moving at a constant 2 m/s velocity, where radial expansion, linear perspective, and relative size cues gave rise to the impression of linear translation of the observer in the anterior-posterior axis (as in Weech et al., 2020a). Participants were permitted to take breaks between trials.

Once the first 12 trials were complete, participants were exposed to three trials consisting of radially-expanding optic flow while they maintained the same tandem stance. Participants were told they might experience the sensation of illusory self-motion, "vection," and were given the example that vection can occur when looking out of a window at a moving vehicle. Each of these trials lasted for 30 s. After each trial, participants were asked to verbally rate their experience of vection (0–10, where 0 indicates feeling no vection and 10 indicates the maximum possible vection). After all trials were completed, participants

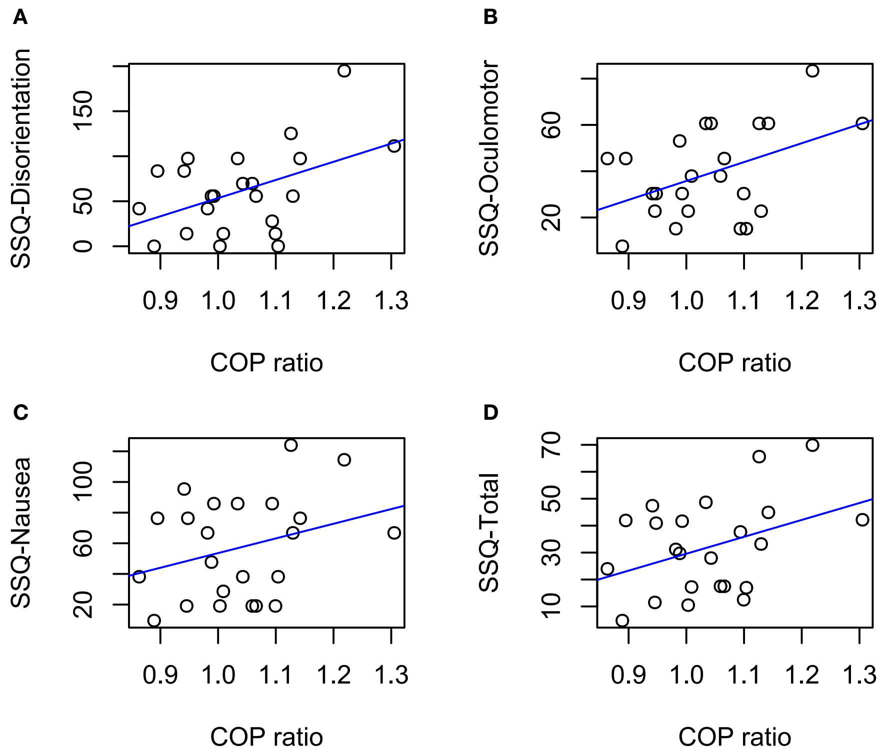

FIGURE 2 | Correlations between COP ratios and SSQ subscales **(A–C)** and SSQ total score **(D)**. Solid lines indicate linear trends. Significant correlations were observed in **(A,B)** (*ps* < 0.05).

were asked if they were experiencing any discomfort or sickness symptoms (none reported any symptoms).

Virtual Reality

In the second part of the study, participants played 30 min of a VR application that has previously been identified as highly nauseogenic (e.g., Weech et al., 2018b), consisting of a zero-gravity space-walk simulation (ADR1FT, Three One Zero). The VR environment was presented with a head mounted display (Rift CV1, Oculus VR, Menlo Park, CA; 90 Hz refresh rate, 1080 × 1200 resolution per eye) and the environment was rendered by a high-end graphics card (NVIDIA GTX1070). The headset position was tracked by a combination of inertial (accelerometer/gyroscope) and optical (1 × infrared Oculus camera) sensors that were part of the commercial device package, and this movement was translated into motion of the observer viewpoint in the VR task. The packaged software of the headset was used to calibrate the capture space and the inter-pupillary distance of the headset for each participant. Participants interacted with the VR environment using a handheld gamepad (Xbox One, Microsoft). The instructions were to "explore the environment, and to investigate the interior and exterior of the space station"; these instructions aimed at encouraging dynamic exploration of the environment and exposure to nauseogenic conflicts between visual and inertial cues. A depiction of the setup is shown in **Figure 1B**.

During exploration in VR, cybersickness levels were collected using a quick verbal report (Fast Motion Sickness scale, FMS: "*On a scale from 0 to 20 with 0 being no sickness and 20 being severe sickness, how do you feel?*"; Keshavarz and Hecht, 2011). Participants were informed that they could request early termination if their sickness level became intolerable, in accordance with ethical considerations for their safety and well-being. A multi-item self-report questionnaire was completed after VR exposure (Simulator Sickness Questionnaire, SSQ; Kennedy et al., 1993). Both measures have been validated (e.g., Kennedy et al., 1993; Keshavarz and Hecht, 2011; Keshavarz et al., 2015).

While participants explored in VR, we used an electroencephalography (EEG) cap to measure their neural activity. This measurement was for the purposes of another research question and as such the results are not reported here.

RESULTS

First, we computed the ratio between average COP path length at high (16 mm) and low (4 mm) visual oscillations, which we term the "COP ratio." COP ratios >1 indicate higher sway at higher visual oscillation magnitudes than at low magnitudes; COP ratios <1 indicate lower sway at high visual oscillations magnitudes; and a ratio of 1 indicates equality between sway at low and high oscillation

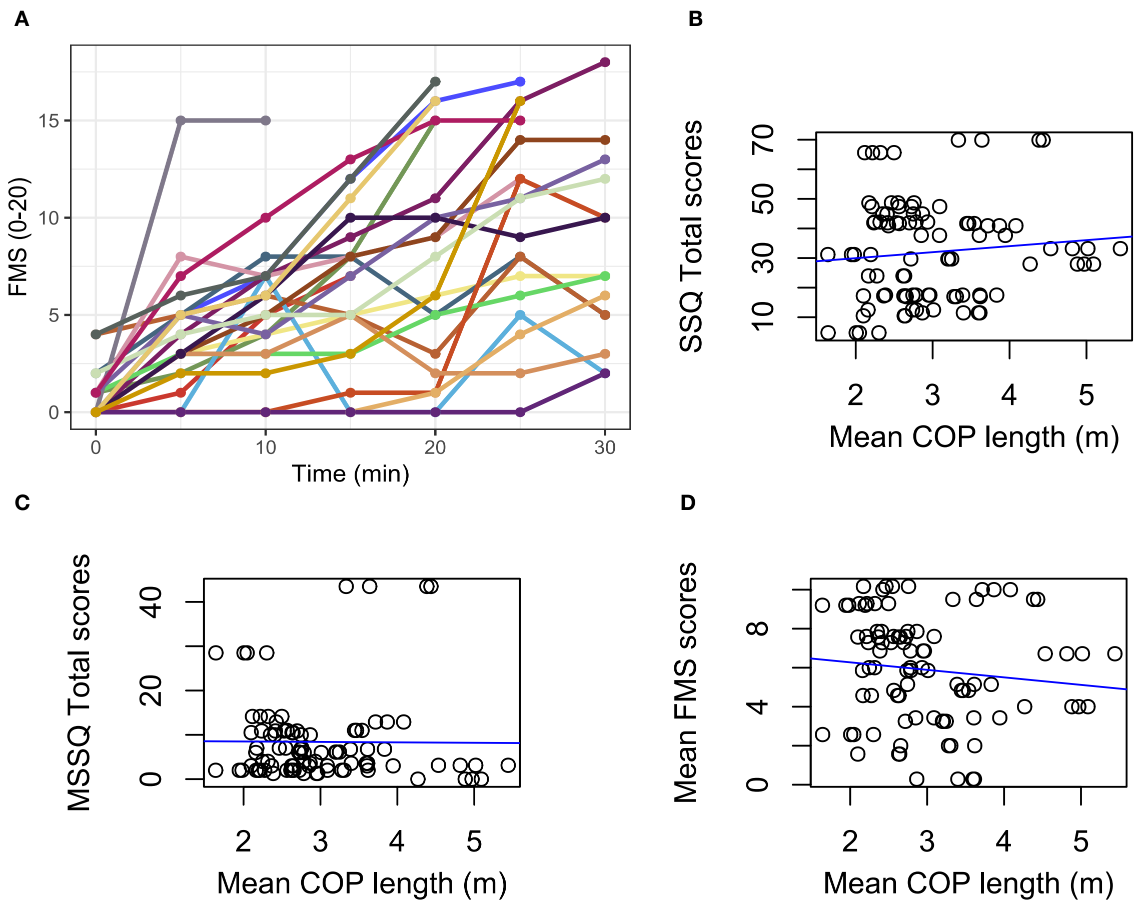

FIGURE 3 | (A) Change in FMS scores over time during the VR task (each participant color coded). Lines that terminate before 30 min indicate the participant asked to stop the task early. Correlations for data pooled over balance control conditions are shown with trends (blue lines). **(B)** SSQ total scores by mean COP length. **(C)** MSSQ total scores by mean COP length. **(D)** Mean FMS scores by mean COP length. All correlations are non-significant (*ps* > 0.05).

magnitudes. The average COP ratio across participants was 1.04 ($SD = 0.11$, range = 0.86–1.31).

Our main result was that we observed a significant, positive correlation between SSQ scores and COP ratios for both the disorientation [Pearson's $r_{(21)} = 0.45$, $p = 0.028$] and oculomotor discomfort [$r_{(21)} = 0.45$, $p = 0.033$] subscales. At the same time, we found no significant relationship between COP ratios and either SSQ total scores [$r_{(21)} = 0.39$, $p = 0.067$] or the nausea subscale [$r_{(21)} = 0.31$, $p = 0.15$] (**Figure 2**).

We found no other significant relationships between COP ratios and MSSQ total scores [$r_{(21)} = 0.13$, $p = 0.54$], mean FMS scores [$r_{(21)} = 0.23$, $p = 0.28$], maximum FMS scores [$r_{(21)} = 0.32$, $p = 0.14$], or the slope of FMS scores over time during the VR task [$r_{(21)} = 0.05$, $p = 0.83$]. Similarly, there was no association between mean COP path length when we analyzed the data across all balance conditions and any of the sickness-related outcome measures [SSQ total scores ($r_{(90)} = 0.10$, $p = 0.35$), MSSQ total scores ($r_{(90)} = -0.01$, $p = 0.94$), mean FMS scores ($r_{(90)} = -0.11$, $p = 0.28$; **Figure 3**)]. In addition, we observed that participant sex had no effect on either COP ratios [$r_{(21)} = 0.20$, $p = 0.36$], COP path lengths ($ps \geq 0.42$), FMS scores [$r_{(21)} = 0.13$, $p = 0.57$], or SSQ scores [total: $r_{(21)} = 0.02$, $p = 0.94$; subscales: $ps \geq 0.32$].

We also found no significant relationships in the vection trials between COP path length and MSSQ total scores, SSQ total scores, or SSQ subscales scores (all $ps \geq 0.18$). Similarly, we found no significant relationships between verbal ratings of vection strength and MSSQ total scores, SSQ total scores, or SSQ subscales scores (all $ps \geq 0.16$).

DISCUSSION

This study aimed to assess the relationship of sensory re-weighting indices with cybersickness, as well as vection and its association with said measures. Our results propose that short-term sensory re-weighting differences are related to susceptibility to cybersickness. This relationship suggests that the non-linear response properties of the balance control system may predict susceptibility to cybersickness. Our results also suggest that measures of postural re-weighting are more sensitive to individual differences in cybersickness than linear measures, specifically COP path length during quiet stance and vection, as well as verbal ratings of vection.

Although there is a rich literature on the use of predictive models for cybersickness (Kim et al., 2005; Dennison et al., 2016; Weech et al., 2018b; Walter et al., 2019), the current results contribute to a previously sparse literature on the link between sensory re-weighting and cybersickness. One previous study examined the relationship between self-reported carsickness and the time course of habituation to galvanic vestibular stimulation (GVS) during balance control (Balter et al., 2004). Carsickness is produced due to large vestibular self-motion cues and limited visual self-motion cues and it was expected that short-term down-weighting of vestibular cues enables habituation to carsickness. No difference in GVS habituation was observed between groups of individuals who were susceptible or impervious to carsickness (Balter et al., 2004). However, the study was limited due to the fact that sickness was only quantified by self-reported measures that rely on accurate recall by participants. Similarly to Balter et al. (2004), we found no significant correlation between sensory re-weighting (COP ratios) and historic recall of motion sickness (MSSQ total scores, which include an item on carsickness). The MSSQ measure is problematic, as it relies on accurate participant recall over a 10 year period. Conversely, in the current study the SSQ was completed after VR exposure, and is often treated as a gold-standard measure of sickness symptomatology (Balk et al., 2013; but c.f. Kim et al., 2018).

Results of the SSQ subscales in relation to COP ratios revealed a significant positive correlation: participants with higher COP ratios reported higher SSQ subscale (oculomotor and disorientation) scores. COP ratios of <1 reflect lower visually induced sway with higher oscillation amplitudes. This reflects the sensory re-weighting occurring during the control of balance and in this case suggests short-term down-weighting of visual cues. The positive correlation with SSQ subscales scores suggests that failure to down-weight visual cues (indicated by higher COP ratios) to maintain postural stability relates to higher cybersickness susceptibility. Therefore, this result can be taken as evidence that sensory re-weighting dynamics play a predictive role in determining cybersickness in virtual reality.

The current results align with previous findings that show effects of "noisy" vestibular stimulation on motion sickness. Stimulation of the vestibular organs via bone-conducted vibration (Weech et al., 2018a) or galvanic vestibular stimulation (Weech et al., 2020b) reduces cybersickness, and these effects are consistent with statistical principles of sensory re-weighting whereby multimodal cues are used according to their reliability, or noise-level (Ernst and Banks, 2002; Ernst and Bülthoff, 2004; Butler et al., 2010). In light of the current results, it would be valuable to identify if individual differences in sensory re-weighting also predict the extent to which a reduction in cybersickness can be achieved using noisy stimulation. Such an investigation would provide valuable insight into how noise affects the perceptual decision-making processes in individuals who demonstrate different baseline levels of sensory re-weighting.

We predicted all SSQ subscales (disorientation, oculomotor, and nausea) and SSQ total scores to be significantly correlated with the sensory re-weighting index. Our results show that both the nausea subscale and SSQ total scores were not significantly related to COP ratios. It may be that factors other than sensory re-weighting are strong contributors to nausea symptoms, although we were unable to identify those factors here. However, it is also possible that the non-significant findings relate to the power of the statistical tests used in the current study. A statistical power analysis based on our data ($n = 23$, alpha = 0.05) was completed for the correlations between the sensory re-weighting index and the SSQ total scores, and SSQ subscales. The effect size (ES) for the COP ratio correlations with the oculomotor and disorientation SSQ subscales is considered to be medium ($r = 0.45$) using Cohen's (1992) criteria. The power for these correlations, with a sample size of $n = 23$ and an alpha of 0.05, is 0.60. The power for the correlations between COP ratios and the SSQ total scores and the SSQ nausea subscale ($n = 23$, alpha = 0.05) were 0.467 and 0.307, respectively. Despite the decrease in power for these two correlations the ES are still considered to be medium ($r = 0.39$ [SSQ total] and $r = 0.31$ [SSQ nausea]) (Cohen, 1992). Thus, it is possible that the non-significant findings are related to the limited amount of statistical power achieved with the current sample size, which suggests that a replication of this study in a larger sample would be a useful way to better understand the discrepancy in correlations across SSQ subscales.

Since sensory re-weighting was measured here via behavioral correlates, and without neurophysiology, alternative explanations for the observed effects are conceivable. For instance, could the current results be equally explained as an effect of visual dominance on cybersickness? Evidence suggests that increased visual dominance over other senses in postural control can modulate the extent to which novel environmental conditions can be accounted for in sensorimotor control (Brady et al., 2012), and that the ability to adapt to unfamiliar conditions can benefit from reducing visual dependency (Bloomberg et al., 2015). However, the current results argue for sensory re-weighting, rather than visual dominance, as the key contributor. The primary outcomes in this study reflect the participant's propensity to switch from a state where vision dominates to one where other cues strongly contribute, indicating a rearranged set of internal weights for sensory cues. Visual dominance, on the other hand, would manifest as strong coupling to the visual stimulus at all magnitudes. If visual dominance were the key factor, we would expect see a correlation between sickness and COP path length for the (e.g.,) 16 mm condition. Given that we do not, it follows that sensory re-weighting is a more likely candidate for the observed effects. At the same time, future efforts should further dissociate these two related factors and their roles in cybersickness. Additionally, it could be considered whether the results simply reflect individual differences in tracking behavior that modulated sickness across participants. Since tracking the fixation dot could be achieved by moving either the eyes or the head-on-body, COP ratios could be partially determined by the tracking strategy adopted. Although head-on-body motion is typically the focus in tasks such as ours

(Oie et al., 2002, 2005; Allison et al., 2006; Jeka et al., 2008), the use of eye tracking in future tasks should be employed to identify strategy differences. Finally, given that our focus here was on the re-weighting of cues to resolve sensory conflicts, we did not compute postural stability measures to assess the ecological theory of cybersickness (Riccio and Stoffregen, 1991); it is conceivable that the COP ratios we measured share some overlap with non-linear measures of postural dynamics, and an experiment designed to separately assess those outcomes would be a valuable next step.

While there is currently no direct evidence for the neural locus of the re-weighting effects discussed here, recent evidence has outlined a possible mechanism linking motion sickness to sensory conflict. Primate neurophysiology research by Oman and Cullen (2014) and Cullen (2012) shows that vestibular neurons in the rhesus brainstem exhibit cancelation of vestibular input produced by active head movement (termed "reafference") while input produced by passive movement (termed "exafference") is not canceled. Although there has been no direct link established between the activation of these vestibular units and other areas of brainstem that are causally involved in the emetic response, such a link has been hypothesized to exist (Suzuki et al., 2012; Oman and Cullen, 2014). At the same time, other research by Cullen and coworkers has shown evidence for neurons in the cerebellum (rostral fastigial nucleus) that preferentially code exafference (Brooks and Cullen, 2013) and it is the activity of these cerebellar units that is thought to drive adaptation of sensorimotor control strategies due to sensory rearrangements (Oman and Cullen, 2014). While it is unclear whether reafferent-canceling cells are responsive to stimuli from other modalities (e.g., optic flow), Oman and Cullen (2014) report informal evidence of negative results. In the context of these findings, we reason that the individual differences in sensory re-weighting we observed here would manifest in differential blood-oxygen level dependent activity, detectable using neuroimaging; in a future study these prospective differences should be identified and used as input to a prediction/classification algorithm with cybersickness as an output. Similar procedures targeting brainstem activity have been used to sensitively identify the perceptual experience of migraine (Cao et al., 2002), which shares some characteristics with cybersickness (e.g., headache, nausea), thus lending hope to the prospect of classifying cybersickness using brainstem fMRI. While other studies have used imaging techniques to identify areas associated with motion sickness (e.g., medial pre-frontal cortex; pre-genual anterior cingulate cortex; Kim et al., 2011), this is currently an understudied area.

It appears likely that the re-weighting process is highly dispersed across multiple cortical and sub-cortical regions (Andersen and Buneo, 2003; Block and Bastian, 2012; Medendorp et al., 2018). The cerebellum plays a central role in adapting to motor sensory prediction errors (e.g., throwing during prism adaptation) as patients with cerebellar lesions do not demonstrate sensorimotor adaptation (Thach et al., 1992; Earhart et al., 2002). There is also evidence that down-weighting vestibular cues relative to other senses during balance control takes place centrally, perhaps at the level of the cerebellum (Dilda et al., 2014; but note that sensory re-weighting may not require intact cerebellar cortex or cerebellar nuclei: Block and Bastian, 2012). The vestibular nuclei are also implicated in multimodal information processing (Angelaki and Cullen, 2008; Sadeghi et al., 2012; Oman and Cullen, 2014), and neuroimaging data shows that the posterior parietal cortex—to which the vestibular nuclei project—is selectively activated during sensory re-weighting (Clower et al., 1996). Yates et al. (2014) identified nausea and emetic centers that are connected to the vestibular system regions. Some of these overlapping regions include those implicated in multimodal information processing–the vestibular nuclei and cerebellum (fastigial nuclei and uvula-nodulus). These regions need to be further probed to reveal their role as nausea, emesis and sensory processing centers. Neuroimaging techniques and single cells animal recordings offer plausible next steps to further examine these subcortical and cerebellar regions in addition to the use of non-invasive brain stimulation (TMS and tDCS) to probe superficial regions strongly implicated in multisensory processing, such as the posterior parietal cortex (Bremmer et al., 2001).

In summary, we used measures of postural fluctuations (sway path length) at different levels of visual oscillation to compute a COP ratio, indicative of sensory re-weighting dynamics. We then exposed participants to a nauseogenic VR experience and collected their reported cybersickness scores. We observed evidence of a positive correlation between cybersickness SSQ subscales (oculomotor and disorientation) and COP ratios. We conclude that a lower COP ratio, indicative of more successful down-regulation of visual cues during high amplitude oscillations, is associated with lower cybersickness: participants who were unable to down-weigh visual information were more susceptible to cybersickness. The proposed mechanism for this association lies in the greater magnitude and number of sensory conflicts experienced when conflicting sensory cues cannot be effectively organized through the sensory re-weighting process (Dilda et al., 2014; Weech and Troje, 2017). These results support the use of postural stability measures and the role of sensory re-weighting as potential indicators of cybersickness susceptibility and tolerance to virtual reality.

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 Waterloo Research Ethics Board. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SW: conceptualization, data curation, formal analysis, investigation, methodology, project administration, software, supervision, visualization, writing–original draft preparation, review, and editing. CMC: investigation, project administration, writing–original draft preparation, review, and editing. MB-C: conceptualization, funding acquisition, project administration, resources, supervision, and writing–review and editing. All authors contributed to the article and approved the submitted version.

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Visually Induced Motion Sickness Susceptibility and Recovery Based on Four Mitigation Techniques

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Virtual reality (VR) usage continues to grow, but visually induced motion sickness (VIMS) can decrease VR effectiveness for some users. This study seeks to compare methods of VIMS mitigation and explore sickness among gender and video game experience groups. Participant discomfort and early dropout are problems for studies that involve virtual environment (VE) exposure, but previous research has demonstrated that natural decay and physical, real-world hand–eye coordination tasks can serve as effective mitigation strategies. In this study, 57 participants wore a head-mounted display (HMD) and navigated a maze VE designed to induce cybersickness. Participants then experienced one of four mitigation techniques: real natural decay (HMD off), virtual natural decay (HMD on with idyllic VE and no locomotion), real hand–eye coordination task (HMD off), and virtual hand–eye coordination task (HMD on). Simulator Sickness Questionnaire (SSQ) measures were taken periodically throughout maze and mitigation tasks. Results demonstrated that peak sickness during the maze VE occurred after approximately 10 min. Analyses of mitigation techniques showed that real natural decay resulted in significantly more sickness recovery when compared with the virtual hand–eye coordination task for SSQ total score, nausea, and oculomotor constructs, but not disorientation. The real natural decay technique was the most effective at bringing participants' final sickness measure back to their initial baseline measure; however, other mitigation techniques yielded effectiveness, but at a lower rate. This study extends previous research about hand–eye mitigation approaches by demonstrating that natural decay and hand–eye tasks in a virtual and real-world setting were effective in reducing VIMS. Real-world natural decay was the most effective at mitigating VIMS, and the virtual hand–eye task was not as effective as the other three tasks. Women experienced more VIMS than men did but also recovered than men did during mitigation. Video gamers experienced less VIMS than non-gamers. These findings bolster extant knowledge about VIMS mitigation techniques and can inform future development of virtual mitigation techniques.

Keywords: virtual environment (VE), mitigation, virtual reality (VR), cybersickness, visually induced motion sickness (VIMS)

INTRODUCTION

Visually induced motion sickness (VIMS) is a subcategory of motion sickness that specifically relates to nausea, oculomotor strain, and disorientation from the perception of motion while remaining still (Kennedy et al., 2010). VIMS presents an obstacle to widespread adoption of virtual reality (VR) experiences because it can have devastating results on any study in which participants move within a virtual environment (VE). VIMS has the potential to compromise a study, but it can also pose a safety risk to participants if they become physically ill. The effects of these symptoms may make using VR, both recreationally and professionally, too uncomfortable in the short and long term for many users. As such, VIMS could render adoption and innovation around VR fruitless. In combination with improving the virtual experience to prevent sickness, it is also critical to provide solutions for users to readapt and reduce sickness after exposure.

The existence of VIMS within VR is well-known (Lo and So, 2001; Jerome et al., 2005; Kennedy et al., 2010; Mousavi et al., 2013; Davis et al., 2014), but less is understood about how to readapt from post-VE exposure symptoms (Champney et al., 2007), so it is unclear how best to mitigate VR-related sickness. If research can provide empirically substantiated solutions to VIMS, it may be possible to increase post-VR exposure adaption and thus reduce individual safety risk, improve experience, and bolster VR growth. The current study extends VIMS research to compare the effectiveness of four mitigation techniques, within and outside of VR, following exposure in order to better understand VIMS recovery.

VIMS recovery techniques vary from breathing exercises (Russell et al., 2014) to medication (Regan, 1995; Regan and Ramsey, 1996), to simply waiting for symptoms to attenuate (Kennedy and Fowlkes, 1992). The last technique, called natural decay, has successfully reduced VIMS following VE exposure but can take up to 24 h to fully eliminate symptoms (Baltzley et al., 1989). An alternative technique involving a hand–eye coordination task was developed in an attempt to more rapidly reduce VIMS by engaging ocular focus and proprioception (Champney et al., 2007). However, both of these techniques require a user to exit the VE, so they do not allow users experiencing VIMS to remain immersed in a VE while mitigating symptoms. Virtual mitigation techniques allow users to remain in the virtual environment, extending the possible exposure periods. A VR version of Champney's hand–eye coordination task was developed to reduce symptoms rapidly within exiting the VE. The virtual hand–eye task successfully reduced VIMS following VR exposure (Curtis et al., 2015) and may be an alternative for the real-world version of the technique. Curtis (2014) also investigated virtual natural decay, which did not perform significantly different from the real natural decay. While these mitigation techniques have shown evidence of VIMS mitigation, it is unclear how all four perform relative to one another. Also, previous analyses have not examined the impact of gender and video game experience on sickness and on mitigation. Further evidence behind successful VIMS mitigation techniques can help (1) develop understandings around VIMS recovery and (2) provide individuals (i.e., companies, app developers, etc.) with methods to reduce the safety risk associated with VEs.

LITERATURE REVIEW

For the purposes of this study, it is worth reviewing previous research on VIMS, individual differences in VIMS susceptibility, and methods of recovery from VIMS. The extant literature is reviewed in order to understand what contributes to sickness symptoms, as well as the effectiveness of current techniques for recovering from VIMS.

Visually Induced Motion Sickness

Motion sickness is a widespread human experience characterized by nausea, oculomotor issues, and disorientation (Kennedy et al., 2010). This discomfort occurs when someone is exposed to a motion stimulus that is sufficient to disrupt the function of their vestibular system (Golding, 2006). Stimuli that induce motion sickness include land movement (e.g., cars, trains), sea travel, air flight, and optokinetic exposure (i.e., slow- and fast-paced eye tracking movement), including virtual reality (VR) simulators (Golding, 2006). VR simulators are rising in prominence as less expensive, less risky alternatives to professional training, such as piloting or surgery. However, some users of these VR systems have reported excessive motion sickness discomfort following exposure to immersive VEs (Estrada et al., 2007), such as VR environments when using head-mounted displays (HMDs) (Boyd, 2014; Lewis, 2015), increasing the demand for methods to mitigate motion sickness resulting from simulators.

Simulator sickness is motion sickness caused by any simulator used for leisure or professional purposes (Buker et al., 2012). In order to better understand simulator sickness susceptibility and recovery, the Simulator Sickness Questionnaire (SSQ) was developed to capture an individual's nausea, oculomotor, and disorientation symptoms during exposure to flight and vehicle simulators (Kennedy et al., 1993). The SSQ has been demonstrated as a both reliable and valid assessment of symptoms (Kennedy et al., 1993). The SSQ remains the most commonly utilized measure for simulator sickness is the Simulator Sickness Questionnaire (SSQ) (Rebenitsch and Owen, 2016). Other subjective assessments for sickness caused by virtual reality have been developed, such as the Virtual Reality Sickness Questionnaire (Kim H. K. et al., 2018) and the Virtual Reality Symptom Questionnaire (Ames et al., 2005). However, such assessments have not been widely utilized in research, thus leaving the SSQ as the most robust choice for measuring simulator sickness symptoms.

Two methodological questions of interest have been explored in the literature when assessing simulator sickness: (1) whether measurements be conducted verbally and (2) whether measurements can be taken while participants are experiencing the VE. Although the SSQ is primarily used as a written response assessment, some studies have verbally administered it because of its concise format that can be used without disrupting visual exposure to a VE (Min et al., 2004; Moss and Muth, 2011; Duzmańska et al., 2018). For example, Moss and Muth (2011) administered a verbal recording of the SSQ participants in between 2-min VR exposures while their HMD was still worn, as well as twice before and after exposure. While they did not administer the SSQ during the VR task, some researchers have concluded that the ideal frequency of SSQ measurement during and after VR exposure remains undecided and should be further addressed (Duzmańska et al., 2018).

Keshavarz and Hecht (2011) were interested in understanding how sickness changed throughout virtual exposure, rather than just the final amount of sickness after exposure. They developed the Fast Motion Sickness Scale (FMS) as a method for verbally assessing motion sickness multiple times during exposure to a VE. In order to cross-validate the FMS with the most common sickness assessment, the SSQ, they administered the SSQ immediately post-exposure, but not throughout. Researchers found that the final FMS measurement was highly correlated with the SSQ total score (TS), as well as its subscales: Nausea (N), Oculomotor (O), and Disorientation (D). Further, the researchers plotted the FMS scores throughout the stimuli and overlaid the SSQ TS and SSQ N regression lines to reveal that the FMS scores and regression slope directly mirrored each other. The authors concluded that the FMS was cross-validated with the SSQ (Keshavarz and Hecht, 2011; Keshavarz et al., 2018), suggesting that verbal assessment of sickness during a virtual stimuli is possible and may result in a similar reported amount of final sickness to an assessment only given at the end of a stimuli, such as the SSQ. These findings could also be used to postulate that other sickness assessments, such as the SSQ, could be verbally administered throughout a virtual stimulus with little negative impact on sickness.

It is unclear how the verbal administration of the FMS (or the SSQ) impacts presence in VR, or the extent to which it interrupts the virtual experience. That answer likely depends on the context, i.e., the authenticity (Gilbert, 2016) or coherence of the task (Skarbez et al., 2018). In a recent review of 20 articles examining the connection between presence and sickness during VR exposure, authors found mixed results (Weech et al., 2019). Among the articles reviewed, 11 reported a negative correlation between presence and sickness, while 9 reported a null or positive correlation between presence and sickness. Although the review postulated that presence and cybersickness most commonly have an inverse relationship, there are enough mixed findings to warrant further investigation. As such, it is possible that the SSQ could be verbally administered throughout a virtual experience and possibly have a null impact on presence, and visually induced motion sickness.

Visually induced motion sickness (VIMS) is another term developed as an additional subcategory to motion sickness that is similar to simulator sickness, referring specifically to symptoms caused by the perception of motion when using contemporary interactive technologies while sitting still (Kennedy et al., 2010). VIMS differs from simulator sickness in that it broadly applies to any VE that causes feelings of sickness while the user does not move, whereas simulator sickness may refer more specifically to flight and vehicle scenarios. The additional term cybersickness is a more popular term for the clinical label VIMS, and the term cybersickness tends to connote sickness related to a digitally enhanced reality, e.g., virtual reality (VR), augmented reality (AR), or mixed reality (MR), all of which can be encompassed with the more general term extended reality (XR).

It is clear that VIMS and other types of motion sickness (e.g., simulator sickness, car sickness) occur, but the reason is not clear. The sensory conflict theory has been used to speculate why sickness occurs (Reason, 1978). It posits that a movement-related visual stimulus causes a neural mismatch wherein the visual input does not match stored neural patterns of movement, resulting in sensory disturbances and thus sickness. An alternative theory, postural instability (Riccio and Stoffregen, 1991; Walter et al., 2019), suggests that sickness occurs when people are in situations in which they are uncertain or unable to maintain postural stability for prolonged periods of time. While these theories are helpful in illuminating how VIMS occurs, the reason for individual differences in susceptibility to VIMS is less known.

Susceptibility to Visually Induced Motion Sickness

Likeliness to get motion sickness varies notably among people in the general population; some people are approximately 10,000 more susceptible to become sick than others (Lackner, 2014). Susceptibility involves individual stimulation sensitivity, stimulation adaptation, and stimulation adaptation rate (Golding, 2006; Lackner, 2014). It is possible that individual differences in susceptibility are due to physiological differences related to the vestibular and somatosensory systems (Golding, 2006). For instance, there is some evidence that motion sickness is less frequent in individuals with bilateral loss of labyrinthine function, when occurs when the deficient vestibulo-oculor reflex of the inner ear, and the retina cannot reconcile visual stimulus (Golding, 2006). Additionally, some individuals may be naturally less reliant on vestibular and ocular inputs, increasing somatosensory dependence for maintaining balance, resulting in increased susceptibility to motion sickness (Nachum et al., 2004). Recent research observed that greater susceptibility was predicted by increased visual sensitivity to sensory cues when viewing motion parallax (Fulvio et al., 2020). Because sensory conflict theory focuses the cause of sickness more on the stimuli than the person, it has more difficulty explaining individual differences in susceptibility. Postural instability theory, on the other hand, focuses more of the cause on the individual's ability to stabilize.

Gender has been discussed as a possible individual difference contributing to VIMS variability. Females generally report higher levels of sickness than males (Koslucher et al., 2016; Munafo et al., 2017). When exposed to linear oscillating visual motion stimuli, women experienced VIMS four times as often as men (Koslucher et al., 2015). Women were also found to be more susceptible to VIMS than men when playing games using an Oculus Rift (Munafo et al., 2017). Contradictory evidence, however, showed no gender differences in VIMS (e.g., Klosterhalfen et al., 2006), neither in severity nor on incidence (Curry et al., 2020). Some research has further suggested that gender differences may stem from male–female differences related to video game experience (Shafer et al., 2017). Other research suggests that differences may result in part from male HMD configurations (Fulvio et al., 2020), potentially confounding gender-related VIMS findings, indicating that there is not yet a full consensus on gender-based susceptibility differences.

Video game play experience has also been examined as an individual difference contributing to variability in VIMS. Prior virtual environment experiences, including video game play, may reduce individual susceptibility to cybersickness (Knight and Arns, 2006). However, other research has found limited to no support for the relationship between video game play experience and VIMS (Gamito et al., 2008, 2010). Given these limited and conflicting results, further investigation of prior VE experience via video game play is warranted. The entire set of factors that contribute to VIMS susceptibility is not yet fully understood.

Recovery From Visually Induced Motion Sickness

While some research has focused on individual susceptibility to VIMS, less is known about recovery from VIMS (Champney et al., 2007). For general motion sickness, individuals may utilize anti-cholinergic medications or wrist acupressure bands to reduce sickness symptoms (Miller and Muth, 2004; Estrada et al., 2007). Hyoscine hydrobromide, an anti-motion sickness anti-cholinergic drug, can be used to inhibit nausea caused by motion sickness. This drug has also successfully reduced VIMS from VR after 20 min of exposure (Regan, 1995; Regan and Ramsey, 1996). However, medications can come with undesirable side effects, such as drowsiness, blurred vision, impaired psychomotor function, and slower information processing (Estrada et al., 2007). Thus, recovery methods that do not rely on chemical intervention have been developed as potentially safer alternatives.

Non-invasive methods for reducing VIMS during exposure have been explored. Some evidence has suggested that paced diaphragmatic breathing during VR exposure results in lower sickness than a control condition, but it is unclear whether this method reduces symptoms post-exposure (Russell et al., 2014). Pilot research successfully implemented air cushions on seats during VR video game play to reduce symptoms of dizziness, headaches, stomach awareness, sweating, and fatigue (Onuki et al., 2017). Due to the approach of reporting results, it is unclear which analyses were utilized and to what extent VIMS were reduced. Regardless, these preliminary findings suggest that the use of air cushions could be beneficial in reducing VIMS from VR exposure. Research relating to adjusting visual settings, such as through dynamic non-salient area blurring (Nie et al., 2019) and restricted field of view (Kim S. et al., 2018), have also mitigated VIMS. There has additionally been evidence that distracting participants from their symptoms through tactile stimulation may be yet another method for reducing VIMS (Gálvez-García et al., 2017). While these methods are promising, there has been little research on mitigation tasks that could be performed within a VE.

Real Natural Decay

A common non-invasive VIMS mitigation technique is natural decay, wherein an individual sits calmly with their eyes open or shut for a given extended period of time (Kennedy and Fowlkes, 1992). It has been suggested that the amount of natural decay recovery time is similar to the amount of virtual time (Baltzley et al., 1989). At least one study has shown that VIMS from 15 min of VR exposure was significantly reduced after 15 min of natural decay (Curtis et al., 2015); however, symptoms of VIMS have been observed up to 24 h after exposure (Baltzley et al., 1989), and the decay time can vary among individuals with a factor of 100 to 1 (Lackner, 2014). The potentially large amount of time required for natural decay to eliminate VIMS symptoms suggests that additional mitigation techniques are needed to expedite recovery.

Real Hand–Eye Coordination Task

Champney et al. (2007) investigated alternative strategies for re-adapting virtual reality users to the real world with a hand–eye coordination task that recalibrates the sensory systems. The task involved a peg-in-hole task wherein participants used a 25-hole pegboard and had to accurately insert a longer wooden peg into and out of the holes, one at a time. After 1 h in a virtual environment, participants who completed the hand–eye coordination task had a significant reduction in VIMS. A more recent study also found that the real hand–eye task significantly mitigated VIMS (Curtis, 2014). It is possible that hand–eye coordination tasks require ocular focus and proprioception to accomplish their respective tasks, thus reconciling sensory systems and reestablishing depth perception. Both natural decay and hand–eye coordination tasks are effective for users who exit VR to re-adapt their senses; however, they do not provide VIMS relief for users need to remain exposed to VR stimuli for extended periods of time without exiting.

Virtual Mitigation

VIMS mitigation within VR could allow users to remain fully immersed in a virtual environment without debilitating sickness symptoms. Curtis et al. (2015) expanded on Champney's work by designing a virtual version of the peg-in-hole hand–eye coordination task. Participants were presented with an identical virtual pegboard that included 25 pegs (five rows, five columns) with different peg colors in each row. The participants were required to use a Logitech gamepad controller to place the pegs. This task was performed for up to 15 min or until the task was completed. In a comparison of VIMS mitigation between real natural decay and the virtual hand–eye task, both conditions significantly reduced symptoms and there were no significant task group differences. However, the real hand–eye task resulted in lower VIMS than the virtual hand–eye task. It is also worth noting that Curtis (2014) did not find significant VIMS mitigation differences between the real natural decay and the virtual natural decay conditions, but no other research could be found regarding virtual natural decay. These findings suggest that a virtual hand–eye coordination task could be a potential solution for reducing VIMS symptoms while remaining in a virtual environment. Given the limited research in the area, additional exploration is needed to better understand how it compares to the real hand–eye coordination task, real natural decay, and virtual natural decay.

Study Motivation

VIMS symptoms of nausea, oculomotor strain, and disorientation pose a potential barrier to an optimal VR experience. While it is clear that VIMS occurs during and after VR exposure, much less is known about how to effectively and efficiently mitigate sickness (Champney et al., 2007). Sickness due to VR exposure can include nausea, oculomotor strain, and disorientation. These side effects may make VR too uncomfortable for many users and ultimately limit the widespread adoption and growth of VR. Limited research has examined VIMS mitigation techniques within and outside of a virtual environment, including natural decay and a hand–eye coordination tasks (e.g., Champney et al., 2007; Curtis et al., 2015). Some research has suggested these methods could be effective, but it remains unclear how virtual and real-world natural decay or hand–eye coordination tasks compare to one another. Thus, the purpose of the current research is to directly compare the effectiveness of a real-world hand–eye coordination task, real-world natural decay, virtual hand–eye coordination task, and virtual natural decay in mitigating VIMS. Understanding the relative effectiveness of various mitigation techniques will bolster recovery and readaptation knowledge and inform the development of future mitigation tasks, in turn reducing the risk posed by VIMS following VR exposure.

TABLE 1 | Demographic Descriptive Statistics.

	n (57)	Min.–max or %
Gender		
Female	21	36.8%
Male	36	63.2%
Physical health		
Great	26	45.6%
Good	29	50.9%
Poor	1	1.8%
Video game play		
No	19	33.3%
Yes	38	66.7%
Average weekly video game time		
Less than 1 h/week	8	14.0%
1–5 h/week	20	35.1%
6–10 h/week	4	7.0%
10+ h/week	6	10.5%
No response	19	33.3%
Prior VR experience		
No	41	71.9%
Yes	15	26.3%
No response	1	1.8%
Amount of sleep the night before		
Less than normal	13	22.8%
Normal	40	70.2%
More than normal	4	7.0%
Eaten the day of the study		
No	5	8.8%
Yes	52	91.2%

MATERIALS AND METHODS

Objective

While author Curtis completed a master's thesis (2014) based on a subset of the data analyzed for this paper, that work has not been published in the academic literature. The current paper analyzes those unpublished data using new methods to explore the effectiveness of four mitigation methods and the impact of individual differences on susceptibility and recovery.

Participants

The sample included 57 participants (21 females, 36 males) ranging in age from 18 to 38 ($M = 21.75$ years old). Participants were recruited from Iowa State University and were compensated with $20 at the completion of the study. Potential participants were screened for and excluded based on a history of seizures or for having taken any motion sickness medication in the prior 24 h. Most respondents reported never or seldom having car sickness (78.3%), plane sickness (84%), sea sickness (83.1%), and train sickness (86.8%). **Table 1** summarizes the participant demographic descriptive statistics. This study was approved by the Iowa State University Institutional Review Board. Participants provided their written informed consent to participate in this study.

Experimental Design Overview

Maze

The experiment was divided into two phases: (1) maze run to induce VIMS and (2) mitigation. In the maze phase, participants navigated the "Corn Maze" virtual environment (VE), which was designed to cause virtually induced motion sickness (VIMS). There were two independent variables in the experiment: Mitigation (4 levels) and Movement Control (2 levels). The subsequent mitigation phase tested mitigation techniques (described in the section Independent Variables) to assess their efficacy.

In the Maze phase, participants navigated the maze for up to 15 min (or until they felt too sick to continue), then completed one of four possible VIMS mitigation tasks for 15 min. The design of the primary sections of the virtual environment was based on tasks from the Virtual Environment Performance Assessment Battery known to induce VIMS (VEPAB; Lampton et al., 1994). One of these tasks, called "Turns," consisted of a total of 44 left and right 90° turns while the user briefly lost control of their movement (Curtis et al., 2015). To ensure a consistent VE path for all participants, it included no decision-making points (i.e., no forking paths). Trampolines and spinning rooms were added to serve as rotational and translational scene oscillations (O'Hanlon and McCauley, 1974; Lo and So, 2001). Spiral slides and non-descript ramps were also included to reduce the number of visual cues the participants could use to determine motion. In addition, the forward movement speed was changed during the virtual environment without indication, reducing the participants' feeling of control. An area in which participants had no control at all and moved at a very rapid pace

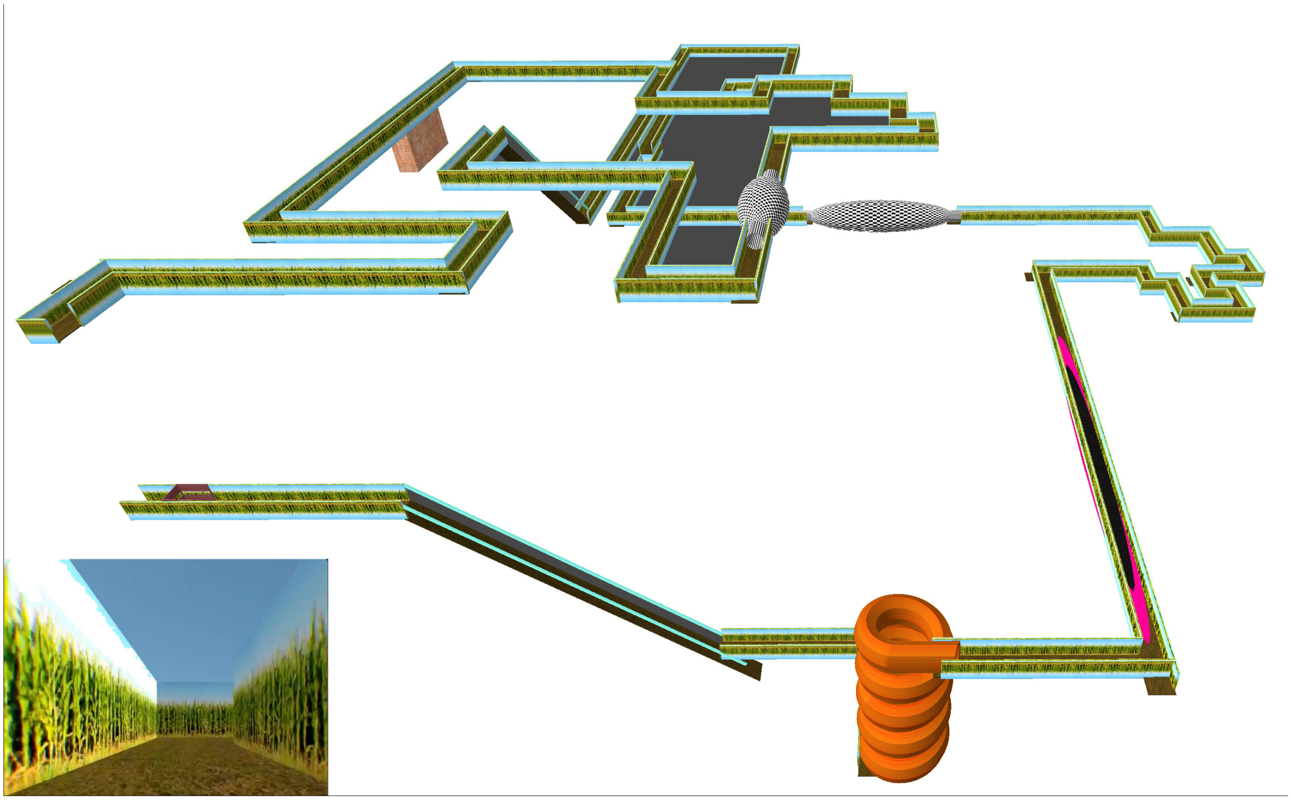

FIGURE 1 | Overview of the corn maze in unity.

was also included to induce sickness (Dong et al., 2011). The maze was navigated using the Logitech Dual Action gamepad; pushing the joystick forward led to forward movement. The maze took approximately 7 min to complete, and participants were tasked with completing the virtual environment twice, for a total stimulus exposure of about 15 min. The Corn Maze was designed and run using the Unity 3D game engine (**Figure 1**). The corn maze code can be found at https://github.com/isuvrac/CyberSickness-Cornmaze.

Headset and Controller

Participants were seated while wearing a HMD and given a gamepad. Participants were able to control movement with the left thumb stick and jump by using their right thumb, which was consistent with typical first-person game controls. The participant's view, or camera in the virtual world, was controlled by the participant's head movement. The head movement was tracked by the Oculus DK1, absent any hardware or software motion sickness mitigation. A typical user of the DK1 would have been able to adjust their FOV via the lenses supplied with the headset. Participants were limited to a single lens setup for 20/20 or corrected vision, which was asked prior to the start of the session. If the participant was in a "no control" condition, the participant could not navigate via the left thumb stick, normally used for motion, nor jump by pressing the bottom button.

Independent Variables

There were two independent variables: Movement control in the Maze phase (two levels) and migration technique in the Mitigation phase (four levels).

In the maze phase, participants were assigned to a no movement control or movement control group. Those in the no movement control group were not able to manually control progress through the maze, but rather automatically traveled through it (i.e., "on-rails"). The movement control group was able to manually progress through the maze using the joystick. The Maze design also included one short segment in which all users lost control once per lap for approximately 7 s. The Control independent variable, however, was not found to impact results. ANOVAs were completed to determine whether participants with movement control and no movement control throughout the entire maze differed in Maze Sickness or Mitigation Recovery (**Table 2**). The movement control group did not have any significant impact on Maze Sickness {[$F(1, 55)_{MSTS} = 0.65$, $p = 0.424$]; [$F(1, 55)_{MSN} = 2.30$, $p = 0.135$]; [$F(1, 55)_{MSO} = 0.21$, $p = 0.646$]; [$F(1, 55)_{MSD} = 0.16$, $p = 0.693$]} or Mitigation Recovery {[$F(1, 53)_{MRTS} = 0.18$, $p = 0.674$]; [$F(1, 53)_{MRN} = 0.53$, $p = 0.471$]; [$F(1, 53)_{MRO} = 0.83$, $p = 0.366$]; [$F(1, 55)_{MRD} = 1.00$, $p = 0.321$]}. Based on these results, the control and no control groups were collapsed for further analysis.

TABLE 2 | Definitions, calculations, and analyses for the dependent variables.

Variable	Description	Calculation	Analyses used for
Final maze SSQ	The final SSQ measurement each participant completed before exiting the maze (SSQ2, SSQ3, or SSQ4).	Not applicable	• Calculating the following variables: Maze sickness and mitigation recovery
Maze sickness	The amount of sickness experienced during the maze. Higher scores indicate greater amounts of sickness.	Final maze SSQ minus baseline SSQ timepoint measurement (SSQ-base-1). Maze sickness = (Final maze SSQ) – (SSQ-base-1)	• Mitigation group differences during the maze period • Gender group differences during the maze • Video game play group differences during the maze
Mitigation recovery	The amount of sickness recovery experienced during the mitigation task (reduction in sickness). Higher scores indicate greater amounts of recovery.	Final maze SSQ minus last SSQ timepoint measurement during mitigation (SSQ-mit-7). Mitigation recovery = (Final maze SSQ) – (SSQ-mit-7)	• Mitigation group differences during the mitigation period • Gender group differences during the mitigation period • Video game play group differences during the mitigation period

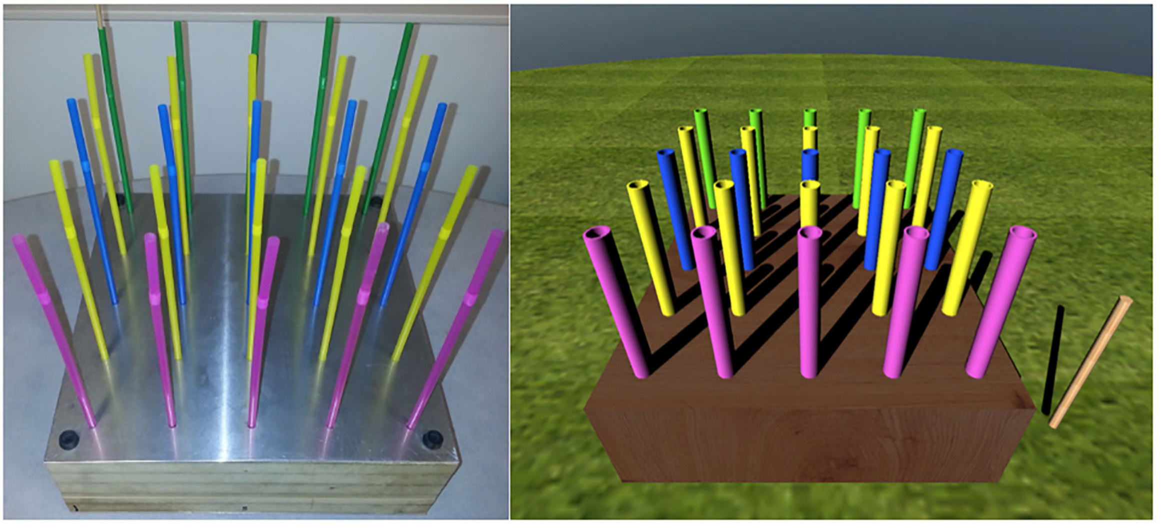

FIGURE 2 | The real hand–eye coordination task (left) (Stone et al., 2012) and the virtual hand–eye coordination task (right).

In the mitigation phase, each participant was randomly assigned to one of four mitigation experimental task groups: real natural decay (RND), real hand–eye coordination (RHE), virtual natural decay (VND), or virtual hand–eye coordination (VHE). The RND required participants to sit quietly with their eyes open or closed for 15 min while not receiving any virtual or real stimuli. In the RHE (**Figure 2**, left), participants were instructed to place a peg into straw-like holes from back to front (Champney et al., 2007; Stone et al., 2012). The pegboard included 25 pegs (five rows, five columns), and each row had different peg colors. This task was performed until participants completed the pegboard or until 15 min elapsed (whichever came first). The VHE (**Figure 2**, right) was the virtual reality equivalent of the real hand–eye coordination task. Using a Razer Hydra with handheld magnetic tracking controllers, participants were required to guide a virtual peg into a virtual pegboard for 15 min or until the task was completed. In the VND (**Figure 3**), participants sat in a calm VE wherein they could look around at fields and mountains. There was no locomotion within the VE. This was completed for 15 min.

Measures

Demographics and Background

Demographic information (**Table 1**) was gathered on age and gender (0 = female, 1 = male). Background information was gathered on whether or not the participant played video games (0 = no, 1 = yes), average weekly video game experience (0 = less than 1 h per week, 1 = 1–5 h per week, 2 = 6–10 h per week, 3 = 10+ h per week, prior experiences with VR (0 = no, 1 = yes), amount of sleep (0 = less than normal, 1 = normal, 2 = more than normal), and if they had eaten the day of the study (0 = no, 1 = yes).

Dependent Variables

The dependent variables were calculated using the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). Responses

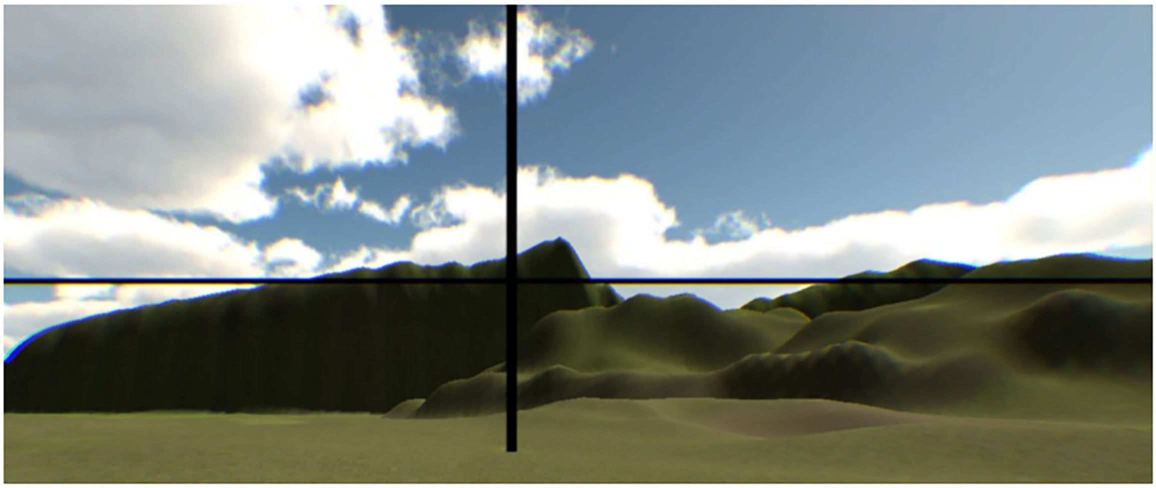

FIGURE 3 | The virtual natural decay environment.

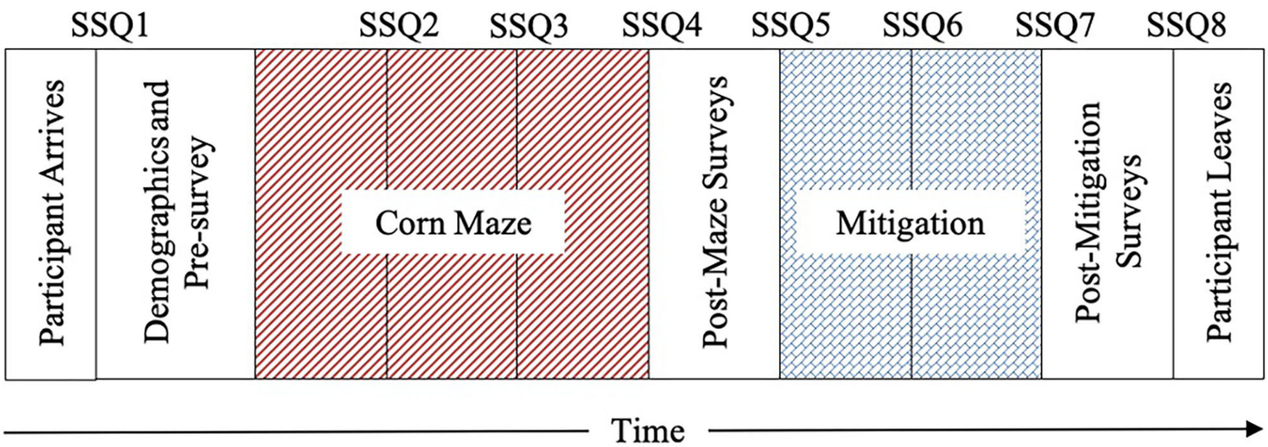

FIGURE 4 | Experimental timeline adapted from Curtis (2014).

to each item were scored on a four-point scale from "*None*" (0), "*Slight*" (1), "*Moderate*" (2), or "*Severe*" (3). The questionnaire is composed of three subscales: nausea, oculomotor, and disorientation. To calculate the score for each subcategory, one must add together all the relevant symptom responses and multiply by the subcategory's multiplier. Likewise, the total severity (TS) score is a sum of the symptom responses given by the participant multiplied by the TS multiplier. The relationship between the subcategory scores and TS scores is not simply additive. The minimum value for each score is 0, signifying no motion sickness symptoms. Higher scores signify more severe symptoms. The maximum value for each score is 200.34 for nausea (N), 159.18 for oculomotor (O), 292.32 for disorientation (D), and 235.62 for TS (Kennedy et al., 1993). Over a large sample of aircraft pilots experiencing aircraft flight simulators, Kennedy et al. (1993) observed an average total score of 9.8 ($SD = 15.0$).

Procedure and Timeline for Measuring Dependent Variables

The study timeline began with a baseline measurement, followed by maze and mitigation phases, ending with debriefing **Figure 4**. At baseline, participants completed the informed consent and demographic questionnaire. The SSQ was verbally measured eight times throughout the experiment: once at baseline (SSQ-base-1), three times during the maze [SSQ-maze-2 (5 min into maze), SSQ-maze-3 (10 min into maze), SSQ-maze-4 (15 min into maze)], three times during the mitigation phase [SSQ-mit-5 (0 min into mitigation), SSQ-mit-6 (5 min into mitigation), SSQ-mit-7 (10 min into mitigation)], and once after debriefing (SSQ-debr-8). Participants were allowed to exit the maze phase of the study at any point that they felt too uncomfortable to continue; not everyone completed all three of the maze SSQ measurements. It should be noted that the SSQ numbering was determined by a specific timepoint, and not based on the number of surveys a participant took. If a participant was not able to complete a specific timepoint, that data is considered missing or incomplete. The SSQ was used to create three dependent variables (DVs): Final Maze SSQ, Maze Sickness, and Mitigation Recovery (**Table 2**).

Final Maze SSQ

The SSQ was taken three times during the maze portion of the experiment at 5 min (SSQ-maze-2), 10 min (SSQ-maze-3), and 15 min (SSQ-maze-4) into the maze. Because participants were allowed to exit the maze phase of the study at any point that they felt too uncomfortable to continue, not everyone completed all three of the maze SSQ measurements. Therefore, the Final Maze SSQ reflects the final SSQ measurement each participant completed before exiting the maze. The Final Maze SSQ was calculated for the SSQ TS and subscales N, O, and D, and those were used to create the Maze Sickness and Mitigation Recovery dependent variables.

Maze Sickness

Maze Sickness was calculated by subtracting the baseline SSQ (SSQ-base-1 taken prior to entering the maze) from the Final Maze SSQ (**Table 2**). The Maze Sickness variable therefore reflects each participant's amount of sickness increase before VR exposure to the mitigation technique. The Maze Sickness variable relates to susceptibility prior to mitigation, so group differences in this could only be examined for gender and video game play experience. Maze Sickness was calculated for the SSQ TS (MSTS), N (MSN), O (MSO), and D (MSD).

Mitigation Recovery

The SSQ was taken three times during the mitigation portion of the experiment: At the beginning of mitigation (0 min into mitigation, SSQ-mit-5), 5 min into mitigation (SSQ-mit-6), and 10 min into mitigation (SSQ-mit-7). Mitigation Recovery was calculated by subtracting the final SSQ measurement during mitigation (SSQ-mit-7) from the Final Maze SSQ to reflect each participant's amount of recovery during their respective mitigation task (**Table 2**). The Mitigation Recovery variable relates to adaptation from sickness from mitigation tasks. Mitigation Recovery was calculated for the SSQ TS (MRTS) and subscales N (MRN), O (MRO), and D (MRD).

Apparatus

An Oculus Rift DK1 HMD was used to display graphics and track user movement for an immersive experience. The Oculus Rift weighed 0.38 kg and had a 110-degree field of view with a total resolution of 1,280 × 800 pixels. It was configured in stereo mode throughout the duration of the experiment. The maze was navigated using the Logitech Dual Action gamepad. For those completing the VHE, directions were given on how to navigate the peg through the peg-in-hole scene using a Razer Hydra handheld controller.

Data Analysis Approach

First, descriptive statistics were assessed for each for the experimental mitigation groups (RND, RHE, VND, and VHE) and the dependent variables: Final Maze SSQ, Maze Sickness, and Mitigation Recovery (Section Descriptive Statistics). Second, group differences during the maze were examined using one-way ANOVAs and Scheffe *post-hoc* analyses (when there were more than two groups. i.e., there were four mitigation groups) in three sections: Experimental Mitigation Group Differences in Maze Sickness; Gender Group Differences in Maze Sickness; and Video Game Play Group Differences in Maze Sickness. Third, group differences during mitigation were examined using one-way ANOVAs and Scheffe *post-hoc* analyses in three sections: Experimental Mitigation Group Differences in Mitigation Recovery; Gender Group Differences in Mitigation Recovery; and Video Game Play Group Differences in Mitigation Recovery.

Interactions between gender and videogame play on Maze Sickness and Mitigation Recovery could not be assessed because the group sizes were too disproportional (i.e., Female-Video Game = 4, Female-No Video Game = 17, Male-Video Game = 34, Male-No Video Game Play = 2). Based on the sample, the majority of females were non-game players and the majority of males were video game players. More data is needed to tease apart the effects of gender and video game play.

All analyses were completed in SPSS version 26. Eta-squared was used to measure effect size, where 0.02 is considered a small effect, 0.13 a medium effect, and 0.26 a large effect (Cohen, 1988). The assumptions for all ANOVAs were met.

RESULTS

Descriptive Statistics

Over 70% of participants remained in the Corn Maze through SSQ-maze-4 ($n = 40$). On average, participants reached their highest level of sickness during SSQ-maze-3. One participant did not complete SSQ-maze-3 and 17 participants did not complete SSQ-maze-4. Additionally, two participants have incomplete data for SSQ-mit-7 and SSQ-debrief-8.

The SSQ TS, N, O, and D raw mean scores at each SSQ measurement point for the entire sample are presented in **Table 3**. During mitigation, there is a slight increase in overall average SSQ scores for all subscales. Paired sample t-tests reveal that the change in SSQ score between SSQ-mit-5 and SSQ-mit-7 was insignificant for TS [$t(54) = -1.627$, $p = 0.110$], N [$t(54) = -1.626$, $p = 0.110$], O [$t(54) = -1.707$, $p = 0.094$], and D [$t(54) = -1.135$, $p = 0.262$], indicating that the increase in scores was minimal and non-impactful. Final Maze SSQ scores for TS ranged from 0 to 175.78 ($m = 77.36$, $SD = 49.74$); N ranged from 0 to 162.18 ($m = 64.44$, $SD = 41.75$); O ranged from 0 to 136.44 ($m = 55.32$, $SD = 35.67$); and D ranged from 0 to 250.56 ($m = 92.31$, $SD = 70.67$), indicating a broad range of differences between individuals. **Table 4** provides the descriptive statistics for Maze Sickness and Mitigation Recovery for each SSQ subscale. Maze Sickness VIMS variables (i.e., MSTS, MSN, MSO, and MSD) ranged from as low as −15.16 up to 236.64. Comparatively, Mitigation Recovery VIMS variables (i.e., MRTS, MRN, MRO, and MRD) ranged from −111.36 to 180.96. These ranges suggest a substantial amount of individual variability in sickness susceptibility and recovery. Finally, in regard to the experimental mitigation groups, the RND experimental group had $n = 16$, the RHE experimental group had $n = 15$, the VND

TABLE 3 | Raw SSQ mean scores at each measurement timepoint for all participants.

	Total score	Nausea	Oculomotor	Disorientation	N
SSQ-base-1	9.45	7.20	10.37	5.62	57
SSQ-maze-2	54.79	39.83	41.76	69.11	57
SSQ-maze-3	73.93	60.48	54.01	87.75	56
SSQ-maze-4	64.52	53.42	47.94	74.12	40
SSQ-mit-5	33.66	24.94	27.26	38.83	57
SSQ-mit-6	37.40	28.12	31.92	39.56	57
SSQ-mit-7	39.37	30.35	32.25	43.03	55
SSQ-debrief-8	27.81	20.29	23.70	30.37	55

Decreases in N values may occur from participants not able to complete that specific survey timepoint (i.e., dropped out early, survey data incomplete, or participant suffering from sickness).

TABLE 4 | Descriptive statistics for maze sickness and mitigation recovery.

	N	*M* (*SD*)	Minimum	Maximum
Maze sickness				
Total score	57	67.91 (48.54)	−7.48	164.56
Nausea	57	57.24 (40.34)	−9.54	143.10
Oculomotor	57	44.95 (34.44)	−15.16	121.28
Disorientation	57	86.69 (70.34)	0.00	236.64
Mitigation recovery				
Total Score	55	37.94 (44.81)	−59.84	142.12
Nausea	55	33.65 (41.50)	−38.16	124.02
Oculomotor	55	23.29 (33.48)	−37.90	98.54
Disorientation	55	49.35 (58.99)	−111.36	180.96

Decreases in N values may occur from participants not able to complete that specific survey timepoint (i.e., dropped out early, survey data incomplete, or participant suffering from sickness).

experimental group had $n = 14$, and the VHE experimental group had $n = 12$.

Group Differences During the Maze

Experimental Mitigation Group Differences in Maze Sickness

There were no significant mitigation group differences in MSTS, MSN, MSO, or MSD {[$F(3, 53)_{\text{MSTS}} = 0.60$, $p = 0.621$]; [$F(3, 53)_{\text{MSN}} = 0.99$, $p = 0.406$]; [$F(3,53)_{\text{MSO}} = 0.57$, $p = 0.636$]; [$F(3, 53)_{\text{MSD}} = 0.28$, $p = 0.842$]} (**Table 5**). This indicates that none of the mitigation groups were predisposed to more VIMS due to sampling bias.

Gender Group Differences in Maze Sickness

Women had significantly more VIMS than men for MSTS, MSN, MSO, and MSD {[$F(1, 55)_{\text{MSTS}} = 8.39$, $p = 0.005$]; [$F(1, 55)_{\text{MSN}} = 9.84$, $p = 0.003$]; [$F(1, 55)_{\text{MSO}} = 4.92$, $p = 0.031$]; [$F(1, 55)_{\text{MSD}} = 7.68$, $p = 0.008$]} (**Table 6**). This indicates that women experienced more sickness from the corn maze than the men did.

TABLE 5 | Maze sickness mean scores, standard deviations, and experimental mitigation group differences using ANOVAs.

SSQ	Mitigation group							
	RND	RHE	VND	VHE	*F*	*df*	*p*	η^2
Total score	75.27 (47.87)	53.61 (52.92)	71.33 (49.13)	72.00 (45.39)	0.60	3, 53	0.621	0.03
Nausea	67.97 (44.32)	43.25 (43.40)	59.28 (36.51)	58.04 (35.10)	0.99	3, 53	0.406	0.05
Oculomotor	47.85 (31.65)	34.87 (36.10)	48.73 (29.71)	49.27 (29.71)	0.57	3, 53	0.636	0.03
Disorientation	93.09 (70.93)	72.38 (74.62)	89.49 (67.03)	92.80 (74.45)	0.28	3, 53	0.842	0.02

RND, Real Natural Decay (n = 16); RHE, Real Hand Eye (n = 15); VND, Virtual Natural Decay (n = 14); and VHE, Virtual Hand Eye (n = 12). Higher values indicate greater amounts of sickness.

TABLE 6 | Maze sickness and mitigation recovery mean scores, standard deviations, and gender group differences using ANOVAs.

SSQ	Gender					
	Female	Male	*F*	*df*	*p*	η^2
Maze sickness						
Total score	90.83^a (39.14)	54.54^b (48.94)	8.39	1, 55	0.005	0.13
Nausea	77.68^a (35.35)	45.32^b (38.79)	9.84	1, 55	0.003	0.15
Oculomotor	57.75^a (26.74)	37.48^b (36.51)	4.92	1, 55	0.031	0.08
Disorientation	118.65^a (64.94)	68.05^b (67.36)	7.68	1, 55	0.008	0.12
Mitigation recovery						
Total score	54.50^a (40.45)	27.72^b (44.85)	4.98	1, 53	0.030	0.09
Nausea	49.97^a (37.43)	23.57^b (41.17)	5.71	1, 53	0.020	0.10
Oculomotor	33.93 (30.19)	16.72 (34.14)	3.59	1, 53	0.063	0.06
Disorientation	67.61 (61.83	38.08 (55.08)	3.40	1, 53	0.071	0.06

Scores with different superscripts are significantly different from each other by row. Group sizes for Maze Sickness: Female (n = 21) and Male (n = 36). Group sizes for Mitigation Recovery: Female (n = 21) and Male (n = 34). Higher values indicate greater amounts of sickness.

Video Game Play Group Differences in Maze Sickness

Those who play video games had significantly less VIMS than those who did not play video games for MSTS, MSN, MSO, and MSD [($F(1, 55)_{\text{MSTS}} = 8.74$, $p = 0.005$]; [$F(1, 55)_{\text{MSN}} = 7.90$, $p = 0.007$]; [$F(1, 55)_{\text{MSO}} = 4.82$, $p = 0.032$)]; [$F(1, 55)_{\text{MSD}} = 10.40$, $p = 0.002$)] (**Table 7**).

Group Differences During Mitigation

Experimental Mitigation Group Differences in Mitigation Recovery

There were significant mitigation group differences in MRTS, MRN, and MRO {[$F(1, 53)_{\text{MRTS}} = 4.98$, $p = 0.030$]; [$F(1, 53)_{\text{MRN}} = 5.71$, $p = 0.020$]; [$F(1, 53)_{\text{MRO}} = 5.13$, $p = 0.004$]} (**Table 8**, **Figure 5**). There were no significant group differences in MRD [$F(1, 53)_{\text{MRD}} = 2.34$, $p = 0.084$]. Specifically, the RND group experienced significantly more recovery than the VHE group for MSTS, MRN, and MRO [(RND-VHE$_{\text{MRTS}}$ = 56.72, 95% CI [10.18,103.25], $p = 0.011$); (RND-VHE$_{\text{MRN}}$ = 50.84, 95%

TABLE 7 | Maze sickness and mitigation recovery mean scores, standard deviations, and video game play group differences using ANOVAs.

SSQ	Video game play		*F*	*df*	*p*	η^2
	No	Yes				
Maze sickness						
Total score	93.11[a] (43.60)	55.31[b] (46.39)	8.74	1, 55	0.005	0.14
Nausea	77.32[a] (38.01)	47.20[b] (38.22)	7.90	1, 55	0.007	0.13
Oculomotor	58.65[a] (29.56)	38.10[b] (35.00)	4.82	1, 55	0.032	0.08
Disorientation	126.01[a] (69.98)	67.04[b] (62.58)	10.40	1, 55	0.002	0.16
Mitigation recovery						
Total score	49.41 (47.35)	31.89 (42.84)	1.93	1, 53	0.170	0.03
Nausea	45.19 (42.41)	27.56 (40.27)	2.30	1, 53	0.135	0.05
Oculomotor	27.53 (34.39)	21.06 (33.27)	0.46	1, 53	0.501	0.03
Disorientation	67.40 (69.33)	39.83 (51.24)	2.81	1, 53	0.100	0.02

Scores with different superscripts are significantly different from each other by row. Group sizes for Maze Sickness: No (n = 19) and Yes (n = 38). Group sizes for Mitigation Recovery: No (n = 19) and Yes (n = 36). Higher values indicate greater amounts of sickness.

TABLE 8 | Mitigation recovery mean scores, standard deviations, and experimental mitigation group differences using ANOVAs.

SSQ	Mitigation group				*F*	*df*	*p*	η^2
	RND	RHE	VND	VHE				
Total score	61.48[a] (34.55)	31.17[a,b] (52.05)	44.88[a,b] (41.93)	4.76[b] (30.34)	4.40	3, 51	0.008	0.21
Nausea	56.05[a] (34.29)	26.08[a,b] (43.64)	38.89[a,b] (41.49)	5.20[b] (31.46)	4.12	3, 51	0.011	0.20
Oculomotor	42.16[a] (28.22)	14.15[a,b] (36.45)	30.90[a,b] (30.55)	−0.69[b] (21.83)	5.13	3, 51	0.004	0.23
Disorientation	69.60 (49.80)	51.97 (69.09)	53.54 (53.26)	11.39 (52.02)	2.34	3, 51	0.084	0.12

Scores with different superscripts are significantly different from each other by row. RND, Real Natural Decay (n = 16); RHE, Real Hand Eye (n = 15); VND, Virtual Natural Decay (n = 13); and VHE, Virtual Hand Eye (n = 11).

CI [7.46,94.22], p =.015); (RND-VHE$_{MRO}$ = 42.85, 95% CI [8.66,77.05], p =.008)].

Gender Group Differences in Mitigation Recovery

Women had significantly more VIMS recovery than men for MSTS and MSN {[$F(1, 53)_{MRTS} = 4.98, p = 0.030$]; [$F(1, 53)_{MRN} = 5.71, p = 0.020$]} (**Table 6**, **Figure 6**). Comparatively, there were no significant gender differences in MRO or MRD, although they approached significance {[$F(1, 53)_{MRO} = 3.59, p = 0.063$]; [$F(1, 53)_{MRD} = 3.40, p = 0.071$]}.

Video Game Play Group Differences in Mitigation Recovery

There were no significant video game play group differences in VIMS recovery {[$F(1, 53)_{MRTS} = 1.93, p = 0.170$]; [$F(1, 53)_{MSN} = 2.30, p = 135$]; [$F(1, 53)_{MSO} = 0.46, p = 0.501$]; [$F(1, 53)_{MSD} = 2.81, p = 0.100$]} (**Table 7**, **Figure 7**).

DISCUSSION

The purpose of this study was to explore the effectiveness of four VIMS mitigation methods (i.e., RND, VND, RHE, VHE) using the Corn Maze designed to induce sickness symptoms measured by Kennedy's SSQ. All mitigation methods reduced VIMS to a certain extent. However, RND resulted in greater Mitigation Recovery, followed by VND, the RHE, and VHE. The largest amount of Mitigation Recovery was seen within the disorientation subscale, followed by the nausea and oculomotor subscales. This is consistent with the VR exposure profile seen in other SSQ research: disorientation is greater than nausea, which is greater than oculomotor strain (Stanney et al., 1997).

Mitigation Techniques

Consistent with previous work (Curtis et al., 2015), RND was the most effective VIMS mitigation technique. However, there were no significant differences in Mitigation Recovery between the RND and VND groups. This suggests that a VR scene could possibly aid in VIMS recovery without removing the user from the VE. What remains unclear for both the RND and VND is how much time beyond exposure is needed for users to completely recover from VIMS, or if that is always possible within VND. The prolonged measurement period needed to measure complete recovery was beyond the scope of the current study. Future research should consider measuring VIMS periodically after exposure (Baltzley et al., 1989), such as once every 15 min up to 1 h after exposure (e.g., Champney et al., 2007) or even longer to better illuminate the amount of time natural decay requires.

These results suggest that mitigation within a VE is possible but may require certain alterations to perform as well as RND. For instance, the VND environment allowed participants to look around a scene with a grass, mountains, and clouds. Because of this rotational visual stimulus within the VND environment, it is possible that ocular focus and proprioception were still engaged, perhaps impeding the reconciliation of the sensory systems (Champney et al., 2007). In RND, participants sat quietly in a room with their eyes open or shut, so there may have been fewer visual stimuli to focus on compared to the VND environment. Because there is extremely limited research on VND (e.g., Curtis, 2014), these findings bolster credibility for the benefits of VND. It remains unclear if virtual natural decay requires prolonged recovery periods, like the real-world version, in order to be fully effective. Future research would benefit from implementing this mitigation technique and measuring VIMS for at least an hour after exposure. These results were not expected. Effectiveness of virtual mitigation tasks could be improved as equipment advances, such as with higher resolution, improved latency, and lower weight. In addition to measuring VIMS for longer post-exposure and with advanced hardware, future research should explore physiological measurements of sickness, such as electrodermal activity or heart rate, to help validate subjective self-assessments of sickness.

Both natural decay mitigation techniques resulted in slightly more, but not significantly more, Mitigation Recovery than the hand–eye coordination techniques. Previous research has

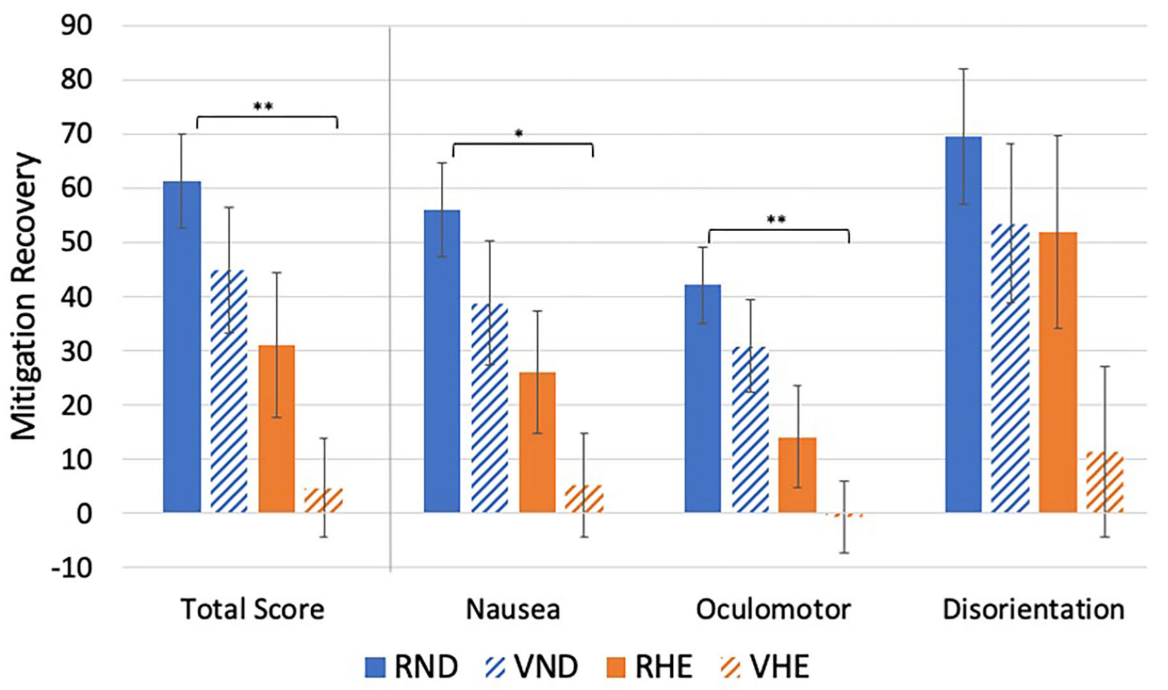

FIGURE 5 | Experimental mitigation group mean differences in mitigation recovery. $^{*}p < 0.05$, $^{**}p < 0.01$. Higher values indicate greater amounts of recovery.

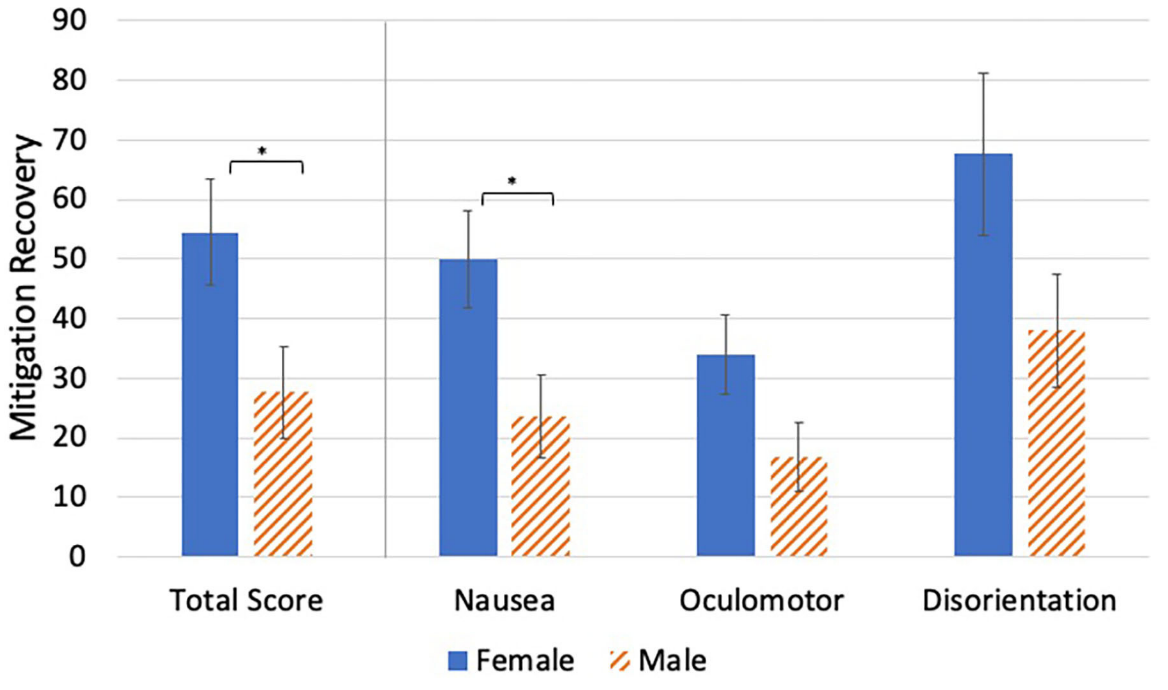

FIGURE 6 | Video game play group mean differences in mitigation recovery. $^{*}p < 0.05$. Higher values indicate greater amounts of recovery.

suggested that a hand–eye task is more effective for VIMS recovery than natural decay because it recalibrates the sensory systems (Champney et al., 2007), an effect that is not supported by the current findings. These differences may be due in part to the hardware and controller used. For the current RHE, the pegboard was larger than in the Champney et al. study, requiring

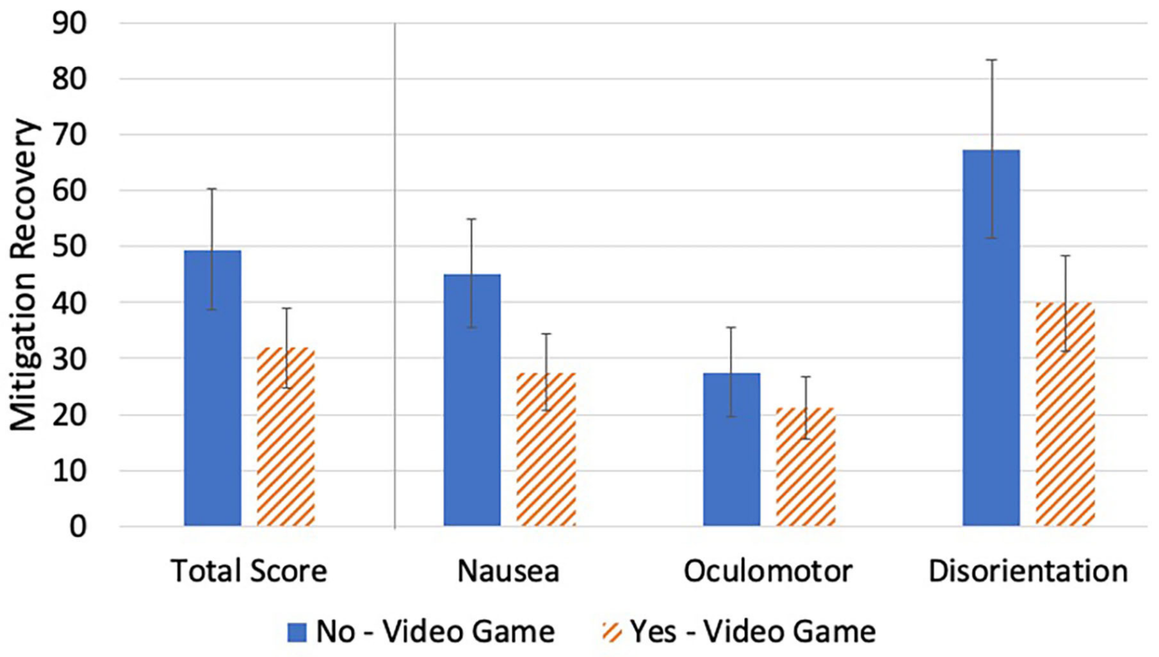

FIGURE 7 | Video game play group mean differences in mitigation recovery. No significant differences in Mitigation Recovery were found.

movement of the entire arm, thus not requiring the same fine motor skills, perhaps impacting effectiveness.

The VHE task was by far the least effective mitigation technique. The VHE group had significantly less Mitigation Recovery than the RND. The motivation behind utilizing a VHE task was that it could potentially provide a task that engages ocular focus and proprioception, which may reduce sickness symptoms per Champney et al. (2007), while remaining immersed in a virtual environment. There are several possible ergonomic explanations for the gap between VHE and RHE scores. Because of the Razer Hydra interface, which felt somewhat like controlling the peg by moving a television remote-sized object through space, the VHE task did not have haptic or force feedback to indicate to the user than the peg and a straw collided. This issue was reinforced by participants mentioning how difficult it was to determine the point of contact. Second, the Razer Hydra was heavier than what participants experienced in the real-world version of the task, lifting the controller rather than a lightweight peg. Third, the real task required the index finger, middle finger, and thumb to pick up the virtual peg and mostly lower arm movement to place the peg. This is an example of finer motor control, closer to a third-class ergonomic motion vs. the less fine motor task of moving the controller with primarily whole arm and wrist (a fourth-class motion) (Freivalds and Niebel, 2013). Finally, participants had a fixed point of view (POV) when completing the VHE task. Not having headtracking of the headset relative to the peg board could yield an awkward positioning above the board. These differences limited the physical affordances of the hand–eye task and potentially altered the experience that would recalibrate one's system to mitigate VIMS. Future iterations of VHE should consider implementing more natural interfaces, perhaps using a controller such as the Phantom or Tap Strap, which could provide haptic feedback for finger-level motion. Further, it could be beneficial to bolster the virtual experience by including 3D sound and/or head-tracking during the peg-in-hole task to increase its similarity to the real peg-in-hole task. These additional affordances may provide the user with a more realistic virtual peg-in-hole task, refined motor control, and more realistic visual orientation, perhaps improving its ability to mitigate sickness. A broader review of the fidelity of the virtual hand–eye coordination task using the lens of authenticity (Gilbert, 2016) or coherence (Skarbez et al., 2018) might be valuable to ensure that the types of fidelity required by the task match the fidelity of the system.

It is interesting, yet unclear, why VIMS slightly increased after the beginning of mitigation. While there was a slight increase and plateau in SSQ TS, N, O, and D across SSQ-mit-5, SSQ-mit-6, and SSQ-mit-7, paired sample t-tests revealed that there were not statistically significant changes in these measurement points. Regardless, future research should closely monitor changes in VIMS during mitigation tasks, use additional measures, such as physiological indicators of sickness, and employ state-of-the-art HMD hardware to cross-validate VIMS experiences.

Within the present study, RND was the most effective mitigation technique; however, all of the mitigation tasks did reduce VIMS. It was somewhat disappointing that RND remained the most impactful mitigation technique, as the other three offered promising potential alternatives. We believe that future research should consider improving the fidelity within the VEs, utilize the most up-to-date hardware, and refine the dexterity capabilities for virtual tasks, like the VHE. It is possible that certain mitigation techniques are more effective based on individual differences, so additional research with larger sample sizes are needed to examine interactions and predictive relationships among individual characteristics and mitigation techniques.

Individual Differences

Gender differences in VIMS were consistent with previous literature that found women to be more susceptible to sickness than men (Koslucher et al., 2015, 2016; Munafo et al., 2017). There has been less research on gender differences in mitigation, however, and this study offers the interesting result that women experienced more recovery than men during mitigation, pointing to a future area of research. Some theorize that gender differences in VIMS could be due to hardware differences (Fulvio et al., 2020). For example, default HMD settings are generally sized to fit the interpupillary distance of men, rather than women (Fulvio et al., 2020). When the interpupillary distance is not calibrated to women, it is possible that they will experience more VIMS. It is unclear why there were no video game play group differences in Mitigation Recovery; however, it is possible that video game players are more de-sensitized to the visual effects of virtual worlds, thus more resistant to VIMS.

Limitations

A limitation of the current sample is that it primarily consisted of men who play video games and women who did not play video games (**Table 3**). Due to this confound in sampling, the comparison between men and women and the comparison between video game players and non-video game players yielded similar results. As such, more data is needed to tease apart the effects of gender and video game play. Future work exploring the independent effects of gender and video game experience on VIMS would help contribute to the broader understanding of cybersickness. It is also possible that the verbal administration of the SSQ during both the maze and the mitigation tasks could have interrupted user attention, potentially affecting presence and increasing sickness levels. Further investigations would benefit from comparing sickness between participants when the SSQ is administered throughout tasks vs. only at the end of tasks. The RHE did not result in more Mitigation Recovery than RND, which may suggest that the experimental equipment was insufficient to realize the benefits, and should thus be reconceptualized in future research with more state-of-the-art hardware and particular attention to the experimental setup. Ongoing work should apply higher resolution HMDs with head tracking to reduce sickness during mitigation and properly highlight the effectiveness of mitigation techniques, as the Oculus Rift DK1 was earlier hardware.

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 Institutional Review Board, Iowa State University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR'S NOTE

The present research extends VIMS research to compare the effectiveness of four mitigation methods, within and outside of VR, following exposure in order to better understand VIMS recovery. These findings extend current knowledge by providing empirical evidence for the effectiveness of not only RND, but also VND, RHE, and, to a lesser extent, VHE. Although VHE was the least effective of all mitigation techniques, modifications to the hardware and controller interface provide promising future steps for the development of VIMS mitigation techniques during VE immersion.

AUTHOR CONTRIBUTIONS

AJ: Primary authorship throughout document, data analysis, figures/tables creation. NC: Secondary authorship throughout document, data analysis, figure/tables creation. CM and MC: Study design, data collection, text revisions. MD: Authorship throughout, figures/tables revisions, study design. SG: Authorship throughout, figures/tables revisions, reference list. All authors contributed to the article and approved the submitted version.

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HYPOTHESIS AND THEORY
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Cybersickness in Head-Mounted Displays Is Caused by Differences in the User's Virtual and Physical Head Pose

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Sensory conflict, eye-movement, and postural instability theories each have difficulty accounting for the motion sickness experienced during head-mounted display based virtual reality (HMD VR). In this paper we review the limitations of existing theories in explaining cybersickness and propose a practical alternative approach. We start by providing a clear operational definition of provocative motion stimulation during active HMD VR. In this situation, whenever the user makes a head movement, his/her virtual head will tend to trail its true position and orientation due to the display lag (or motion to photon latency). Importantly, these *differences in virtual and physical head pose* (*DVP*) will vary over time. Based on our own research findings, we propose that cybersickness in HMD VR is triggered by large magnitude, time-varying patterns of *DVP*. We then show how this hypothesis can be tested by: (1) systematically manipulating display lag magnitudes and head movement speeds across HMD VR conditions; and (2) comparing the estimates of the user's *DVP* in each of these conditions to their own reports of cybersickness severity. We believe that this approach will allow researchers to precisely predict which situations will (and will not) be provocative for cybersickness in HMD VR.

Keywords: head-mounted display, motion sickness, cybersickness, motion-to-photon latency, sensory conflict, postural instability

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INTRODUCTION

Anyone who has tried *virtual reality (VR)* using modern *head-mounted displays (HMDs)* cannot help but be impressed by their potential. These increasingly affordable, consumer-friendly devices are now able to transport their users to highly immersive computer-generated worlds. The interactive, multisensory feedback that they provide can generate compelling feelings of presence (or "being there") and realistic user responses to these virtual environments (Schubert et al., 2001; Cummings and Bailenson, 2016; Skarbez et al., 2017).

The promise of this revolutionary technology can clearly be seen by the host of applications already developed for its use (e.g., in SteamVR, Oculus and Viveport). To date, HMD VR applications have been created for advertising, archaeology, architecture, business, clinical psychology, defense, design, education, engineering, entertainment and the arts, health and safety, gaming, manufacturing, medicine, real estate, research, simulation training, sport, social media, telecommunications, tourism, and urban design (e.g., Tate et al., 1997; Hogue et al., 1999; Blascovich et al., 2002; Simons and Melzer, 2003; Mujber et al., 2004; Villani et al., 2007; Ch'ng, 2009; Phan and Choo, 2010; Wiederhold et al., 2014; Gonizzi Barsanti et al., 2015; Grabowski and Jankowski, 2015; Elliman et al., 2016; Eubanks et al., 2016; Khor et al., 2016; Ortegon-Sarmiento et al., 2016; Bernardo, 2017; Andersen and Popescu, 2018; Jensen and Konradsen, 2018; Pot-Kolder et al., 2018; Han and Cho, 2019; Yildirim, 2019a,b; Chen et al., 2020).

Unfortunately, despite the potential of HMD VR, user experiences of motion sickness continue to limit its adoption (Biocca, 1992; Draper et al., 2001; Patterson et al., 2006; Merhi et al., 2007; Sharples et al., 2008; Lawson, 2014; Rebenitsch and Owen, 2016, 2020; Munafo et al., 2017; Palmisano et al., 2017; Weech et al., 2018; Arcioni et al., 2019; Clifton and Palmisano, 2019; Risi and Palmisano, 2019). This paper is focused on better understanding this cybersickness[1], as well as proposing new ways to study, and potentially mitigate, it.

The Problem of Cybersickness

Despite heavy investment in possible hardware and software solutions over the last decade, many users still become sick during HMD VR (Rebenitsch and Owen, 2016, 2020). For example, in our recent research using modern HMDs and commercial video games, more than 80% of participants reported some cybersickness after only 10–15 min of HMD VR gameplay (Clifton and Palmisano, 2019; Risi and Palmisano, 2019; Teixeira and Palmisano, 2020). From their own anecdotal reports, these HMD users appear to transition quite rapidly from pleasurable feelings of immersion to unpleasant experiences of cybersickness (see Boyd, 2014; Lewis, 2015). This cybersickness can present as a variety of signs and symptoms, including nausea, stomach awareness, increased/decreased salivation, sensations of bodily warmth, sweating, changes in facial pallor, disorientation, dizziness, vertigo, fainting, light headedness, fullness of head, blurred vision, eye strain, difficulty focusing, drowsiness, headache, fatigue, and sometimes even vomiting and retching (Ebenholtz, 1992; McCauley and Sharkey, 1992; Stanney et al., 1998b; LaViola, 2000; Lawson, 2014; Rebenitsch and Owen, 2016; Gavgani et al., 2017a).

Unfortunately, cybersickness in HMD VR tends to be more provocative than the sickness produced by other types of VR (Howarth and Costello, 1997; Sharples et al., 2008; Kim et al., 2014; Dennison et al., 2016; Yildirim, 2019a,b). For example, in a recent study, Dennison et al. (2016) found that while 11 of their 20 participants were too sick to continue the HMD VR simulation, none of them dropped out when the same simulation was presented via desktop VR. Similarly, Yildirim (2019a) found that cybersickness was common after only 6 min of HMD VR gameplay, whereas minimal sickness was produced when playing desktop versions of the same games.

[1]Cybersickness refers to sickness experienced in both HMD and non-HMD VR. It can also be used to describe the adverse effects produced by large projection/dome screens, Cave Automatic Virtual Environments (CAVE), and VR theaters (McCauley and Sharkey, 1992).

If this cybersickness cannot be substantially reduced, then HMD gaming may fail commercially (as 3D television did recently for home entertainment). We therefore need a better understanding of both the causes and the development of cybersickness in HMD VR, so that we can find more effective ways to mitigate it. While the experience of cybersickness can vary substantially from one HMD user to another (McCauley and Sharkey, 1992): (1) disorientation appears to be a very common symptom (Lawson, 2014; Rebenitsch and Owen, 2016); and (2) vomiting during or after HMD VR is rare (Stanney et al., 1998b; Kingdon et al., 2001). According to Kennedy et al. (2010), HMD VR also tends to cause more nausea, and fewer oculomotor, symptoms than non-HMD VR. These cybersickness symptoms can persist even after the user removes their HMD. In some cases, they can still be reported up to 12 h after the exposure (Kennedy and Lilienthal, 1994; Kennedy et al., 1994; Merhi et al., 2007).

Lawson (2014) has recently noted that there is "no comprehensive and universally accepted theory of motion sickness etiology" (p. 533). This statement also applies to the cybersickness experienced in HMD VR. Thus, in this paper, we propose a new way to understand and study this cybersickness. However, before we outline our hypothesis and recommend an approach for testing it, we will first review the existing theories of cybersickness and their supporting evidence.

PART 1: REVIEW OF EXISTING THEORIES OF CYBERSICKNESS

Most current theories of cybersickness were originally created to explain motion sickness in the real world (such as car, sea, and air sickness) or in vehicle simulators. A variety of different triggers have been proposed for this sickness, including sensory conflict, neural mismatch, visual illusions of self-motion, errors in perceiving the direction of gravity or which parts of the scene are stationary, increased postural instability, excessive eye-motion, and even misperceptions of poisoning (Reason and Brand, 1975; Treisman, 1977; Reason, 1978; Oman, 1982, 1990; Hettinger et al., 1990; Riccio and Stoffregen, 1991; Ebenholtz, 1992; Ebenholtz et al., 1994; Bles et al., 1998; Stoffregen and Smart, 1998; Nalivaiko et al., 2014). Below we outline these different explanations of motion sickness and discuss the evidence for and against them (including data in HMD VR where it is available).

Sensory Conflict Theories of Motion Sickness

Sensory conflict remains the most cited explanation for all types of motion sickness, including cybersickness (Keshavarz et al., 2014; Rebenitsch and Owen, 2016; Yildirim, 2019a). These theories focus on the self-motion and orientation information provided by vision, the vestibular system of the inner ear and the other non-vestibular proprioceptive senses (Guedry, 1991; Palmisano et al., 2011a,b; Keshavarz et al., 2014). Each of these sensory systems has its own specializations and limitations. For example, while vision can detect a variety of self-motions (based on the optic flow that we see when we move), the vestibular system is specialized for detecting accelerating head motion and orientation with respect to gravity (with the semicircular canals and otolith organs responding best to angular and linear head accelerations, respectively; Howard, 1982). Other useful sources of information are also provided about our orientation with respect to gravity based on visual frame and polarity cues, as well as the inertia of our limbs and the forces acting on our bodies (Lishman and Lee, 1973; Lee and Lishman, 1975; Howard, 1982; Howard and Childerson, 1994; Allison et al., 1999; Howard and Hu, 2001).

It is commonly assumed that motion sickness can be triggered whenever two or more of the above sensory systems provide contradictory information (Claremont, 1931; Reason and Brand, 1975). For example, Hettinger et al. (1990) argued that the motion sickness experienced during visually induced illusions of self-motion was due to visual-vestibular conflict. In this case, the observer's optic flow indicates that he/she is moving, but the lack of corresponding activity from the inner ears suggests (correctly) that he/she is stationary. However, this is only one of a number of different sensory conflict accounts of motion sickness (see Treisman, 1977; Reason, 1978; Oman, 1982, 1990; Bles et al., 1998; Prothero and Parker, 2003). Below we first describe the best known, and most highly cited, of these *sensory conflict theories* of motion sickness: the *sensory rearrangement theory* (Reason, 1978). We then proceed on to describe: (1) the modifications that have been made to this theory over the years; and (2) some alternative hypotheses about the exact relationships between sensory conflict and motion sickness.

Sensory Rearrangement Theory

According to this theory, sensory conflict alone is not sufficient to induce motion sickness (Reason, 1978). It is assumed that we have access to a **neural store** of every pattern of motion stimulation that we have ever been exposed to. Whenever we plan a movement, the expected pattern of multisensory stimulation for this movement is chosen from the *neural store*. After the movement is initiated, this expected pattern is then compared to the actual pattern of stimulation arriving from our senses. According to the theory, motion sickness should only occur when there is a discrepancy between our currently sensed and expected patterns of stimulation, referred to as a **neural mismatch**. The likelihood of us becoming sick, and the severity of our sickness, should increase with the degree of this neural mismatch. Our motion sickness should also decrease with repeated exposures to an initially provocative stimulus. This is because our neural store will be recalibrated during each exposure, resulting in a little less neural mismatch on each subsequent exposure. While the theory is focused on planned self-motions, it predicts that motion sickness should be even more likely when we are not in control of our motion (e.g., when we are passengers in a moving automobile).

Criticisms of sensory rearrangement theory

It is generally acknowledged that *sensory rearrangement theory* can provide convincing *post-hoc* explanations of the motion sickness findings of many past studies (Rolnick and Lubow, 1991; Howarth and Finch, 1999; Hill and Howarth, 2000; Draper et al., 2001; Akiduki et al., 2003; Bonato et al., 2005, 2008, 2009; Bubka et al., 2007; Palmisano et al., 2007, 2017; Howarth and Hodder, 2008; Keshavarz and Hecht, 2011a; Nishiike et al., 2013; Chen et al., 2016; Gavgani et al., 2017b). However, it has often been criticized for its inability to make precise, quantitative predictions about motion sickness in the future (Stoffregen and Riccio, 1991; McCauley and Sharkey, 1992; Bles et al., 1998; Draper et al., 2001; Davis et al., 2014; Keshavarz et al., 2014; Lawson, 2014; Lackner and DiZio, 2020). In their recent review, Keshavarz et al. (2014) noted that "the range of conceivable conflicts is so wide that it is difficult to devise experiments [that] would falsify the theory" (p. 654). Lackner and DiZio (2020) have also argued that because "we do not have an adequate understanding of the formation, nature and operation of [the neural store]" (p. 1212) this limits the predictive and explanatory capability of the theory. Researchers attempting to test the theory are forced to make assumptions about: (1) whether a particular stimulus will produce a neural mismatch or not; and (2) if it does, how much mismatch will be generated. The need to make such assumptions clearly limits the practical utility of the theory for studying motion sickness. Thus, as Ebenholtz et al. (1994) note "in its present form, [*sensory rearrangement theory*] may be untestable" (p. 1034).

Mathematical model of sensory rearrangement theory

In an attempt to address these criticisms, Oman (1982, 1990) created a mathematical model of *sensory rearrangement theory*. In this model: (1) muscular activity ($\mathbf{m}$) is generated to move toward a desired destination ($\mathbf{x}_d$), (2) due to actual body dynamics ($\mathbf{B}$), this results in movement to position $\mathbf{x}$ at time 1; (3) the consequences of this movement are detected by the senses ($\mathbf{S}$) in the presence of external noise ($\mathbf{n}_e$), resulting in a sensory outcome ($\mathbf{a}$); (4) the neural store computes the expected sensory outcome ($\hat{\mathbf{a}}$) of the movement, based on $\mathbf{m}$ and internal estimates of the other components (i.e., $\hat{\mathbf{x}}$, $\hat{\mathbf{S}}$, and $\hat{\mathbf{B}}$); and 5) the motion sickness produced is estimated as the vector difference between these actual ($\mathbf{a}$) and expected ($\hat{\mathbf{a}}$) sensory outcomes. The greater the vector difference, the more likely the model will be to trigger motion sickness, and the more severe it will be. A weighted amount of this vector difference is also fed back into the model to update the neural store, allowing it to simulate the sensory adaptation/habituation that occurs during repeated exposures to initially provocative stimuli (Hill and Howarth, 2000; Howarth and Hodder, 2008).

While this mathematical model represents a considerable improvement on earlier versions of *sensory rearrangement theory* (Reason and Brand, 1975; Reason, 1978), assumptions still need to be made about its input parameters, connection weightings, and the non-linearities involved. Thus, some practical problems making predictions using this theory remain even after the mathematical model is implemented.

Other Sensory Conflict Accounts

In our everyday life we are exposed to many potentially provocative sensory conflict situations (at least as they are defined by Reason and Brand, 1975). However, we rarely experience any motion sickness (Stoffregen and Riccio, 1991). Thus, Ebenholtz et al. (1994) have argued that "[w]hat is needed are a priori criteria for distinguishing conflict from non-conflict situations" (p. 1034). In recent years, theorists have attempted to precisely specify exactly which types of sensory conflicts cause motion sickness. Below we outline four different hypotheses about what these critical conflicts might be.

The vection conflict hypothesis

According to this hypothesis, visual illusions of self-motion (**vection**; see Palmisano et al., 2015) are required to trigger both visually induced motion sickness (**VIMS**) and cybersickness (Hettinger et al., 1990; Kennedy et al., 1990; McCauley and Sharkey, 1992; Stanney et al., 1998a; Hill and Howarth, 2000; Howarth and Hodder, 2008). When stationary observers are exposed to visual self-motion simulations only some of them become sick. According to Hettinger et al. (1990), what differentiates "sick" from "well" observers is their experience of vection. Even though both groups are exposed to the same sensory conflict (i.e., their visual stimulation indicates self-motion, whereas their inertial stimulation suggests they are stationary), it is only when this multisensory stimulation induces vection that sickness symptoms emerge. This could explain why many sensory conflict situations do not provoke sickness (because they do not induce any, or sufficient, vection). It might also explain why there are individual differences in susceptibility to VIMS and cybersickness since the vection experienced during the same visual motion stimulation can vary quite widely across individuals (Seno et al., 2017).

Empirical evidence. This hypothesis predicts that VIMS and cybersickness should: (1) never occur without vection; and (2) be more likely to occur, and more severe, during stronger vection. Consistent with the hypothesis, the findings of a number of VIMS and cybersickness studies appear to support these predictions (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). However, other studies have reported non-significant or negative relationships between vection and sickness (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, 2015; Riecke and Jordan, 2015; Gavgani et al., 2017b; Palmisano et al., 2017, 2018; Palmisano and Riecke, 2018; Kuiper et al., 2019; Teixeira and Palmisano, 2020). Nooij et al. (2017) recently found that the relationship between vection strength and VIMS was stronger when it was examined within (as opposed across) participants. They proposed that such relationships might not always be detectable at the group level—possibly explaining the mixed findings above. However, while the exact relationship between vection and motion sickness is currently unclear, Ji et al. (2009) have shown that VIMS can occur without *any* vection. This appears to be clear evidence against the strict *vection conflict hypothesis* (as vection was not required in their study to induce motion sickness).

The subjective vertical conflict hypothesis

According to this hypothesis: "all situations which provoke motion sickness are characterized by a condition in which *the sensed vertical* … is at variance with the **subjective vertical** as predicted on the basis of previous experience" (Bles et al., 1998, pp. 481–482—see also Bos and Bles, 1998, 2002; de Graaf et al., 1998; Bles et al., 2000; Bos et al., 2008). Bles et al. (1998) also implemented this hypothesis as a mathematical model that constructs: (1) a *sensed vertical* (by integrating incoming sensory information from the visual, vestibular, and proprioceptive senses); (2) an *expected vertical* (based on past experiences); and (3) a *subjective vertical* (which is based on the difference vector between the *sensed* and *expected verticals*). According to their hypothesis, it is the *vector difference* between (1) and (3) that generates motion sickness. Thus, sensory conflicts that do not affect the *subjective vertical* should not provoke any motion sickness. Like the classical *sensory rearrangement theory* (from which it evolved), this hypothesis can also explain why motion sickness decreases with repeated exposure to initially provocative stimuli.

Empirical evidence. This hypothesis also provides several readily testable assertions. Consistent with its predictions, motion sickness appears to be more likely when our head moves away from alignment with gravity (Lackner and DiZio, 2006; Thornton and Bonato, 2013; Chen et al., 2016). Bubka and Bonato (2003) have also reported that VIMS increases with (assumed) *subjective vertical conflict*. When their physically upright observers were placed inside a large rotating drum[2], VIMS occurred more rapidly when the drum was tilted away from alignment with gravity (by 5° and 10° compared to the 0° control). While at first glance these findings appear consistent with the *subjective vertical conflict hypothesis*, it is problematic that motion sickness was induced by their 0° tilt control. According to the hypothesis, no motion sickness should have been induced in this condition, because: (1) the drum had vertical stripes on its inner wall and was rotating smoothly (not wobbling) about a true Earth-vertical axis, and (2) the observer's head was always upright and fixed at the center of the drum's rotation. Several other studies have confirmed that VIMS during pure yaw rotation is not due to inadvertent roll or pitch head-movements (Bonato et al., 2005; Nooij et al., 2017). Thus, based on this evidence, *subjective vertical conflict* also does not appear to be necessary for motion sickness.

The rest frame conflict hypothesis

According to this hypothesis, motion sickness is caused by conflicting information about what is (and is not) stationary in our surrounding environment (Prothero et al., 1999; Prothero and Parker, 2003). While there are often multiple scene features that could be stationary, it is proposed that only one of them is chosen to serve as a **rest frame**. This *selected rest frame* then acts as an important reference for making spatial judgements. According to the *rest frame hypothesis*: (1) motion sickness should only occur when sensory conflicts prevent the stable perception of a single rest frame (all other sensory conflicts should not be provocative); and (2) adding an *independent visual background* to displays should reduce this motion sickness (as

[2]Their optokinetic drum apparatus rotated in a wobbling fashion when its axis of rotation was tilted away from gravity. However, its rotation was smooth when its tilt was 0°.

this background would be selected as the rest frame and be perceived to be consistent with the available inertial information). The latter prediction suggests that cybersickness should be reduced in HMD based augmented reality[3] (compared to HMD VR), because users would always be able to see the real world beyond the superimposed synthetic content.

Empirical evidence. Compared to the other theories/hypotheses discussed above, there has been less empirical investigation of the *rest frame hypothesis*. Consistent with the hypothesis, Prothero et al. (1999) found that cybersickness was reduced when their laboratory wall was also visible in the HMD (compared to when it was blocked from view using a mask). Duh et al. (2004) also found that providing an independent visual background (a distant grid) reduced VIMS in a driving simulator (compared to a no background control). However, while both findings appear consistent with the *rest frame hypothesis*, they may simply reflect differences in the vection or subjective verticals experienced with and without stationary backgrounds[4]. Further complicating the interpretation of these findings, it appears that cybersickness can also be reduced by superimposing stationary foreground (as opposed to background) surfaces onto virtual environments (Chang E. et al., 2013; Cao et al., 2018). Thus, we conclude that the available data for the *rest frame hypothesis* are currently inconclusive.

The poison hypothesis

This *hypothesis* is an evolutionary account of why motion sickness exists. It is often used to explain the particular signs and symptoms of motion sickness. It is not designed to predict which stimulus conditions will induce it or how it will develop afterwards. Thus, some theorists do not regard it as a competitor for the above explanations of motion sickness. According to this poison hypothesis, motion sickness only occurs when a sensory conflict suggests that we have ingested poison (Treisman, 1977). When swallowed, we will often purge harmful substances from our bodies by vomiting. It is proposed that in some cases responses related to purging (such as stomach awareness, vertigo and dizziness) are triggered by the activity of our visual, vestibular, and proprioceptive control systems. According to Treisman these senses act as an early warning system for the effects of neurotoxins. However, when they register patterns of motion stimulation similar to those during actual intoxication, this can accidently trigger emesis (a reflexive response involving vomiting, nausea, and retching). This hypothesis has recently been extended by Nalivaiko et al. (2014) who propose that: (1) motion sickness triggers *defensive hypothermia* that acts to cool the sufferer's body; and (2) sweating and changes in skin conductance should therefore provide useful, objective information about the onset and development of motion sickness (Gavgani et al., 2017a,b, 2018).

Empirical evidence Like *sensory rearrangement theory*, Treisman's hypothesis has also been criticized for being difficult to test. Consistent with the hypothesis, research has shown that: (1) bilateral vestibular loss not only prevents motion sickness in humans, but it also impairs the vomiting responses of dogs to certain poisons (Kennedy et al., 1968; Money and Cheung, 1983; Cheung et al., 1991); and (2) motion sickness is often accompanied by significant changes in body temperature and skin conductance levels (see Min et al., 2006; Guo et al., 2012; Kim et al., 2014; Gavgani et al., 2017a,b, 2018). It should be noted that vomiting responses are extremely rare in HMD VR. For example, Kingdon et al. (2001) found that only 15 of their 1,028 university student participants vomited during, or after, HMD VR. Given the rarity of vomiting (and retching) responses in HMD VR, Treisman's *hypothesis* does not appear to be well-suited for understanding this type of cybersickness. It certainly appears to be limited in terms of predicting the occurrence of cybersickness in HMD VR.

The Eye-Movement Theory of Motion Sickness

According to this theory, motion sickness is triggered by extraocular eye muscle proprioception (not sensory conflict) (Ebenholtz, 1992; Ebenholtz et al., 1994). It is proposed that excessive eye muscle traction[5] not only stimulates cells in the vestibular nuclei, but also the vagus nerve, which in turn triggers emesis (the reflexive purging response described above). This theory is particularly focused on nystagmus—the compensatory rhythmic eye-movements made in response to prolonged visual/vestibular motion stimulation. However, according to Ebenholtz (1992), "any condition yielding an error in eye-movement control, along with the ensuing feedback and error-correcting signal, is a potential source of motion sickness" (p. 303). Several different oculomotor reflexes attempt to keep vision single, stable, and clear during real/apparent motion. Consider what happens when a person seated on a spinning chair repeatedly rolls their head between upright and tilted toward one shoulder. This not only generates torsional eye-movements (triggered by the otolith organs), but also horizontal and vertical nystagmus (triggered primarily by the cross-coupling of the semicircular canals). According to Ebenholtz et al., the excessive eye muscle traction generated by these complex and competing oculomotor responses should stimulate the vagus nerve. However, while their theory explains why this particular situation should, and does, cause motion sickness (Guedry and Montague, 1961), it is unclear: (1) exactly how much eye muscle traction is required to trigger sickness; and (2) why some eye-movements are provocative and others are not. Thus, the theory appears to suffer from similar problems to *sensory rearrangement theory* in terms of predicting the occurrence and severity of cybersickness in HMD VR.

[3]HMD AR differs from HMD VR in that the visual environment is only partially produced by the computer (Azuma, 1997). Typically, the virtual content is superimposed over real views of the user's actual environment.

[4]E.g., adding a stationary visual background should have prevented/impaired vection in both studies (Ohmi et al., 1987). Similarly, adding a large background grid could have altered perceptions of the subjective vertical.

[5]The theory is based on observations that extraocular muscle traction can trigger other vagal reflexes, such as the oculocardiac reflex (Apt et al., 1973). Gupta (2005) also proposed that extraocular muscles trigger motion sickness but does not refer to Ebenholtz et al. (1994).

Empirical Evidence

Consistent with the predictions of this theory, VIMS has been found to: (1) increase with the frequency and slow phase velocity of optokinetic nystagmus (Hu and Stern, 1998; Ji et al., 2009); (2) decrease when optokinetic nystagmus is suppressed (Flanagan et al., 2002; Webb and Griffin, 2002; Ji et al., 2009); and (3) be related to the decay rate of this optokinetic nystagmus (Guo et al., 2017). These results do not however provide conclusive evidence for the theory—as the conditions used in these studies would also have altered visual-vestibular conflict and vection (Stern et al., 1990; Hu et al., 1997). Further complicating the story, and contrary to the hypothesis, Nooij et al. (2017) recently failed to find significant relationships between optokinetic nystagmus and VIMS. According to the hypothesis, preventing the observer from making any eye-movements should also prevent them from experiencing motion sickness (since there will be no eye muscle traction signals to trigger symptoms). However, contrary to this key prediction, Money and Wood (1970) found that preventing visual and vestibular eye-movements did not alter the amount of physical motion required to make dogs vomit.

The Postural Instability Theory of Motion Sickness

While most researchers have assumed that sensory conflict plays an important role in motion sickness, Riccio and Stoffregen (1991) argue that sensory conflict does not actually exist[6]. Instead they propose that prolonged postural instability (of either our body or its segments) is the cause of all types of motion-sickness. According to their *postural instability theory*, motion sickness occurs when our mechanisms for maintaining postural stability are undermined. It predicts that: (1) individuals who are naturally unstable will be more likely to become sick; (2) this motion sickness will be preceded by increases in postural instability and persist until stability is restored; and (3) motion sickness will be more likely, and become more severe, the longer we remain unstable (Riccio and Stoffregen, 1991; Stoffregen and Smart, 1998; Munafo et al., 2017). While the severity of this sickness is also expected to increase with the degree of postural instability, Riccio and Stoffregen (1991) note that what constitutes postural instability is "not yet well-understood" (p. 213).

Empirical Evidence

When taken at face value, the evidence for *postural instability theory* appears to be mixed. While the theory is supported by the findings of many VIMS and cybersickness studies (e.g., Baltzley et al., 1989; Stoffregen and Smart, 1998; Stoffregen et al., 2000, 2008, 2010, 2014; Smart et al., 2002, 2014; Flanagan et al., 2004; Yokota et al., 2005; Bonnet et al., 2006; Merhi et al., 2007; Tanahashi et al., 2007; Reed-Jones et al., 2008; Villard et al., 2008; Chang et al., 2012; Chang C. H. et al., 2013; Koslucher et al., 2015, 2016; Keshavarz et al., 2017; Munafo et al., 2017; Cook et al., 2018; Palmisano et al., 2018; Arcioni et al., 2019; Risi and Palmisano, 2019; Teixeira and Palmisano, 2020), other studies have failed to find relationships between postural instability and motion sickness (Kennedy and Stanney, 1996; Cobb and Nichols, 1998; Warwick-Evans et al., 1998; Cobb, 1999; Akiduki et al., 2003; Dennison and D'Zmura, 2017). In the latter (null finding) studies, postural instability was typically assessed only in terms of the spatial magnitude of the person's movements (e.g., with longer sway paths, larger sway areas and greater positional variability being interpreted as evidence of greater postural instability). However, such measures assume that postural activity is locally self-similar over time. As this is rarely the case, we also need to consider the temporal dynamics of the person's movements when looking for postural precursors of motion sickness (Stoffregen et al., 2010; Koslucher et al., 2016; Munafo et al., 2017). Thus, it is possible that the relationships predicted by this theory could still be found in the data of the latter studies when they are subjected to non-linear analyses (such as detrended fluctuation analysis or recurrence quantification analysis—see Apthorp et al., 2014 and Palmisano et al., 2018 for related discussions).

Research on *postural instability theory* currently appears to be limited by the state of our knowledge. For example, Keshavarz et al. (2014) recently stated that "it would appear that [Stoffregen and his colleagues] view postural instability theory as consistent with an increase in postural sway prior to [motion sickness], a decrease in postural sway prior to [motion sickness], or an increase in the variability of postural sway prior to [motion sickness]" (p. 660). This suggests that better (or more reliable) methods of identifying postural instability, and increases in postural instability, may be required in the future.

Problems With Existing Theoretical Approaches to Cybersickness

In the review above, we identified problems with existing theories of cybersickness in terms of their proposed mechanisms, their ability to be tested, or their level of support from the empirical data.

We first considered the *sensory conflict theories* of motion sickness. Based on our review, we concluded that: (1) it remains difficult to determine a priori which types of sensory conflict will provoke VIMS and cybersickness; (2) classical *sensory rearrangement theory* and the *poison hypothesis* lack predictive power and are difficult to test; (3) the data for the *rest frame hypothesis* are inconclusive; and (4) VIMS and cybersickness can occur without either *vection conflict* (Ji et al., 2009) or *subjective vertical conflict* (Bonato et al., 2005). Thus, adopting these *sensory conflict* approaches has not yet dramatically increased our understanding of the causes of either VIMS or cybersickness.

We also reviewed Ebenholtz's *eye-movement theory* of motion sickness. In its current form, we believe this also has difficulty precisely predicting the occurrence and severity of cybersickness in HMD VR. While a recent review concludes that the human data for the theory is insufficient (Keshavarz et al., 2014), the animal findings have not thus far been supportive (Money and Wood, 1970).

Finally, we also reviewed the evidence for the *postural instability theory* of motion sickness. While studies using this approach have been quite successful in identifying which users

[6]Stoffregen and Riccio (1991) argue each pattern of multisensory stimulation represents a specific animal-environment situation irrespective of whether the stimulation from the different senses is "redundant" or not.

will become sick in HMD VR (Munafo et al., 2017; Arcioni et al., 2019; Risi and Palmisano, 2019; Teixeira and Palmisano, 2020), researchers have not always found its predicted relationships between postural activity and cybersickness (e.g., Dennison and D'Zmura, 2017). As what constitutes postural instability is not yet well-understood, it may be some time before major progress can be made in understanding cybersickness using this approach.

PART 2: A NEW APPROACH FOR STUDYING CYBERSICKNESS IN HMD VR

Existing *sensory conflict*, *eye-movement* and *postural instability* theories all appear to have difficulties predicting when, and how much, cybersickness will be induced in HMD VR. This may be (at least in part) because they are general theories of motion sickness. That is, they were not specifically created to explain this type of cybersickness. Hill and Howarth (2000) caution that while some cybersickness symptoms can mimic those of other types of motion sickness (e.g., VIMS), their origins are not necessarily the same (see also Stanney et al., 1998b; Lawson, 2014; Palmisano et al., 2017). This was the impetus for us to develop a new approach to understanding and studying cybersickness in HMD VR. As the hypothesis we will outline for this cybersickness is focused on display lag (also known as *motion-to-photon latency* or *end-to-end latency*), we will first review the past findings of HMD studies on display lag effects below.

Display Lag Effects on Cybersickness in HMD VR

Display lag refers to the time required for the user's tracked head movements to change the visual scene presented in their HMD. In HMD VR, this lag is the combined result of sensing, processing, data smoothing, transmission, rendering and frame rate delays (Allison et al., 2001; Wu et al., 2016; Stauffert et al., 2018). Research has shown that: (1) users are sensitive to small changes in display lag (i.e., <20 ms; Ellis et al., 2004; Mania et al., 2004); and (2) display lag can have detrimental effects on user perceptions, performance and well-being (Frank et al., 1988; DiZio and Lackner, 1997; Allison et al., 2001; Meehan et al., 2003). Thus, in recent years, considerable efforts have been made to reduce the effective display lag in modern HMD systems. Nevertheless, some lag remains despite improvements in the technology as well as the use of *asynchronous time warping* (ATW) and *predictive tracking* software techniques[7].

Importantly, display lag is thought to be the main cause of cybersickness in active HMD VR (Howarth and Finch, 1999; Golding, 2016; Kinsella et al., 2016). To test this proposal, researchers have typically injected additional display lag on top of their system's baseline lag[8] and examined its effects on cybersickness. Most of these studies have examined the effects of adding simple constant display lags. However, display lag in HMD VR is not constant, but rather changes over time (Wu et al., 2016; Stauffert et al., 2018). Thus, a few studies have also examined the effects of time-varying display lag. Below we review the effects that adding constant, periodic, and jittering display lags have on cybersickness during active HMD VR.

Effects of Adding Constant Display Lag on Cybersickness

Research has shown that imposing an additional constant lag into the system increases the likelihood and severity of cybersickness (DiZio and Lackner, 1997; Jennings et al., 2000, 2004; Caserman et al., 2019; Feng et al., 2019; Palmisano et al., 2019; Kim et al., 2020). While a small number of studies have failed to find such effects (Draper et al., 2001; Moss and Muth, 2011; Moss et al., 2011), we note that the baseline lags of their systems were already quite high (∼40–70 ms). Our own research has consistently found that cybersickness is increased by imposing additional constant lag into the system (Feng et al., 2019; Palmisano et al., 2019; Kim et al., 2020). Participants in these studies were simulated to either be seated inside a virtual room (**Figure 1**, Right) or moving forwards through a 3D cloud of randomly positioned objects (**Figure 1**, Left). They were instructed to make continuous yaw (Feng et al., 2019; Palmisano et al., 2019) or pitch (Kim et al., 2020) head rotations during each 12 second VR exposure. Irrespective of the simulation/environment, or the axis/speed of head rotation, we consistently found that cybersickness severity increased in a monotonic fashion with increases in this constant display lag (**Figures 2A–C**).

Effects of Periodic Display Lag on Cybersickness

Periodic variations in display lag can occur during HMD VR due to system clocks, asynchronous processes, buffer times, and sensor drift errors (Wu et al., 2016). Kinsella et al. (2016) and St. Pierre et al. (2015) both examined the effects of periodic variations in display lag on cybersickness. In these studies, participants made natural head movements while completing an object location task. As they moved their heads, the video images of their surroundings were delayed by a variable or constant amount of time before presentation on the HMD[9]. St. Pierre et al. (2015) found that cybersickness was greater when a variable display lag with a frequency of 0.2 Hz and an amplitude of 100 ms was added to their baseline system lag of ∼70 ms. This 0.2 Hz display lag was found to be even more provocative for cybersickness when its amplitude varied (from 20 to 100 ms) instead of being fixed (at 100 ms). Kinsella et al.

[7]In ATW, scene views are rendered based on the user's initial head pose, but then shifted (to correct for head motion during rendering) before being sent to display (Van Waveren, 2016). However, as this warping process only corrects for head rotations, stereo and motion cues to 3D layout will be distorted during head translations. Predictive tracking can also reduce the effects of display lag (using dead reckoning, Kalman or alpha-beta-gamma filters to predict where the user's head will be in the future; Kiruluta et al., 1997). However, this can cause the opposite problem (where the user's virtual head can lead its physical position and orientation).

[8]This refers to the estimated latency of the HMD VR simulation without any added artificial display lag. It is typically estimated by tracking the optical motions of reference and delayed landmarks on the HMD via high-speed digital cameras (Kim et al., 2015; Zhao et al., 2017; Feng et al., 2019). Note: in systems using prediction algorithms and ATW this will estimate the effective lag (not the actual *motion-to-photon latency*).

[9]Note: this technique only simulates the display lag effects produced by head tracking errors in HMD VR (as HMD tracking data is not actually used to update the display).

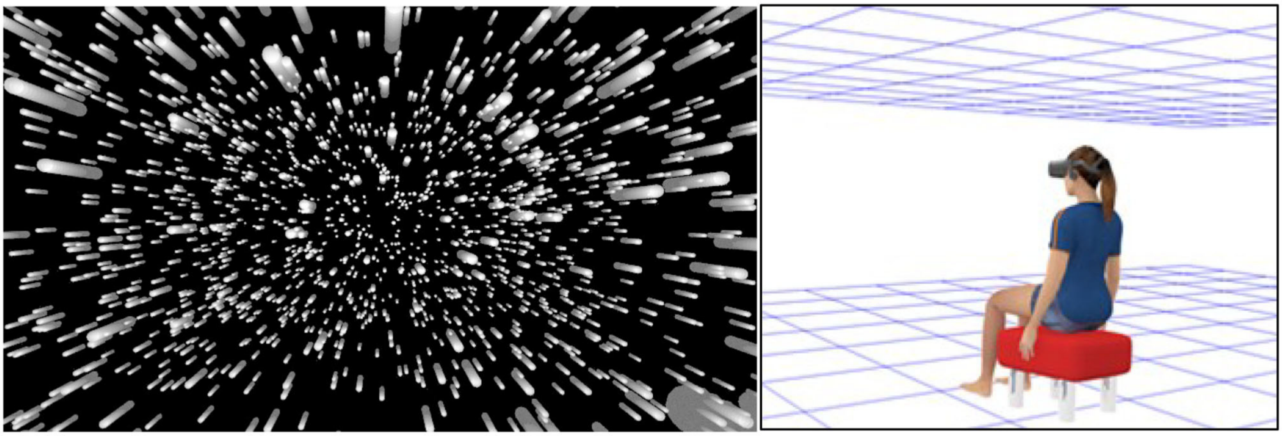

FIGURE 1 | Representations of the simulated virtual environments used in our display lag studies. **(Left)** In Feng et al. (2019) participants were presented with a radially expanding pattern of optic flow simulating forwards self-motion through a 3D cloud of randomly positioned objects. **(Right)** In Palmisano et al. (2019) and Kim et al. (2020), the participant was instead simulated to be seated inside a "Tron-like" virtual room (with a wireframe ceiling and ground plane). Note: in the actual displays environmental objects were always blue and the background of the virtual environment was always black (never white).

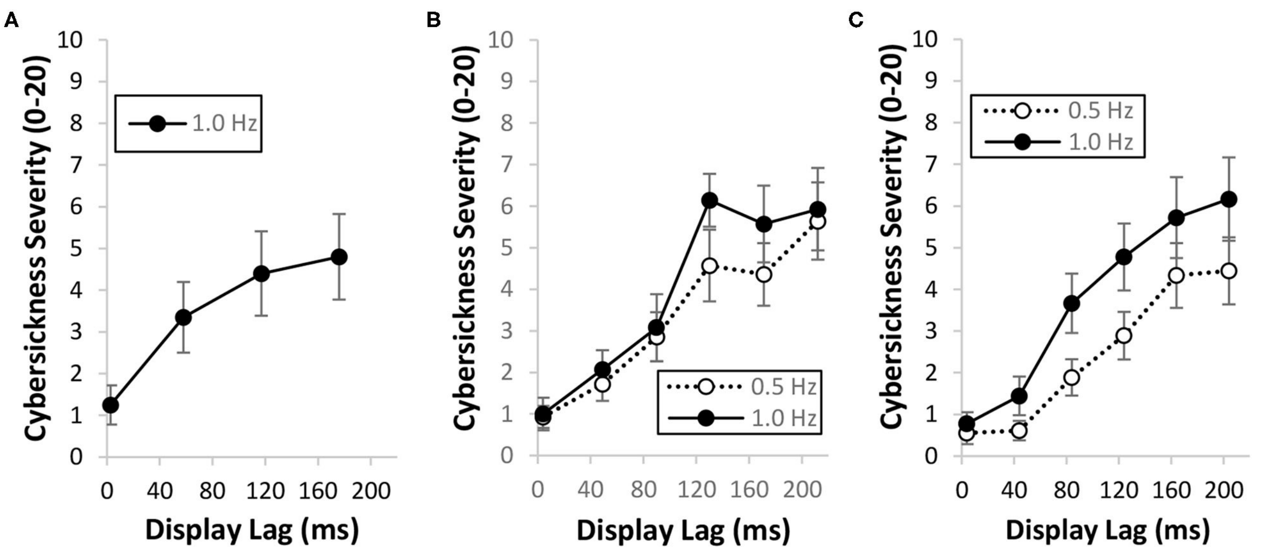

FIGURE 2 | Effects of increasing the mean display lag from ∼4 to ∼204 ms on cybersickness severity ratings when participants made continuous: **(A)** yaw head rotations during visually simulated forwards self-motion (Feng et al., 2019); **(B)** yaw head rotations while they were simulated to be seated inside the "Tron-like" virtual room (Palmisano et al., 2019; binocular viewing condition data only) and **(C)** pitch head rotations while they were again simulated to be seated inside the "Tron-like" virtual room (Kim et al., 2020). Error bars in each of the three different plots represent standard errors of the mean. Mean data obtained during slow (0.5 Hz) and fast (1.0 Hz) head movements are also identified.

(2016) subsequently found that the cybersickness induced by this 0.2 Hz variable lag was more severe than that induced by a 1.0 Hz variable lag[10]—suggesting that both real and apparent motions around 0.2 Hz might be particularly provocative for motion sickness (Golding et al., 2001).

[10] That is, cybersickness was more provocative when it took 5 s (compared to 10 s) for the periodic display lag to complete a full cycle. Note: in our studies on the effects of constant display lag, each HMD VR exposure only lasted 12 s.

Effects of Jittering Display Lag on Cybersickness

Recently, Stauffert et al. (2018) also examined the effects of brief latency spikes on cybersickness. Participants in their study performed a virtual search task requiring them to make tracked head movements. They were split into two groups. One group had latency spikes injected into their HMD VR (on top of the baseline system lag of ∼36 ms), whereas the other group did not. These latency spikes were scheduled to occur randomly (similar to the jittering display lag produced by underperforming systems). When a latency spike was scheduled to occur, head tracking data were delayed by a minimum of 1.8 ms up to a maximum of 60.7 ms (determined by a probability distribution). Stauffert et al. found that cybersickness was significantly greater for the group with the added latency spikes compared to the control. Thus, it appears that randomly occurring spikes in display lag can also exacerbate cybersickness.

A Hypothesis Specifically Developed for Cybersickness in HMD VR

As noted above, this hypothesis was created to explain *and* predict the effects of display lag on cybersickness **during active HMD VR**. In this situation, display lag will cause inconsistencies between the user's available visual, vestibular, and non-vestibular proprioceptive information about head position and orientation. Consider the person in **Figure 3A**, who is actively rotating her head in pitch while looking at the real world. When she subsequently makes the same head movement while wearing an HMD, the orientation of her virtual head (**Figure 3B**, pink) will trail its true orientation (**Figure 3B**, green) due to the display lag. These *Differences in her Virtual and Physical head pose* (*DVP*) could be interpreted as either intersensory conflict or non-redundant multisensory information. However, irrespective of their interpretation, we propose that provocative patterns of *DVP* are the primary trigger for cybersickness in HMD VR. As can be seen in **Figure 3B**, the user's *DVP* will vary over time. Not only will it increase when she initiates a head movement, and decrease sometime after this movement has completed, but it will also vary throughout the movement (due to changes in her head velocity, as well as variations in the display lag, over time). Large changes in this *DVP* over time will not only make her virtual world appear to swim and oscillate around her (Allison et al., 2001; see **Figure 3C** for an explanation), but it will also increase the likelihood of cybersickness (Kim et al., 2020). It is proposed that time-varying *DVP* should still be capable of triggering cybersickness even when it fails to reach the threshold for conscious perception (e.g., when it is generated by brief latency spikes—Stauffert et al., 2018). However, when it does reach consciousness, learned associations between perceived scene instability and past experiences of cybersickness could also act to exacerbate symptom severity.

While the above example is focused on user head rotation in pitch, our research suggests that head rotations in yaw (and presumably also in roll) can generate provocative *DVP* during HMD VR (Feng et al., 2019; Palmisano et al., 2019). During each of these head rotations, *DVP* will increase in magnitude and become more variable when: (1) additional (constant or time-varying) display lag is injected into the system; and (2) the user's head-movement speed increases. We therefore expect that both situations should increase the likelihood and severity of cybersickness. We would however expect HMD users to be more tolerant to the same display lags and head speeds during head translations compared to head rotations, because: (1) evidence suggests that vestibular sensitivity is lower for head translations[11] (Bronstein and Gresty, 1988; Collewijn and Smeets, 2000); and (2) changes in head pose may be more difficult to detect from the complex patterns of visual motion produced by head translation[12]. Thus, head translations are expected to be less likely to produce provocative *DVP* compared to head rotations. We also expect that once cybersickness is triggered, it will persist until *DVP* decreases in both magnitude and variability (e.g., after the HMD user minimizes her head motion and keeps it still for some time).

Our Explanation of Cybersickness During Passive HMD VR

While the *DVP hypothesis* outlined above is focused on active HMD VR, it can be extended to explain the VIMS and cybersickness experienced during **passive viewing conditions**. For example, when the HMD user passively views a first-person simulation of a virtual roller coaster ride. Let us first assume that she is physically restrained to prevent any head or body motion. In this case, the roller coaster simulation will still generate large magnitude, time-varying *DVP* due to the absence of non-visual stimulation confirming her visually simulated self-motion. This *DVP* should still increase the likelihood of VIMS even though display lag and head motion does not contribute significantly to it in this case. Now let us assume that the HMD user has been released from her postural restraints and is shown the same simulation again. On her second passive viewing of this virtual roller coaster ride, she will now tend to make small, inadvertent compensatory head-movements (despite her best efforts to keep her head still). If she is asked to stand freely (rather than being seated), she will also tend to sway in response to the roller coaster's visual motion. Under these more ecological passive viewing conditions, additional *DVP* will be generated by the display lag, which should further increase the likelihood and severity of motion sickness. However, in these head-free and free-standing conditions, any sickness experienced would now be referred to as cybersickness, rather than VIMS (since it would not be due solely to the visual motion*; DVP* due to head motion and display lag would also contribute to this experience).

Why Is Cybersickness More Severe in HMDs?

Our *DVP hypothesis* also explains why this might be the case. Let us compare the visual consequences of the same observer making a tracked head rotation in HMD VR and non-HMD VR. When she makes this head rotation in non-HMD VR (e.g., while viewing a simulation on a large external display), the visual motion expected to accompany her head-movement will be produced immediately and correctly (because it is all generated by her physical head rotation relative to the earth-fixed display). That is, she will effectively experience no *DVP*. By contrast, when she later makes the same head rotation in HMD VR, the expected visual motion will now be delayed by

[11] E.g., the otolith-ocular reflex (∼32 ms) tends to be triggered later than the vestibulo-ocular reflex (∼8.6 ms).

[12] During head rotations, all visual scene elements will move across the user's retinas at similar speeds (irrespective of simulated depth or eccentricity). By contrast, during head translations, there will be a gradient of retinal velocity, with the simulated nearer scene elements moving faster and further than those simulated to be further away (Gibson, 1950).

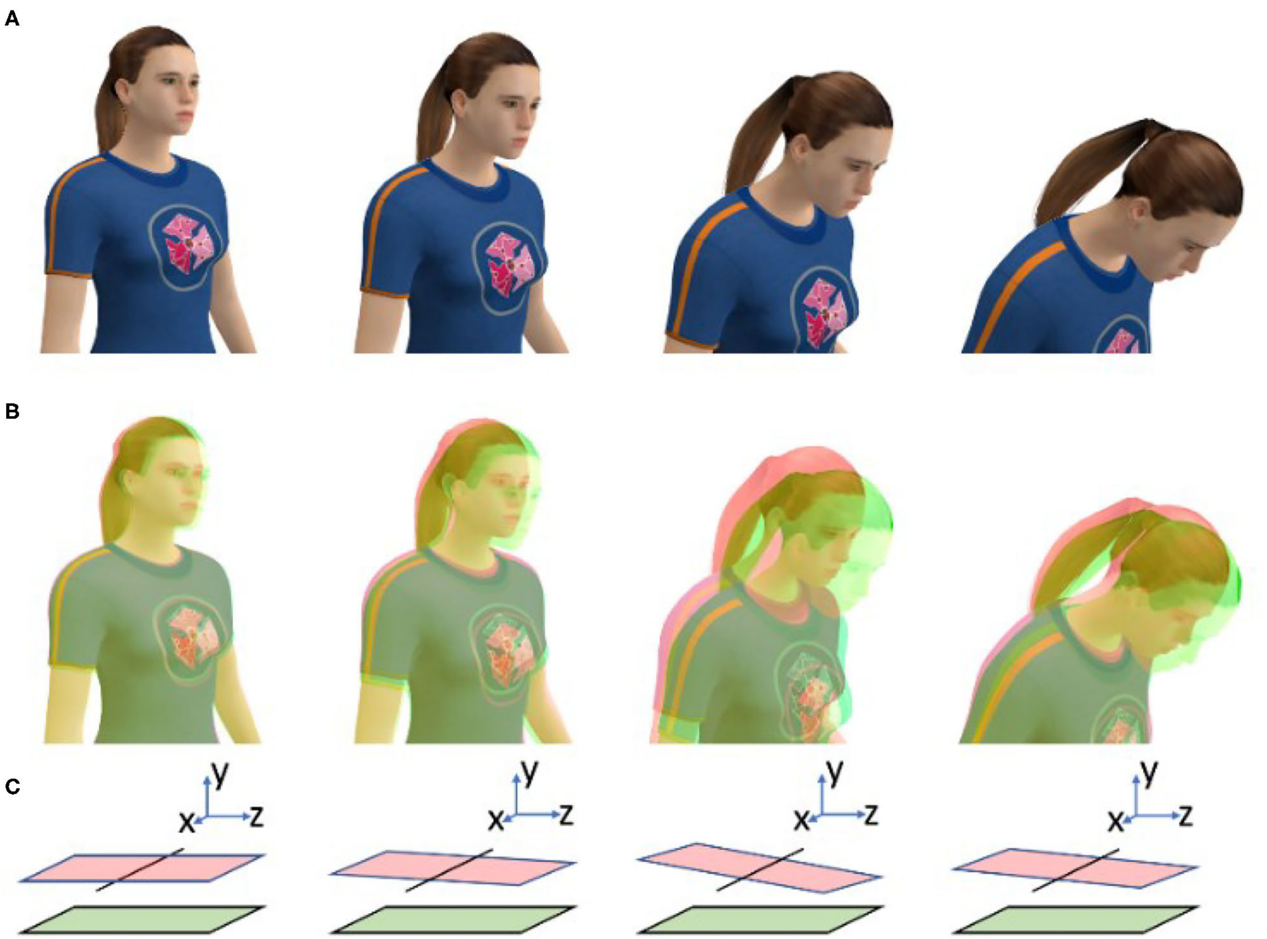

FIGURE 3 | Explanations of the adverse effects of display lag during HMD VR. **(A)** When this person physically rotates her head in pitch this movement will generate consistent/redundant visual and non-visual information. **(B)** However, when she makes the same head movements in HMD VR, display lag will generate Differences in her Virtual (pink) and Physical (green) head orientation (DVP). We propose that large magnitude, time-varying DVP will automatically trigger cybersickness in susceptible users. **(C)** This DVP will also bias the perceived orientation of the ground plane (pink) relative to its true orientation (green). As the DVP (and orientation bias) will change over time, they will be consciously perceived by the HMD user as scene instability.

the system's display lag (since the HMD's screens move with her head and the expected visual motion is computer generated in this case). The longer and more variable this display lag is, the more provocative the *DVP* should be for cybersickness. However, since there is some (as opposed to no) *DVP*, this explains why HMD VR is more provocative than non-HMD VR. It is important to note however that such differences in display lag/*DVP* only occur during head rotations. During head translations, the visual consequences of the user's head motions are similarly delayed for both types of VR (because the expected visual motion parallax[12] must be computer generated). While this display lag should cause *DVP* during both types of VR, it should be less provocative than that generated by head rotations in HMD VR (as explained above). Thus, we propose that HMD VR is more provocative for cybersickness than non-HMD VR primarily because it produces some (as opposed to no) *DVP* during head rotations.

Summary of Predictions

Our *DVP hypothesis* predicts that faster head movements and HMD VR systems with longer/more variable display lags should both increase the likelihood and severity of cybersickness in susceptible users. Active HMD users should therefore be less tolerant to the same display lag when making faster head-movements. These users should also be more likely to become sick when making head rotations as opposed to head translations. During both active and passive HMD VR, we also expect the likelihood of cybersickness to increase when the users' heads are free (as opposed to restrained), and when they are standing freely (as opposed to seated).

All the above predictions are for display lag effects on cybersickness. However, our hypothesis predicts that provocative *DVP* will sometimes occur when there is minimal display lag (e.g., ∼4 ms; which is possible using an ideal system with display optimizations, impoverished scene content, as well as ATW and predictive tracking software techniques—Feng et al., 2019). As noted above, vection in physically restrained HMD users could produce provocative *DVP* without any display lag effects. However, movement calibration errors during active HMD VR could also generate provocative time-varying patterns of *DVP* (e.g., when the user's real-to-virtual head movement gain is not at unity).

Our Approach for Testing the DVP Hypothesis

Our experiments on cybersickness have often examined the effects of imposing additional constant lags (from 0 to ∼200 ms) on top of the baseline system lag (of ∼4 ms in Feng et al., 2019, Kim et al., 2020, and Palmisano et al., 2019). The different display lag conditions used in these studies were created using the memory buffer method described in the next section *Memory Buffer Method for Imposing Additional Constant Display Lag.* Our use of this method also allowed us to objectively estimate the user's *DVP* throughout each trial (based on comparisons of their tracked head pose at different times in the trial). The exact procedure we used to calculate this DVP time series data is described in the following section *Method for Estimating DVP Due to Display Lag.*

Memory buffer method for imposing additional constant display lag

Before each trial, a circular memory array (of element length **N**) was constructed to store the user's head tracking data (see **Figure 4**). The user's head position and orientation data were then continuously sampled from the HMD sensors over the course of the trial. These data were written to the memory array on every single frame.

In the example shown in **Figure 4** below, current head position and orientation data are being written to the array element located at index $\mathbf{t}_i$. They will be held there until all head pose data written earlier have been used for rendering. Next, the array counter will be incremented to read the head pose data stored at index $\mathbf{t}_{i+1}$. These data from $\mathbf{t}_{i+1}$ are then used to update the user's virtual environment.

As can be seen in **Figure 4**, small constant increments in display lag can be added to the system simply by increasing the number of elements in this circular memory array. In the case of a single element array ($N = 1$), there will be no additional imposed display lag (i.e., the scene updates should only be delayed by the system's baseline lag). However, when using an 18-element array there will be an additional delay of 18 frames on top of the system's baseline lag (resulting in ∼200 ms imposed lag + ∼4 ms baseline lag = ∼204 ms in our experiments; as HMDs with a 90 Hz refresh rate were used; either the Oculus Rift CV1 or the Oculus Rift S).

Method for estimating DVP due to display lag

Let us assume that a participant made continuous oscillatory pitch head movements at 0.5 Hz during a VR exposure lasting 12 s (similar to one of the conditions in our recent Kim et al., 2020 study). After the participant completed the trial, we would first use the rotation vectors from their HMD sensor data to build a 3D view matrix for each eye (to account for their interocular separation—see Equation 1). Then we would obtain their yaw, pitch, and roll angular head orientation data from this view matrix (in Euler angles) using the mathematical transformations shown in Equations (2)–(4):

$$View = \begin{Bmatrix} right_x & up_x & forward_x & position_x \\ right_y & up_y & forward_y & position_y \\ right_z & up_z & forward_z & position_z \\ 0 & 0 & 0 & 1 \end{Bmatrix} \quad (1)$$

$$Yaw\ (\theta\ ) = \text{atan}\left(-\frac{right_y}{right_x}\right) \quad (2)$$

$$Pitch\ (\varphi\ ) = \text{atan}\left(\frac{up_z}{forward_z}\right) \quad (3)$$

$$Roll\ (\psi\ ) = \text{atan}\left(\frac{right_z}{sqrt\left(up_z^2 + forward_z^2\right)}\right) \quad (4)$$

As the participant was asked to make pitch head movements in this case, we could estimate their *DVP* using only the pitch orientation data for the trial (ignoring the smaller differences in yaw and roll head orientation shown in **Figure 5A**)[13]. However, we would first need to know the display lag for the trial. As added lag was injected into the system using the memory buffer method outlined in the previous section, this could be approximated as the temporal offset between the time of writing to, and the time of reading from, the memory buffer. In other words, the added lag would be the element length **N** of the memory array used for that trial. This temporal offset (in frames) would then be used to simulate the user's virtual head orientation in pitch throughout the trial (**Figure 5B**). At each instant, the participant's physical head orientation would be estimated as their recorded pitch head orientation for that time, and his/her virtual head orientation would be estimated as their recorded pitch head orientation from a time N frames earlier. The *DVP* experienced at this time could then be calculated as the difference in head orientation between these two estimates. **Figure 5C** shows an example of the *DVP* time series data estimated from the original data shown in **Figure 5A**. Similarly, **Figure 5D** shows the unsigned magnitudes of this *DVP*. Based on our hypothesis, we would expect cybersickness to be more likely and severe as the peak and standard deviation of this estimated *DVP* increases.

Empirical Support for the DVP Hypothesis

Kim et al. (2020) recently used the approach outlined above to test our DVP hypothesis for cybersickness. In this study, 30 participants were asked to make continuous oscillatory **pitch** head movements (**Figure 6**, Top Right) while viewing a "Tron-like" virtual room environment through an Oculus Rift CV1 HMD (**Figure 6**, Left). On different trials: (1) we examined the effects of imposing additional constant lags (ranging from 0 to ∼200 ms) on top of the baseline system lag (of ∼4 ms; using the *memory buffer method* described in the section *Memory Buffer Method for Imposing Additional Constant Display Lag*);

[13] *DVP* could also be estimated based on orientation differences across all three axes, or even based on the differences in position and orientation across these axes.

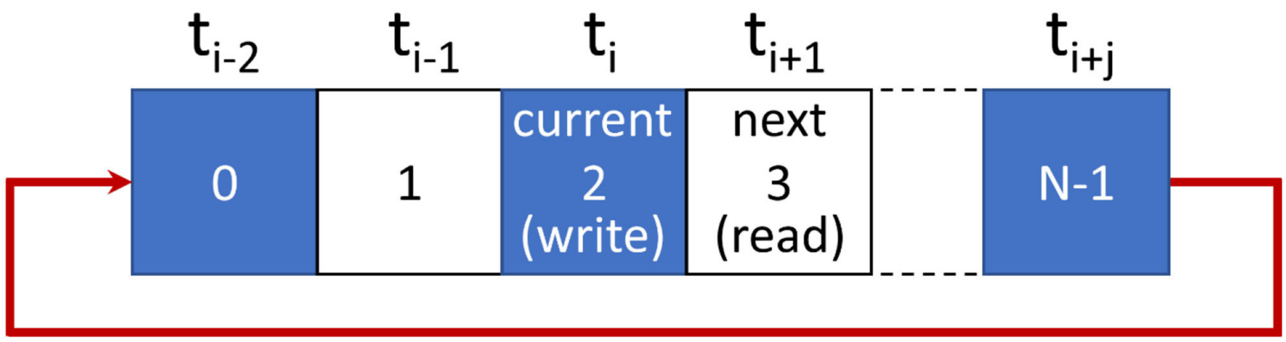

FIGURE 4 | The memory buffer method used to impose system lag in our studies. HMD sensor data are written to memory at the current index (t_i). The index is then incremented to read the next element for updating the display. Incrementing beyond the last array element (i.e., N-1) resets the index to 0. Increasing the total number of elements in the array (N) above 1 allows us to increase display lag above the baseline latency.

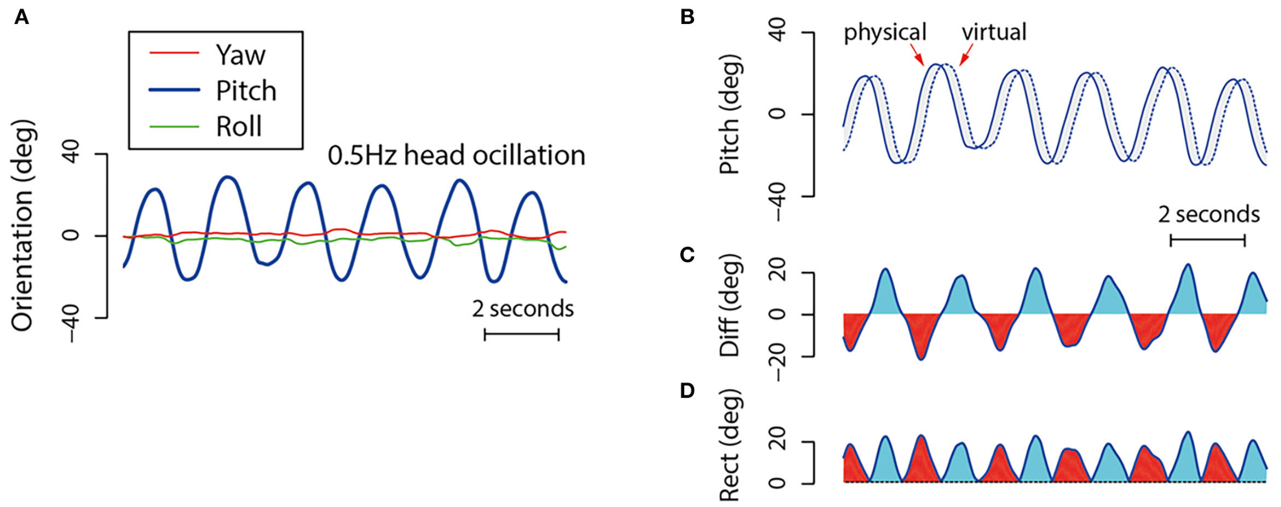

FIGURE 5 | This depicts the method used to estimate DVP in Kim et al. (2020). **(A)** An example of the yaw, pitch and roll head orientation time series data produced by a participant oscillating their head in pitch for 12 s. **(B)** Shows both the recorded (physical) and estimated virtual (virtual) pitch head orientation data for the participant across the trial. In order to estimate the effects of display lag on virtual head pose, these simulated data were assumed to be the same as the recorded head pose from a time **N** frames earlier. **(C)** Shows the per-sample DVP over the course of the entire trial. **(D)** Shows the unsigned differences in this DVP over the same time period.

and (2) our participants made either fast (1.0 Hz) or slow (0.5 Hz) head movements with approximately equal amplitudes. Head pose time series data (obtained from the HMD's sensors) and cybersickness severity ratings (using the *Fast Motion Sickness scale*; Keshavarz and Hecht, 2011b[14]) were recorded for each trial. After participants completed the experiment, we then estimated their *DVP* time-series data for each trial using the method outlined in the section *Method for Estimating DVP Due to Display Lag*. As can be seen in **Figure 7A**, the unsigned mean of this *DVP* increased with both the imposed display lag and the participants' head speed for the trial. Consistent with our *DVP hypothesis*, we reported a strong positive linear relationship between mean unsigned *DVP* and cybersickness severity (**Figure 7B**). Since mean unsigned *DVP* also increased with the participant's head speed, the finding that cybersickness was greater in the 1.0 Hz (compared to the 0.5 Hz) conditions was also interpreted as support for our hypothesis.

In this paper we propose that large magnitude, time-varying *DVP* is the trigger for cybersickness. However, Kim et al. (2020) only reported mean unsigned *DVP* in their recent cybersickness study. Thus, we re-examined their data to see whether peak *DVP* (**Figure 7C**) and the standard deviation of the *DVP* (**Figure 7D**) also predicted cybersickness [For a description of these new analyses and statistics please see our **Supplementary Materials** document: "1. Relationships between *DVP* and Cybersickness in the Kim et al. (2020) study"]. Consistent with our hypothesis, both the peak and the standard deviation of the *DVP* were found to have significant positive linear relationships with cybersickness severity.

[14]Cybersickness was also confirmed using the Simulator Sickness Questionnaire (Kennedy et al., 1993).

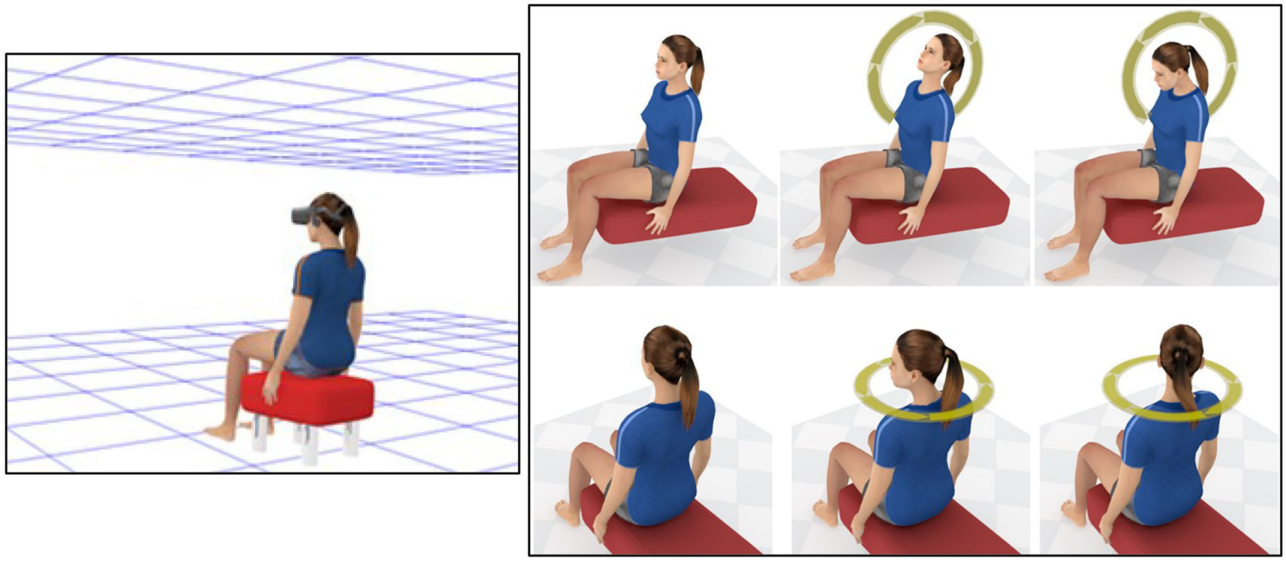

FIGURE 6 | (Left) Representation of the "Tron-like" virtual environment used in both Kim et al. (2020) and Palmisano et al. (2019). Note that the background used in the actual simulation was black (not white). **(Top Right)** This shows the continuous pitch head-movements made during HMD VR in the Kim et al. (2020) study; **(Bottom Right)** This shows the continuous yaw head movements made in the Palmisano et al. (2019) study.

The above findings (and our new analysis) provide evidence that *DVP* can be used to predict cybersickness in HMD VR during pitch head rotations. To investigate whether *DVP* can also predict cybersickness during yaw head rotations, we re-examined the data from another of our recent studies. In this Palmisano et al. (2019) study, 14 participants made continuous oscillatory **yaw** head rotations (**Figure 6**, Bottom Right) while viewing the same "Tron-like" virtual room through an Oculus Rift CV1 HMD (**Figure 6**, Left). The binocular viewing conditions of this experiment were otherwise identical to those in the Kim et al. (2020) study. After estimating the *DVP* time series data for each trial, we calculated the unsigned mean, peak and standard deviation of this *DVP*, and used detrended fluctuation analysis (DFA) to also examine its temporal dynamics. The DFA scaling component (α) was calculated for each trial (this indicates the relative distribution of the variance in the *DVP* across different timescales[15]). We then investigated whether each of these four different *DVP* indices were able to predict cybersickness severity [For a description of these analyses and statistics please again see our **Supplementary Materials** document: "2. Relationships between *DVP* and Cybersickness in the Palmisano et al. (2019) study"]. Consistent with Kim et al. (2020), we again found significant positive linear relationships between the mean unsigned *DVP* and cybersickness severity (**Figure 8A**). We also found significant positive linear relationships between peak *DVP* and cybersickness severity (**Figure 8B**) and between the standard deviation of the *DVP* and cybersickness severity (**Figure 8C**). Positive relationships were also observed between the DFA α values and cybersickness severity ratings (**Figure 8D**). However, in contrast to the other three *DVP* measures, these relationships involving DFA α did not remain significant after statistical corrections were made for multiple comparisons.

[15]DFA α values greater than 0.5 indicate that an autocorrelation has occurred at some timescale in the data. An α of 1 represents the maximum possible self-similarity. As α increases above 1, a greater proportion of the fluctuations occur at longer time scales. As α was always 1.47 or greater in Palmisano et al. (2019), the fluctuations in the *DVP* over time appear to be most similar to Brownian noise.

Could Our Findings Be Explained by Other Theories of Motion Sickness?

In the studies reviewed above, longer imposed display lags and faster user head speeds were both shown to increase the magnitude and variability of the HMD user's *DVP* (**Figure 7A**). Consistent with the predictions of our *DVP* hypothesis, both manipulations also resulted in more severe cybersickness. Below we consider whether these cybersickness findings could also be explained by any of the other theories of motion sickness.

Vection conflict hypothesis

According to this hypothesis: (1) vection is required for cybersickness; and (2) cybersickness severity should increase with vection strength. However, in both the Kim et al. (2020) and Palmisano et al. (2019) studies, participants were always simulated to be seated and stationary inside a virtual room. The only motion stimulation they experienced during their brief 12 s exposures to HMD VR was generated by their own physical head motions (as well as the visual consequences of the display lag). While they should have experienced little to no vection under these conditions, they still reported cybersickness in both studies. Interestingly, their cybersickness severity ratings were quite similar to those in Feng et al. (2019), even though the conditions in that study were much more likely to induce

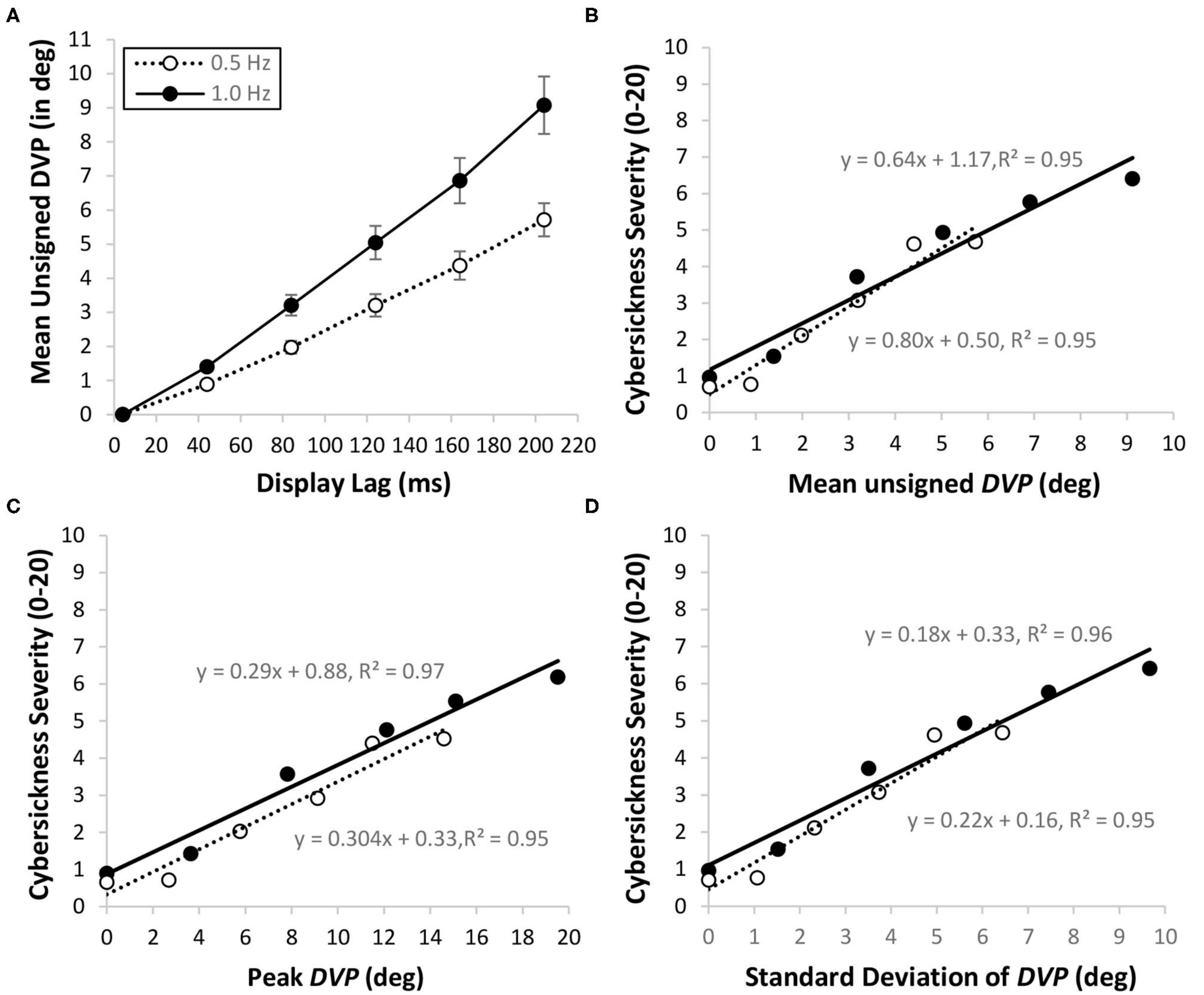

FIGURE 7 | Relationships between display lag (ms), DVP (in degrees) and cybersickness severity ratings (0–20) during pitch head rotation in the Kim et al. (2020) HMD VR study. Data is shown separately for slow (0.5 Hz; hollow points) and fast (1.0 Hz; solid points) head speed conditions. **(A)** Mean unsigned DVP increased with both the level of imposed display lag and the participant's head speed (error bars represent standard errors of the mean). For both the fast and slow head speed conditions, cybersickness severity ratings increased with the mean unsigned DVP **(B)**, the peak DVP **(C)**, and the standard deviation of the DVP **(D)**.

vection[16] (**Figures 2A–C** show the cybersickness ratings for the Feng et al., 2019, Palmisano et al., 2019 and Kim et al., 2020 studies, respectively). Thus, the findings of the Kim et al. (2020) and Palmisano et al. (2019) studies do not appear to support either prediction (1) or (2) of this *vection conflict hypothesis*.

Subjective vertical conflict hypothesis

According to this hypothesis, only sensory conflicts that affect the *subjective vertical* should cause cybersickness. In the Kim et al. (2020) study, participants made pitch head movements, whereas in Palmisano et al. (2019) they made yaw head movements. However, only pitch head movements should have produced significant instability in their perceived orientation (and that of the ground) relative to gravity. Therefore, the subjective vertical conflict hypothesis predicts that: (1) cybersickness should be more severe in the Kim et al. study; and (2) any cybersickness in the Palmisano et al. study would be due to inadvertent pitch and roll (but not yaw) head motions. Contrary to both predictions, pitch rotation conditions were not more provocative than yaw rotation conditions. In fact, cybersickness severity ratings were similar for equivalent levels of display lag and head speed (see **Figures 2B,C**). As was noted above, significant cybersickness was also found in the Feng et al. (2019) study (see **Figure 2A**). Like the Palmisano et al. (2019) study, this was also focused on the effects of display lag on cybersickness during yaw head rotations. Thus, the findings of the Kim et al. (2020) and Palmisano et al. (2019)

[16]The participants in this study were simulated to be moving forwards at a constant velocity.

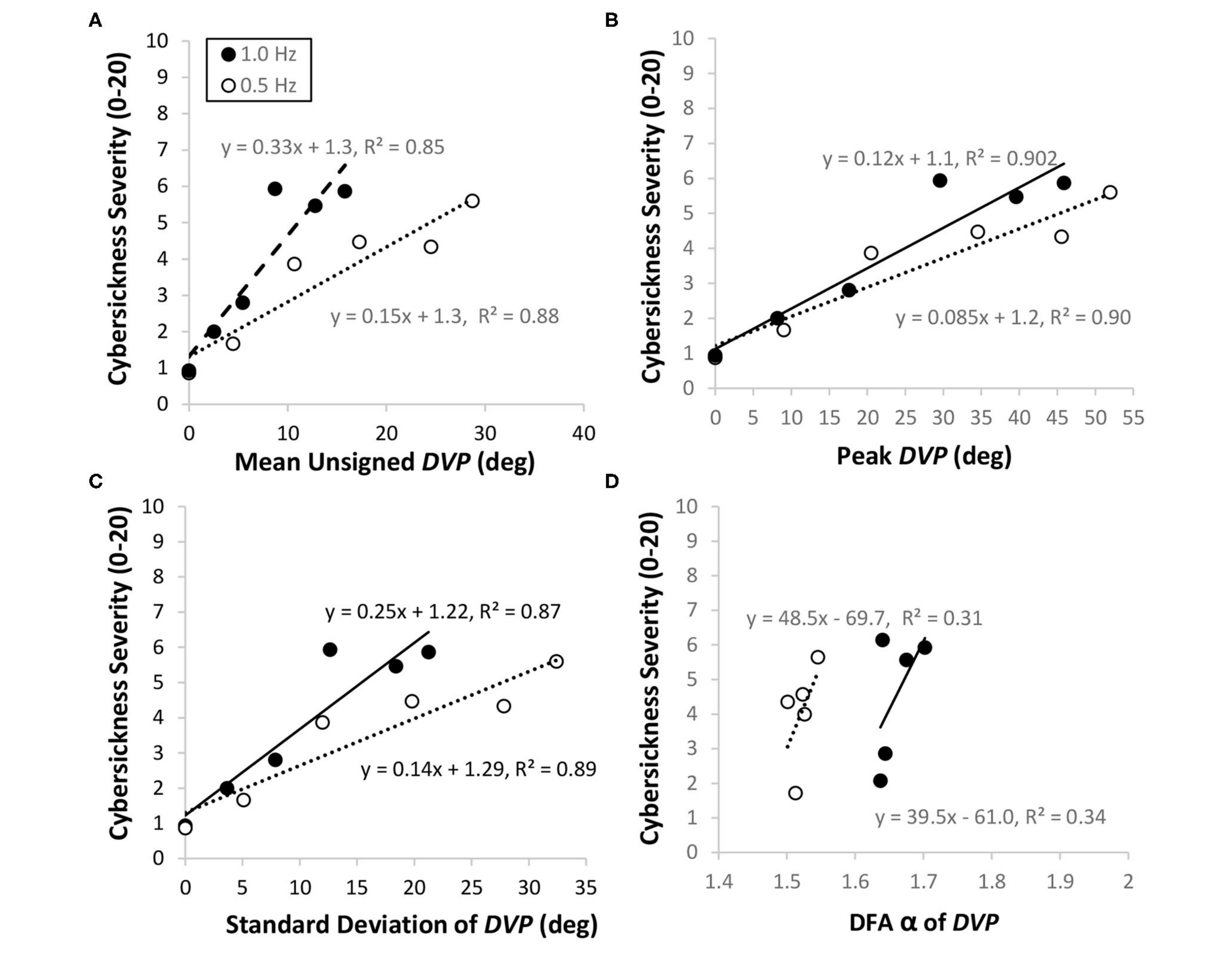

FIGURE 8 | Data from the binocular viewing conditions of the Palmisano et al. (2019) HMD VR study. Participants in this study made continuous slow (0.5 Hz; hollow points) and fast (1.0 Hz; solid points) head rotations in yaw. For both head speed conditions, cybersickness severity ratings increased with the mean unsigned DVP **(A)**, the peak DVP **(B)**, the standard deviation of the DVP **(C)**, and the DFA α for the DVP **(D)**.

studies do not appear to support either prediction (1) or (2) of the *subjective vertical conflict hypothesis*.

Rest frame conflict hypothesis

According to this hypothesis, cybersickness should only occur when sensory conflict prevents the stable perception of a single rest frame. In both the Kim et al. (2020) and Palmisano et al. (2019) studies, participants only saw a wireframe ceiling and ground plane (the rest of their virtual environment was completely black; see **Figure 6**, Left). These environmental surfaces were always simulated to be stationary. Thus, since all of their visual motion was produced by the user's head motions, there should have been little or no rest frame conflict and cybersickness in either study (as both surfaces should have appeared to move together in a rigid fashion, they could have effectively served as a single rest frame). However, contrary to the predictions of this hypothesis, cybersickness was still found to occur in both studies.

The poison hypothesis

According to this hypothesis, vomiting, retching, and related responses should occur during sensory conflicts which suggest we have ingested poison. None of the participants vomited in either the Kim et al. (2020) or the Palmisano et al. (2019) studies. Also, as noted previously, the poison hypothesis cannot be used to make testable predictions about the effects of stimulus factors or the development of predicted symptoms.

The eye-movement theory

This theory predicts that cybersickness is triggered by excessive extraocular eye-muscle traction. As we did not record participant eye-movements in the Kim et al. (2020) and Palmisano et al. (2019) studies, it is not possible to directly relate their *DVP* and cybersickness findings to this theory. Increasing the participant's

DVP (by increasing the display lag or having them make faster head movements) should have altered their eye-movements and retinal motion, which could conceivably have increased the likelihood of cybersickness. However, we note that some sickness was still experienced in the slow head movement, baseline display lag conditions of both studies (see **Figures 2B,C**). It does not seem likely that these conditions would have produced enough eye-muscle traction to trigger such symptoms.

Postural instability theory

As we did not record postural activity during HMD VR in either study, we cannot directly relate their *DVP* and cybersickness findings to this theory. However, it is possible that the preconscious pickup of time-varying *DVP* triggered postural activity and instability in our participants, which in turn generated the cybersickness reported in the Kim et al. (2020) and Palmisano et al. (2019) studies. This possibility will be discussed in more detail in the section *DVP and Individual Differences in Cybersickness* below.

Reconciling our DVP Hypothesis With Well-Known Findings

There are still several well-known cybersickness findings that our hypothesis has yet to explain. Below we attempt to reconcile two of these findings with our *DVP hypothesis*.

DVP and adaptation to cybersickness

Currently our *DVP hypothesis* does not have a specific mechanism that explains why cybersickness adapts/habituates with repeated exposures to provocative stimuli. However, if our proposed trigger for cybersickness (*DVP*) is treated as a sensory conflict involving head pose, then a *neural mismatch* type explanation (see the section on *Sensory Rearrangement Theory*) could work for our hypothesis as well. When users move in HMD VR, it would be assumed that their *DVP* is continuously compared to the expected multisensory stimulation for the movement. Thus, upon first entering HMD VR, users should be more likely to experience cybersickness, because at this time, their expected stimulation will be what they would normally experience in the real world. This should result in a significant neural mismatch, as the actual stimulation they are receiving has *DVP* due to display lag. However, with repeated exposures to HMD VR, users should gradually become recalibrated to this *DVP,* resulting in a little less neural mismatch and cybersickness on each subsequent exposure. If this explanation is valid, then according to our hypothesis, it should be easier to adapt to the *DVP* produced by adding constant and periodic display lags to HMD VR than to the *DVP* produced by random latency spikes. This would therefore be an important topic for future research on our *DVP hypothesis*.

DVP and individual differences in cybersickness

When presented with the same HMD VR simulation, some users are much more likely to become sick, and also experience this sickness more severely, than others (Munafo et al., 2017; Arcioni et al., 2019; Cao et al., 2019; Clifton and Palmisano, 2019; Risi and Palmisano, 2019; Curry et al., 2020; Teixeira and Palmisano, 2020). Currently, our *DVP hypothesis* does not have a specific mechanism to explain individual differences in cybersickness during HMD VR. In principle, such findings could be due to differences in user sensitivities to motion, visual-vestibular conflict or even the specific patterns of *DVP* produced by HMD VR. Vestibular thresholds for angular acceleration appear to vary quite widely in healthy individuals across studies (e.g., from 0.035 to 4 deg s^{-2}; Clark and Stewart, 1970; Guedry, 1974; MacNeilage et al., 2010). This is (in part) because there appear to be significant individual differences in vestibular motion detection/discrimination thresholds (Clark and Stewart, 1970; MacNeilage et al., 2010; Roditi and Crane, 2012; Valko et al., 2012). Thus, one possibility is that users who are more sensitive to physical head pose/motion are also more susceptible to cybersickness due to *DVP*.

Alternatively, it may be that *DVP* can only explain within-subject effects on cybersickness (such as the effects of increasing the magnitude of the display lag or the speed of the user's head movement). In order to explain known/possible age (e.g., Cao et al., 2019), sex (e.g., Munafo et al., 2017) and other between-subject effects on cybersickness in HMD VR, we may need to look to other existing theories for inspiration. For example, if *DVP* is treated as non-redundant multisensory stimulation, then our *hypothesis* is potentially compatible with the *postural instability theory* of motion sickness. According to this view: (1) the preconscious pickup of large amplitude time-varying *DVP* could signal that the user's head pose is unstable; and (2) the automatic postural activity produced by this *DVP* could then increase the likelihood of him/her becoming posturally unstable and cybersick. Individual differences in the user's natural stability could then determine how destabilizing these automatic postural responses are, and how quickly he/she can return to a state of relative stability/wellness. Consistent with this idea, several recent HMD VR studies have found that individuals who are naturally unstable are more likely to become sick (Munafo et al., 2017; Arcioni et al., 2019; Risi and Palmisano, 2019; Teixeira and Palmisano, 2020). Each of these studies first examined their participants' spontaneous postural activity when standing quietly before entering HMD VR. In all four studies, pre-exposure postural activity was found to differ between the participants who later became sick and those who remained well during HMD VR. These findings suggest that it might be possible to predict susceptibility to cybersickness (before any exposure to HMD VR) based on individual differences in natural spontaneous postural stability.

Benefits of Studying Cybersickness Using DVP

Below, we compare our approach to studying cybersickness to traditional approaches based on *sensory conflict* and *postural instability*.

Comparing DVP and conflict approaches

If one treats *DVP* as an intersensory conflict regarding head pose, then our proposed approach has some advantages over traditional conflict-based approaches to cybersickness. Instead of merely speculating about the presence, or degree, of sensory conflict in a condition (like many past studies), our approach allows researchers to quantify the amount of *DVP* produced during each exposure to HMD VR. This metric is an objective measure of the stimulation rather than an internal model of the HMD user's sensory processing. In the sections on *Memory Buffer Method for Imposing Additional Constant Display Lag* and *Method for Estimating DVP Due to Display Lag*, we show how objective estimates of the *DVP* produced by display lag can be calculated from the participant's own head tracking data for each trial. Using such estimates, it should be possible to determine whether a particular VR condition is likely to be provocative (or not) for cybersickness. This determination could be based on the patterns of *DVP* that such conditions: (1) have generated in the past with other HMD users, or (2) are currently being generated while the user is actively experiencing HMD VR.

Comparing DVP and postural instability approaches

Our approach also appears to have some practical advantages over approaches using postural instability. According to *postural instability theory*, motion sickness is caused by prolonged postural instability of either the body or its segments. So, researchers using this approach must carefully examine both the spatial magnitudes and the temporal dynamics of their users' head, body and limb movements during HMD VR. There is also another obstacle to understanding cybersickness based on postural instability. Unfortunately, what constitutes postural stability and instability is currently not well-understood (e.g., there are more than nine different proposed operational definitions or "signatures" of postural instability; Riccio and Stoffregen, 1991). This makes it difficult to determine whether a change in the user's postural activity represents an increase in their postural instability or not. For example, an increase in their gross body motion alone would not be sufficient (as the postural activity in this case might be well-controlled/deterministic as opposed to random/chaotic). Researchers would therefore need to look for additional evidence of an increase in postural instability (such as changes in physiological tremor, spreading instability across joints, or increasing variability in the phase relations between the various degrees of freedom involved in the movement).

By contrast, our *DVP* approach to cybersickness is only focused on the user's head movements, not on the movements of their body or their limbs. This focus on the head seems particularly appropriate for HMD VR, given the greater influence that tracked head movements have on the user's point of view and avatar. We have shown that cybersickness can be predicted by simple summary measures of time-varying *DVP* (e.g., its mean, peak and standard deviation). If the HMD user is asked to make head rotations about a single axis (e.g., pitch), these predictions appear to hold even when *DVP* is only calculated using the head orientation data for that same axis (i.e., ignoring any differences in yaw and roll head orientation in the case of this example).

Thus, as our *DVP* hypothesis provides a simpler operational definition of the provocative stimulation during HMD VR, it should be much easier to identify and examine possible *DVP*-based precursors of cybersickness compared to possible precursors of sickness based on postural instability.

Future Directions and Implications

Future studies on DVP and cybersickness

In this paper, we proposed that cybersickness in HMD VR is triggered by large magnitude, time-varying *DVP*. However, a considerable amount of research still needs to be done to investigate and validate our *DVP hypothesis*.

Identifying precursors of cybersickness based on DVP. Our research to date has focused on the relationship between *DVP* and cybersickness severity. We still need to determine the exact nature of the changes in *DVP* that initially trigger this cybersickness. In such a study, participants would need to remain in active HMD VR until either their first report of cybersickness or the simulation times out. Then the estimated *DVP* for the trial could be analyzed using a windowing procedure similar to that used by Dong et al. (2011). For sick participants, we would calculate summary and temporal dynamic measures of the *DVP* for the first, middle and final Y seconds of the trial. For those who remained well, we would also calculate those measures for the same average time windows. This would allow us to identify triggering changes in the *DVP* by: (1) comparing the sick participant's *DVP* measures in their final window to those in their first and middle windows; and (2) comparing *DVP* measures in the final windows for sick and well participants.

Periodic and jittering display lags. In our studies to date *DVP* was always manipulated by introducing additional constant display lag into the system. Research is therefore still needed to determine the effects that periodic and jittering display lag have on *DVP* and cybersickness during active HMD VR. Such studies could use a similar approach to that outlined in the section on *Our Approach for Testing the DVP Hypothesis*. Researchers could inject artificial periodic/jittering lag on top of the HMD's baseline system lag, and then, using time-stamped information about the added lag, they could estimate the *DVP* experienced at each instant from the user's own head tracking data. Summary and temporal dynamics measures based on this *DVP* could then be compared to the user's cybersickness ratings.

Other types of head movements. Thus far, we have only examined the relationship between *DVP* and cybersickness when users make continuous yaw and pitch head rotations. Thus, we still need to examine the effects of head rotations in roll and head translations during HMD VR. While we expect that the relationships observed for yaw and pitch head movements should also generalize to roll, it is predicted that the *DVP* produced by head translations will be substantially less provocative for cybersickness.

For angular head movements like those made in our HMD VR studies (Feng et al., 2019; Palmisano et al., 2019; Kim et al., 2020), frequency also appears to be important. For example, Grabherr et al. (2008) found that the vestibular thresholds for discriminating left-right yaw rotations were quite similar within the range of 0.5–5 Hz (~0.6–0.7 deg s^{-1}). However, vestibular discrimination thresholds were much higher for movements of 0.2 Hz or less (e.g., the minimum velocity required for direction discrimination was 2.8 deg s^{-1}

on average for a 0.05 Hz movement). The relative precision of vestibular (compared to visual) thresholds also appears to depend on head movement frequency. For example, Karmali et al. (2014) found that for physical rotations between 0.1 and 1 Hz, vestibular thresholds appear to be higher than visual thresholds for discriminating roll motion direction. However, this relationship appears to reverse for physical movements above 2 Hz, with vestibular thresholds appearing to be lower than visual thresholds. So it will be important to examine whether the current cybersickness findings for 0.5 and 1.0 Hz generalize to other head movement frequencies.

It will also be important to examine the relationship between *DVP* and cybersickness during free/naturalistic head movements—e.g., using virtual search tasks similar to those in Kinsella et al. (2016), St. Pierre et al. (2015) and Stauffert et al. (2018).

Different ways to estimate DVP. In our studies to date we asked participants to rotate their head in either pitch or yaw, and then we estimated their *DVP* based simply on the changes in head orientation along that same axis. However, this approach ignored the *DVP* produced by their linear head motions and any head rotations about the other two axes. Future research and analysis are therefore needed to determine whether calculating the combined *DVP* across all three axes (x,y,z) and both types of head movements (rotation and translation) improves the prediction of cybersickness in HMD VR.

Effects of DVP on eye-movements and postural instability. Finally, the effects of *DVP* on both the user's eye-movements and their postural stability also need to be investigated. For example, eye-movement recordings made during HMD VR could be used to determine the extent to which *DVP* generates nystagmus and errors in gaze holding during head rotation. Similarly, center of foot pressure recordings during HMD VR could be used to determine how the user's *DVP* affects their overall postural activity, as well as their head movements and experiences of cybersickness.

Possible role of DVP in mitigating cybersickness

In a laboratory context, *DVP* should allow researchers to precisely predict the effects that different HMD VR conditions will have on cybersickness. Researchers could extrapolate the likelihood/severity of cybersickness in a particular experimental HMD VR condition based on the user's own *DVP* and sickness data (e.g., obtained during past exposures to similar conditions/simulations). However, we believe that *DVP* could also be useful outside the laboratory. In the future, *DVP* could be used to mitigate (or even prevent) the cybersickness experienced when using commercial HMD VR apps. For example, real-time estimates of the user's *DVP* calculated during the exposure could be used to provide warnings whenever he/she makes potentially provocative head movements. Alternatively, developers could script the storyline of the HMD VR gameplay/experience to intermix more and less provocative periods of *DVP*—with the latter, calmer periods either being used to prevent the user from reaching the threshold for sickness or allowing him/her time to recover from any sickness that has been triggered.

Will cybersickness disappear as baseline system lags are reduced?

It is now possible to achieve an effective display lag of ∼3–4 ms in HMD VR. However, some participants still report sickness symptoms even under these minimal lag conditions (see **Figures 2A–C**). Studies testing recent commercial VR games also continue to find quite high rates of sickness in their users even when modern HMD systems are used (e.g., Yildirim, 2019a; Teixeira and Palmisano, 2020). As noted earlier, provocative *DVP* can still be produced when baseline lag is artificially reduced to very low levels. We believe that latency spikes are the most likely explanation for cybersickness in this situation. According to our hypothesis, the change in *DVP* produced by brief latency spikes should be sufficient to trigger sickness in susceptible users. Consistent with this proposal, latency spikes have been shown to exacerbate cybersickness in HMD VR, even when participants do not notice them (Stauffert et al., 2018). Thus, researchers need to better understand the *DVP* generated by this unpredictable display lag. However, even when lag is adequately compensated, other errors in tracking the moving viewpoint could also produce provocative *DVP*. For example, ocular parallax produces small shifts in the effective vantage point during large eye movements (Mapp and Ono, 1986; Bingham, 1993). The high magnification of the near-eye displays used in HMDs can amplify these effects, but this *DVP* is not typically modeled when rendering HMD displays (Kudo and Ohnishi, 2000; Jones et al., 2015; Konrad et al., 2020). The above considerations therefore suggest that software techniques which artificially reduce the effective display lag (e.g., ATW) will not be a complete solution to cybersickness in HMD VR.

Implications for HMD based augmented reality (AR)

While this paper has focused on the cybersickness experienced in HMD VR, display lag can also be a problem for HMD AR (Bajura and Neumann, 1995; Yokokohji et al., 2000). For example, with video-see through HMDs, delay in the video camera feed can introduce an additional source of display lag. When the user makes a head-movement, their delayed camera images will often not match the virtual scene content. Different parts of the visual display will appear to be moving at different speeds (depending on whether they are real or virtual), promoting perceived scene instability and further increasing the likelihood of cybersickness. In a recent study, Freiwald et al. (2018) showed that cybersickness in HMD AR could be considerably reduced by imposing an additional constant delay to their HMD's tracking system so that it matched the latency of the video stream. By minimizing the discrepancies between visual real world and virtual scene content motion, this "CamWarp" technique should have reduced the users' perceived scene instability. However, it should have had little effect on their virtual head pose, as this would have been determined by the motion of their visual background. Since CamWarp only delayed the virtual foreground scene content, the user's *DVP* should have been largely unaffected by this technique. This intriguing finding suggests that perceived scene instability also plays an important role in cybersickness in HMD-AR (i.e., in addition to the user's *DVP*).

CONCLUSIONS

There have been substantial improvements to HMD hardware and software over the last decade. However, we are still far from fully understanding the cause of cybersickness and how it can be mitigated. This understanding is critical for HMD VR to reach its full potential and make access to the technology a preferred option for future ways of working (e.g., in education, training and health). In this paper, we present a new hypothesis for understanding cybersickness in HMD VR, based on *Differences in the user's Virtual and Physical head pose* (or *DVP*). We propose that *DVP* is the primary cause of cybersickness in HMD VR (not excessive eye-movements, or increases in postural instability, or conflicts involving vection, subjective verticals and rest frames). Our hypothesis is supported by empirical evidence that *DVP* can be used to predict the effects of display lag and head speed on cybersickness severity. Of the measures examined thus far, the mean, peak and standard deviation of the *DVP* appear to be the best predictors of cybersickness. However, we acknowledge that the current data are limited. Using *DVP* researchers and developers should be able to objectively estimate the likelihood and severity of cybersickness in virtual environments viewed using HMDs. It is hoped that in the future, estimates of this *DVP* could also be used to mitigate (or even prevent) the cybersickness experienced when using commercial HMD VR apps.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: These datasets were published in the journal Computers in Human Behavior and the proceedings of VRST 2019. Requests to access these datasets should be directed to juno.kim@unsw.edu.au and stephenp@uow.edu.au.

ETHICS STATEMENT

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

AUTHOR CONTRIBUTIONS

SP: critical review of the literature. SP and JK: development of the hypothesis. SP, RA, and JK: theoretical analysis and wrote the paper. All authors: contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Visually Induced Motion Sickness on the Horizon

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Visually induced motion sickness is an unpleasant but common side-effect of many simulations and VR-applications. We investigated whether an earth-fixed reference frame provided in the simulation is able to reduce motion sickness. To do so, we created a moving starfield that did not contain any indicators of the spatial orientation of the observer. As the observer was simulated to move through the randomly oscillating starfield, a time-to-contact task had to be carried out. Two colored stars on collision course with each other had to be spotted, then they disappeared and the time of their collision had to be judged. Eye-movements, task performance, and motion sickness were recorded. This condition without visual reference to the observer's upright was supplemented with three conditions containing either an earth-fixed fixation cross, an earth-fixed horizon line, or a line that was yoked to the head. Results show that only the earth-fixed horizon was able to significantly reduce visually induced motion sickness. Thus, a mere earth-stationary anchor does not suffice, a clear indication of earth horizontal seems necessary to reap a modest benefit.

Keywords: reference information, motion sickness, visually induced motion sickness, virtual reality, artificial horizon, performance, time-to-contact (TTC)

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INTRODUCTION

Motion sickness (MS) is a common physiological and psychological response to unfamiliar motion patterns and a frequent side-effect induced by provocative motion environments, as associated with many forms of transportation, such as ships, aircraft, and automobiles. Motion sickness can also occur during Virtual Reality (VR) applications (e.g., driving or flight simulators), typically labeled as visually induced motion sickness (VIMS). VIMS is a special case of MS, which is primarily caused by stimulation of the visual system in the absence of real, physical movement (Keshavarz et al., 2014).

The nomenclature regarding VIMS is highly inconsistent and often dependent on the technology being employed, with studies referring to VIMS as *cybersickness* (e.g., McCauley and Sharkey, 1992; Davis et al., 2014), *simulator sickness* (e.g., Kennedy et al., 1992; Hettinger and Haas, 2003), *gaming sickness* (e.g., Chen et al., 2016; Oldenburg, 2018), and *virtual reality sickness* (e.g., Guna et al., 2019; Saredakis et al., 2020). However, we will use the term VIMS, as it includes all of the above-mentioned types of MS (Keshavarz et al., 2014).

Several theories have been proposed to explain VIMS, including the role of postural control (Riccio and Stoffregen, 1991) or eye movements (Ebenholtz et al., 1994), but the true ethiopathogeny and the biological mechanisms underlying VIMS still remain elusive. Claremont (1931) originally suggested the theory that sea sickness is caused by an inter-sensory conflict, which was later refined by Steele (1961), Guedry (1965), and Reason (1969). Reason and Brand (1975) later formalized and distilled the previous research into the framework of *sensory conflict theory,* which is probably the most commonly accepted notion for the development of VIMS today. It states that VIMS is caused (a) if conflicting information is provided by the visual, vestibular, and somatosensory senses; (b) if the configuration sensed among these three modalities does not match what would be expected based on previous experience. For instance, the visual stimulation in an immersive but stationary driving simulator may suggest apparent self-motion of the driver (known as vection), whereas the vestibular and somatosensory senses signal stasis. This visual-vestibular conflict can, under certain circumstances (e.g., lack of adaptation mechanisms) result in the sensation of VIMS.

In the context of traditional MS (i.e., sea sickness), anecdotal evidence suggests that leaving the cabin and finding a spot on the deck of the ship may help to reduce feelings of MS. Fresh air might contribute to subdue the symptoms (D'Amour et al., 2017), but, at the same time, the horizon becomes visible when on the ship's deck, which reduces the intersensory conflict between the visual and vestibular senses (Hill, 1936; Bruner, 1955; Rolnick and Bles, 1989; Turner and Griffin, 1995; Tal et al., 2012; Keshavarz et al., 2014). Interestingly, Mayo et al. (2011) found a reduction in body-sway when viewing the horizon on deck of a ship, which supports the idea that being able to see the horizon helps to reduce MS, as increased body sway has been associated with elevated levels of MS and VIMS in the past (Stoffregen and Smart, 1998; Smart et al., 2002).

It is thought that a visible horizon reduces the sensory conflict by providing a frame-of-reference that allows the visual system to synchronize with the perceived motion. In aviation, an extended horizon line or *Malcolm Horizon* (Malcolm, 1983) makes use of this concept by projecting an artificial horizon line across the cockpit, providing pilots with a line that is parallel to the true horizon, regardless of the aircraft's orientation with respect to the ground. The Malcolm Horizon has been shown to reduce tilt sensations in pilots (Lackner, 1990, p. 47). In fact, artificial horizons were amongst the earliest standard instruments used in aeronautical navigation (Schroer, 2003), and maintaining visual contact is recommended to reduce MS in poor viewing conditions (Burcham, 2002, p. 5).

The understanding of the mitigating effect of a horizon can be supplemented by considering *rest frames*. As suggested by Prothero (1998) and Prothero and Parker (2003), the concept of rest frames is derived from the observation that humans have a strong innate perception of stationary objects. By their definition, rest frames are particular visual frames that are perceived to be stationary and are used as a neurological comparator for spatial judgments. In contrast, *reference frames* define a positional reference system for spatial features, allowing comparative localization with respect to position, orientation, and motion. According to Prothero (1998), a scene can be divided into two distinct elements: (1) the content-of-interest and (2) the independent visual background. The content-of-interest is the entirety of all the foreground cues, for instance a scene in which an observer is driving a car, whereas the independent visual background is a visual object that, which is consistent with inertial cues and provides an earth-fixed reference frame (e.g., a fixation cross or a static horizon).

With regard to VIMS in virtual environments as experienced when wearing a head-mounted display (HMD), the absence or presence of visual reference information would produce different predictions for VIMS severity according to the following reasoning. According to the wide-spread conflict theory of VIMS, malaise increases as a function of the conflict between visual and vestibular/proprioceptive information (see e.g., Nooij et al., 2017). Now, how does the reference frame play into this? When the comparator pits consistent visual information against consistent but disagreeing vestibular information, the conflict, and thus VIMS, should be largest. If visual information is inconsistent, this should reduce the conflict. A stimulus devoid of reference information should be most provocative. A stimulus providing an earth-stable reference, in contrast, should minimize the conflict as it is maximally consistent with the vestibular information. Other visual references, such as a fixation dot, or a reference that is yoked to the head of the observer, such as the visible frame of the HMD, should fall somewhere in-between. Previous studies have examined the effect of an artificial horizon and found it to be beneficial in the reduction of VIMS symptoms (Rolnick and Bles, 1989; Lin et al., 2004; Tal et al., 2012, 2014). However, they have not compared degrees of visual reference frame information.

Eye-movements have been taken to indicate visual information processing and have been discussed as a potential contributor to the genesis of MS and VIMS (Ebenholtz et al., 1994) and have been linked to the occurrence of MS via stimulation of the vagal nerve. Thus, minimizing the amount of eye movements should reduce the occurrence of MS and VIMS. Providing a visual reference frame should thus reduce eye-movements and VIMS if the two are causally related. In fact, several studies successfully demonstrated that a fixation cross presented in the center of a visual scene can reduce nystagmus and VIMS at the same time (Stern et al., 1990; Flanagan et al., 2002; Webb and Griffin, 2002).

The objective of the present study was to further investigate the role of stationary rest frames and eye movements in the occurrence of VIMS; that is to determine whether different rest frames can serve as a potential countermeasure and effectively reduce VIMS. To achieve this, we exposed our participants to a potentially nauseating optic flow stimulus (starfield) in a VR-setup using an HMD. The starfield stimulus was chosen based on the theoretical and methodological considerations of Keshavarz et al. (2019), who successfully induced VIMS with this type of stimulus. To provide a meaningful stimulus, we designed a time-to-contact (TTC) task to be performed during the experiment. It fulfilled the function to direct the subject's attention to the stimulus and at the same served as a performance measure. TTC is the time remaining until a collision occurs between two objects that approach each other provided they will continue on the same trajectory at the same speed. This prediction task ensured a high level of alertness.

Four distinct experimental conditions were chosen which varied with respect to the presence of additional visual cues that were superimposed on the screen: two conditions included earth-stationary visual cues (*Fixation Cross* and a *Fixed Horizon*), one condition included a visual cue that was congruent with the camera's random motion (*Moving Horizon*), and one condition acted as control with no additional visual cues (*No Visual Cues*). Apart from self-reported VIMS scores, we measured heart-rate and eye-movements, which have been linked to the occurrence of VIMS in previous studies (Crampton, 1955; Cowings et al., 1986; Stout et al., 1995; Holmes and Griffin, 2001), considering that the majority of VIMS symptoms is related to an increase in sympathetic activity and a decrease in parasympathetic activity (Hu et al., 1991; Doweck et al., 1997; Holmes and Griffin, 2001). Although a strong relationship between heart-rate/heart-rate variability and VIMS could not be established in the past (Mullen et al., 1998), we added these measures to gather further insights into the physiological changes associated with VIMS. Perceptual measures (vection, immersion, realism) regarding the stimulus were collected following stimulus presentation and are analyzed in relationship to FMS ratings (Fast Motion Sickness Scale; Keshavarz et al., 2014, 2015) and gender (Hemmerich et al., 2019). While the relationship between vection and VIMS is not yet fully understood, the probability of experiencing VIMS increases with the occurrence of vection, making it a potential prerequisite for VIMS, given that other factors are also in place (Keshavarz et al., 2015). Similarly, correlates between VIMS and immersion (e.g., Yang et al., 2012; Duan et al., 2018), as well as realism have been reported (e.g., D'Amour et al., 2017; Pouke et al., 2018).

METHODS

Participants

Thirty-three participants volunteered for this study. Eight participants (7 female) chose to terminate the experiment prematurely due to severe levels of VIMS and 3 participants were excluded because they reported medical conditions (chronic pain), resulting in a final sample of $n = 22$ (15 female, 7 male). Participants' age ranged from 19 to 33 years ($M = 24.2$ years, $SD = 3.3$ years). Inclusion criteria were normal or corrected-to-normal (lenses only) vision. Correction with eyeglasses was an exclusion criterion during recruitment due to the restricted space in the head-mounted display (HMD). The study was conducted in accordance with the Declaration of Helsinki. Participants received partial course credit as compensation. All participants were naïve with respect to the purpose of the study and were not familiar with the experimental task and rationale.

Design, Stimulus, and Apparatus

In a within-subjects design, all participants were exposed to four experimental conditions: (1) Moving Horizon, (2) Fixed Horizon, (3) Fixation Cross, and (4) No Visual Cues. Note that we deliberately chose a within-subjects design over a between-subjects approach, as MS varies considerably among subjects, increasing the interindividual variability and complicating the comparison across different experimental groups. The order of conditions was randomized and presented in a single test session. The Moving Horizon was identical to the Fixed Horizon with the exception that the Moving Horizon was not fixed in virtual space but rather moved synchronously with the camera's random motion through the virtual environment. Both the Fixed Horizon and the Fixation Cross created an earth-stationary reference in VR, which was invariant to the randomly generated motion but changed its relative position in the display depending on the observer's head movements. Strictly speaking, the Horizon was a narrow rectangle, 11.10×0.07 relative units in size, whereas the Fixation Cross was comprised of two 2.19×0.07 rectangles, which were perpendicular to each other at their geometric center. All objects were positioned at the Cartesian origin in virtual space.

The optic flow stimulus consisted of a 14 min simulated flight through a virtual starfield. The visual reference condition was randomly changed every 3.5 min, such that each participant saw all 4 conditions during the 14 min flight. The stimulus was created and presented using Unity3D, a cross-platform game engine with emphasis on rendering-speed and realism. The starfield was generated using a particle system, which spawned a constant conic torrent of random particles (i.e., white spheres) toward the camera object, with ∼4.000 visible particles being rendered at any given time, although, due to the vastness of the virtual space, far fewer were visible (see **Figure 1**). The stars grew in retinal size according to their proximity in virtual space. Random motion was produced using the plugin *Jitter* (Virtual Escapes, 2019). Motion profiles were randomly generated using a seeded pseudorandom number generator and, therefore, they were practically identical between subjects. A post-render bloom shader was applied to the particles to increase the overall stimulus realism and to amplify the nauseogenic effect (Bonato et al., 2015). After all, the goal was to trigger measurable VIMS without incapacitating the participants. To guarantee a high level of alertness and to evaluate participants' performance as a function of VIMS, the time-to-contact task was incorporated into the simulation.

In a pilot study ($n = 11$) prior to the actual experiment, we identified the rotational and transitional parameters controlling the motion of the attached camera objects. The plugin Jitter requires three parameters (magnitude, amplitude, and frequency) which we set to the values found in **Table 1** following the pilot study. Magnitude controls the amount of noise, with larger values corresponding to an increase in the noise level; the amplitude specifies a range which defines the upper and lower bound between which random values can vary; frequency controls the speed at which the random noise varies, with larger values indicating a more abrupt transition to the next value.

The stimulus was presented stereoscopically on an HTC Vive HMD with an integrated Pupil Labs binocular eye-tracking add-on. The HTC Vive has a combined resolution of 2,160 × 1,200 px (1,080 × 1,200 px per eye) and 110° field of view horizontally, 100° field of view vertically, rendering at 90 Hz; the Pupil Labs eye-tracker has a sampling frequency of 100 Hz per eye, with a gaze accuracy of ∼1.0° and a gaze precision of ∼0.08°. Participants used the Vive controller in their preferred hand to respond to the TTC task. As per the recommendations of Santini et al. (2018), only samples with a confidence rating > 0.66 were included in the analysis.

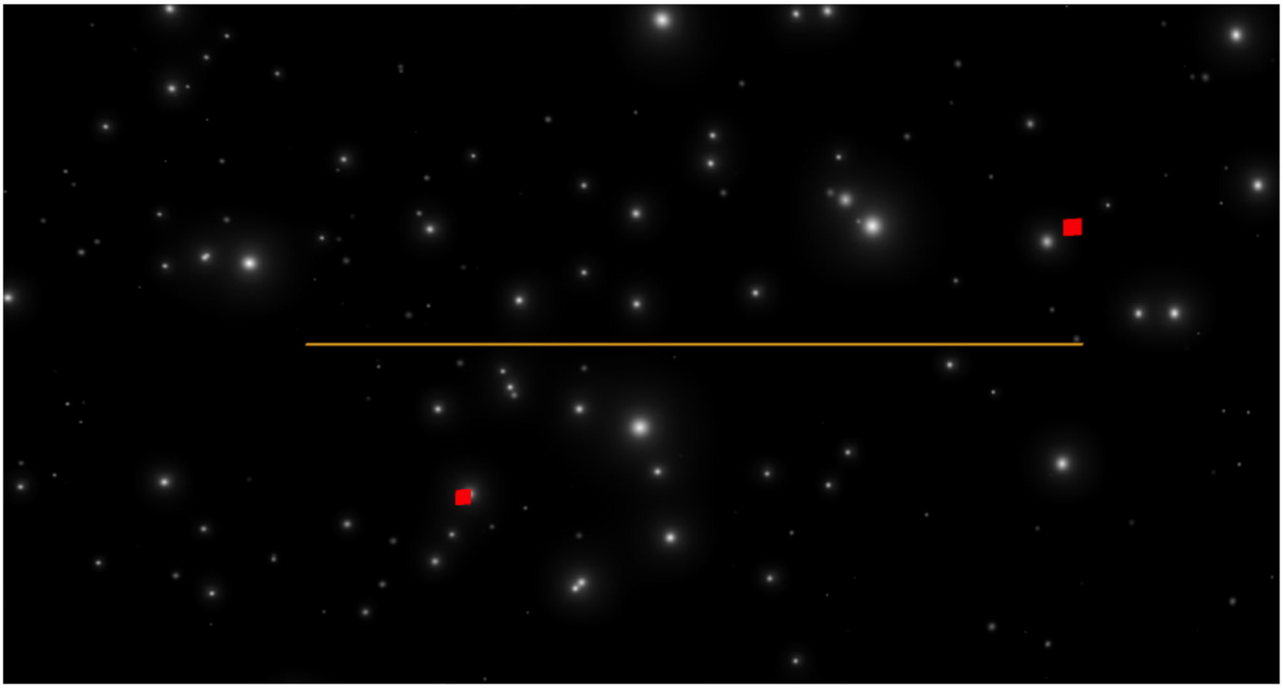

FIGURE 1 | The starfield stimulus used, here as seen in the Fixed Horizon condition. The yellow line marks the artificial horizon; the two red squares gravitated toward one another before disappearing (TTC-task).

TABLE 1 | Rotational and transitional stimulus parameters determined after piloting.

Dimension	Magnitude	Amplitude Range	Frequency
Translation			
x-axis	0.75	[−1, 1]	2.11
y-axis	0.75	[−1, 1]	2.11
z-axis	1.00	[−1, 1]	0.5
Rotation			
x-axis	0.75	[−25, 25]	2.11
y-axis	0.75	[−25, 25]	1.59
z-axis	0.75	[−75, 75]	1.5

Time-to-Contact (TTC) Task

At intervals of 7 s, participants were presented with two red squares, which started moving toward one another at varying speeds but disappeared before colliding. Participants were tasked to press the trigger button on the Vive controller at the moment when the objects would have collided had they continued on their trajectory. Speeds of the red squares were chosen such that collision times ranged between 600 and 1,500 ms, with 10 different speed conditions in total. The red squares were positioned slightly behind the horizon or cross and presented at three varying inclinations (−25°, 0°, 25°), pivoting at the Cartesian origin, 50 relative units apart at their starting position. This resulted in 30 unique combinations that were repeated at random for each of the four experimental conditions. Non-response trials were followed by a red flash. Absolute and constant errors in completed TTC judgments were used for statistical analysis.

Physiological Measures

Heart rate and eye movements were measured during the experiment. Heart rate was measured continuously at 1 Hz using the Covidien Nellcor PM10N and then averaged in 1 min blocks for subsequent analysis, for all correlational analysis. This way, heart rate was down-sampled to the frequency of the VIMS ratings. Eye-movements were recorded using the Pupil Labs binocular eye-tracking add-on, which integrates into the HTC Vive.

Measures of VIMS, Vection, Immersion, and Realism

The Fast Motion Sickness Scale (FMS; Keshavarz and Hecht, 2011) was used to measure the level of VIMS during stimulus presentation. The FMS is a verbal rating scale ranging from 0 (no sickness) to 20 (severe sickness) and focuses on subjects' general discomfort, nausea, and stomach problems. The FMS has been shown to have high correlations with the Simulator Sickness Questionnaire by Kennedy et al. (1993), and its rapid administration allows for the quantification of the time course of MS. The FMS allows for unobtrusive rapid self-report while participants are engaged in the VR task and was used every 60 s during the stimulus presentation. Ratings of the subjective intensity of vection, as well as immersion and realism of the display were obtained once at the end of the session. Participants rated the maximal strength of the vection they had experienced, that is the feeling of moving forward through the starfield (as opposed to stars moving by) on a scale ranging from 1 (no vection) to 7 very strong vection. Then they indicated how often throughout the 14 min of stimulus presentation they were in a state of vection, on a similar scale from 1 (never) to 7 (pretty much the entire time). Immersion, the sophistication of the virtual world, and realism, the sense of being in the simulation, were likewise rated on 7-point scales.

Procedure

Written consent was obtained from the participants prior to the experiment. Participants were instructed in the use of the HMD, the TTC task, and the FMS scale but remained naïve as to the objective of the study until the end of the experiment. Once participants were comfortable and all pending questions had been answered, testing began with the connection and setup of the HMD and the pulse oximeter, followed by a calibration of the eye-tracker. Participants' FMS baseline readings were taken and the stimulus was started. Participants were not given any specific instructions as to what position to remain in during stimulus presentation and they were free to move their head within the virtual environment, should they choose to do so. Note that the TTC-task required them to move the head in order to spot both targets at their initial positions. FMS readings were taken in 1 min intervals for the duration of the stimulus. Upon completion, participants were asked to fill in a questionnaire asking for the overall ratings of vection, immersion, and realism. Then they were debriefed about the background of the study.

RESULTS

Statistical analyses were performed using SPSS 26, JASP 0.13, and R 3.6.3. We determined within-subject correlations using the rmcorr package (Bakdash and Marusich, 2017). First, we performed a general assessment to verify that VIMS had indeed been elicited. Accordingly, a paired t-test with baseline and peak FMS scores showed a significant increase and, therefore, a successful manipulation, $t_{(21)} = -5.827$, $p < 0.001$, $d = -1.242$.

It is common to use peak FMS-scores for analysis purposes (see the original validation study by Keshavarz and Hecht (2011) which used peak FMS scores in a between-subjects design. However, this was no longer possible in our within-subjects design, as VIMS accumulates over the course of the entire session. Thus, we used average FMS scores per condition instead. As the relationship between FMS-scores over time was cumulative and best modeled by a quadratic function, FMS values were averaged using the geometric mean (Streiner, 2000; De Muth, 2006; Pal and Bharati, 2019).

FMS Scores

The average FMS-scores per condition are plotted in **Figure 2**. A repeated measures ANOVA including the within-subjects factor experimental condition (Moving Horizon, Fixed Horizon, Fixation Cross, and No Visual Cues) was calculated for the averaged FMS scores. Sphericity was assumed, Mauchly-Test $p > 0.05$. Results showed a significant main effect of experimental condition, $F_{(3,63)} = 2.867$, $p = 0.043$, $\eta_p^2 = 0.120$. Planned contrasts revealed significant differences between the fixed horizon and all other conditions: Fixed Horizon vs. Moving Horizon, $t_{(63)} = -2.165$, $p = 0.034$, Fixed Horizon vs. Fixation Cross, $t_{(63)} = -2.492$, $p = 0.015$, Fixed Horizon vs. No visual

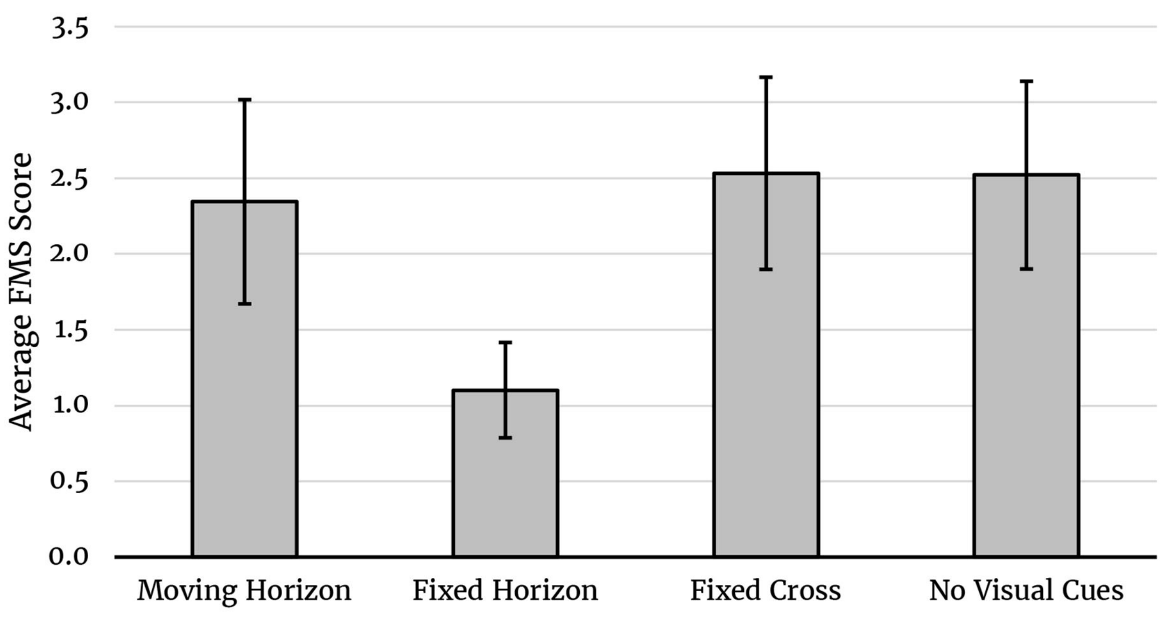

FIGURE 2 | Average FMS scores for each condition. Averages represent the geometric mean. Error bars indicate the SEM.

cues, $t_{(63)} = -2.471$, $p = 0.016$, Fixed Horizon vs. all other conditions (equally weighted), $t_{(63)} = -2.905$, $p = 0.005$, but not between any other conditions (p's > 0.744).

To provide an impression for the distribution of VIMS among subjects, we have also computed the peak FMS scores across all subjects, as well as the peak scores associated with each condition disregarding the cumulative effects. **Figure 3** shows these distributions as a box-plot, illustrating that VIMS varied considerably among subjects.

Secondary Measures

The means of the other measures per condition are given in **Table 2**. Added to this table are the results of an rmANOVA for the factor condition and each secondary measure. Heart rate did not, but absolute TTC-error did vary significantly among conditions.

Note that the scanpath length of all eye-movements was calculated by computing and summing the Euclidean distances between consecutive eye-fixation data points. The dispersion of scanpath length is the standard deviation of these distances.

Furthermore, repeated measures correlations were calculated among FMS, heart-rate, TTC-judgments, and scanpath length. For these correlations, data were averaged over 1 min intervals to make them compatible with the respective corresponding FMS values taken at the end of the same intervals (see **Table 3**).

Table 4 shows the correlations between peak FMS scores (i.e., the highest FMS rating during the entire 14 min stimulus presentation), gender, and post-stimulus ratings for vection, immersion, and realism.

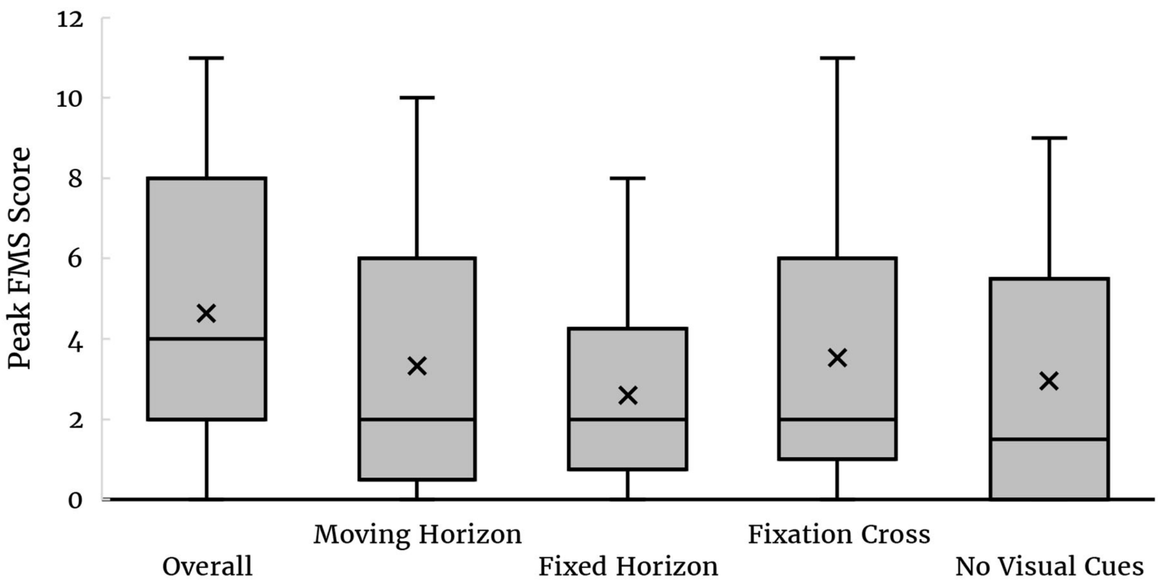

FIGURE 3 | Box-plots of overall peak FMS across all conditions and peak FMS scores for each condition. The line in the middle of the box indicates the median value. The cross represents the mean.

TABLE 2 | Means (standard deviations in parenthesis) for each measure for each condition.

Measure	Means and Standard Deviations				*F*	*p*	η_p^2
	Moving Horizon	Fixed Horizon	Fixation Cross	No Visual Cues			
Heart Rate (bpm)	83.75 (14.23)	82.92 (13.53)	85.48 (13.76)	84.16 (14.62)	2.298	0.087	0.103
TTC (Absolute Error in s)	0.71 (0.61)	0.72 (0.61)	0.64 (0.60)	0.60 (0.60)	3.655	0.017*	0.148
TTC (Constant Error in s)	0.07 (0.82)	0.03 (0.84)	0.02 (0.80)	0.08 (0.81)	0.693	0.560	0.032
Eye Movements (Scanpath Length)[a]	101.86 (204.84)	88.93 (168.25)	97.72 (185.21)	89.00 (172.72)	1.498	0.235	0.067
Eye Movements (Dispersion)	0.07 (0.06)	0.08 (0.08)	0.08 (0.07)	0.09 (0.08)	0.270	0.847	0.014

$^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$. [a]Greenhouse-Geisser corrected due to violation of sphericity.

TABLE 3 | Repeated Measures correlations among time and frequency domain measures ($n = 22$).

	1	2	3	4	5	6
All subjects ($n = 22$)						
1. FMS	—					
2. Heart Rate	0.160**	—				
3. TTC (Absolute Error)	0.021	−0.117	—			
4. TTC (Constant Error[a])	−0.163**	0.095	−0.580***	—		
5. Eye Movements (Scanpath Length)	0.160**	−0.030	−0.019	0.018	—	
6. Eye Movements (*Dispersion*)	0.182**	−0.012	−0.060	0.009	0.406***	—

**p* < 0.05, ***p* < 0.01, ****p* < 0.001. [a]*The constant error was calculated by subtracting participants' judgments from the actual collision time, with negative values indicating an underestimation of TTC. The absolute error was computed by averaging the unsigned TTC errors.*

TABLE 4 | Means, standard deviations, and correlations among VIMS-specific variables.

	M	*SD*	1	2	3	4	5	6
1. Peak FMS	4.64	3.57	—					
2. Gender[a]	0.68	—	0.506*	—				
3. Immersion[b]	5.50	1.30	−0.298	−0.179	—			
4. Vection frequency[b]	4.68	1.86	−0.076	−0.133	0.423*	—		
5. Vection strength[b]	4.50	1.90	−0.106	−0.086	0.338	0.884***	—	
6. Stimulus realism[b]	4.18	1.47	0.050	0.470*	0.524*	0.423*	0.428*	—

*Correlations are Pearson correlations with the exception of the binary variable Gender, where Spearman correlations are reported for all pairs. *p < 0.05, **p < 0.01, ***p < 0.001.* [a]*Males are coded 0, females are coded 1.* [b]*Scale ranges from 1 to 7.*

DISCUSSION

The purpose of this paper was to further investigate if an artificial earth-reference within a virtual environment is able to reduce the degree of VIMS, which is a common and serious side-effect of VR-displays. Participants had to perform a TTC-estimation task in a virtual starfield that did not provide any orientation cues except for the experimental references (earth-fixed fixation cross, earth-fixed horizon line, head-fixed horizon line, control). An earth-fixed reference is thought to reduce the sensory conflict by providing a frame-of-reference, allowing for the synchronization of the visual system with the perceived motion (Harm et al., 1998; Prothero et al., 1999). We found that VIMS occurred in all experimental conditions, to the extent that many participants chose to abort the experiment. Among those who were able to finish the experiment, the fixed horizon line caused less VIMS than did the other conditions.

Both this horizon and the fixation cross were fixed with respect to true earth horizontal, that is, they visualized a reference consistent with the vestibular information of the horizontal. The horizon-line effect is in line with previous studies, which also found reports of lower MS with an artificial or real visible horizon (Bruner, 1955; Rolnick and Bles, 1989; Turner and Griffin, 1995; Tal et al., 2014). Interestingly, participants only experienced reduced VIMS when viewing the fixed horizon line, but not when provided with the fixation cross. This is striking, as both provide a stationary region within the visual field, which should—in theory—minimize the sensory conflict or rather provide a rest-frame congruent with inertial cues.

A possible explanation for this difference may be the narrow attentional focus when looking at the cross. The short cross-hairs of this fix-point provided an orientation cue but only when foveated. However, participants were required to focus the target stars in order to perform the TTC task. The horizon line extended into their peripheral visual field, providing a constant source of spatial orientation but the orientation of the cross was not discernable in peripheral vision. This would be consistent with previous evidence regarding the Malcolm Horizon (Malcolm, 1983; Comstock et al., 2003).

Another explanation may be that due to the TTC task, subjects performed more medio-lateral head-movements to keep both targets discernable within their field-of-view. The earth-fixed horizon line remained more or less stable when making medio-latera head turns, and was thus not obtrusive while still providing a predictably motionless area. In contrast, the vertical bar of the fixation cross—as soon as it was no longer foveated—produced the impression that it moved, sometimes causing apparent motion while scanning along the azimuth. This may have substantially reduced its ability to serve as an earth-fixed reference point.

The peak FMS scores did not explain any variance in the ratings of vection, immersion, and realism: none of the correlations were significant. The correlations between immersion, realism, and vection frequency can be explained by the conceptual overlap among these measures. The failure of perceived vection to partially explain VIMS is not uncommon. Findings here have been inconsistent across studies (for a full review, see Keshavarz et al., 2014, 2015). We did not find a significant main effect of gender, probably due to the small number of male subjects. The positive correlation of FMS and gender indicates that women tended to experience higher FMS scores than men, which is often the case in larger samples (but see Hemmerich et al., 2019).

Physiological and Autonomic Correlates

The relationship between VIMS and eye-movements and heart-rate is tenuous at best. We found a small, but significant correlation of FMS ratings with heart-rate, which is consistent with some previous studies (Crampton, 1955; Cowings et al., 1986; Stout et al., 1995; Holmes and Griffin, 2001), but has not been found by others (Graybiel and Lackner, 1980; Mullen et al., 1998). While the exact physiological effects of VIMS on heart rate require further investigation, it is most commonly assumed that a shared process in the autonomic nervous system is responsible for the association, consistent with a stress response (Harm, 2002; Keshavarz et al., 2014). We could not detect any differential effects of our experimental conditions on such a response, that is, the slight elevation of heart rate with increasing VIMS was the same for all visual reference conditions.

Furthermore, we observed a small but significant positive correlation between eye movements and VIMS ratings. While the correlational analysis did reveal a general relationship between FMS scores and scanpath length and -dispersion, this association was not modulated by the experimental condition. Many studies have investigated the role of nystagmus and MS (e.g., Quarck et al., 2000; Flanagan et al., 2002; Gupta, 2005). However, our objective was not to specifically investigate nystagmus, as it was dictated more or less by the TTC-task, but rather to look into general metrics of ocular motion. Webb and Griffin (2002) observed lower MS ratings when participants were asked to fixate in order to reduce their eye movements. Elbin et al. (2019) found that subjects with a higher susceptibility to MS also exhibited more saccadic eye movements. Ebenholtz et al. (1994) proposed that MS may be elicited by nystagmus in such a manner that the corresponding afferent signals stimulating the *nervus vagus* conjointly affect the adjacent *nuclei vestibulares*. This spill-over may hold an explanation of the interactions responsible for this association. Clearly, further research is required to understand the contribution of eye movements to VIMS.

TTC Judgments and VIMS

This is the first study that investigates the relationship between visual TTC judgments and VIMS. We determined both the average absolute and constant errors when making TTC judgments. Participants performed the task very well. They were on average only about 70 ms too late in their judgments of the collision. This is remarkable given the unusual environment. For instance, Gray and Regan (2000) found larger errors in a non-provocative visual environment. This suggests that the VR-setup and the associated level of VIMS did not interfere with the TTC-task. Notwithstanding, there was a significant tendency to underestimate TTC a little more with increased VIMS. This result is compatible with studies showing that the emotional valence of the stimulus modulates TTC response times. Threatening stimuli caused TTC to be underestimated (Brendel et al., 2012) and Vagnoni et al. (2012), speculating that MS may have its evolutionary roots in the response to ingested toxins which constitutes a response to a threatening stimulus (Treisman, 1977).

Note, however, that the absolute TTC errors, which indicate variability of the TTC-judgments, were uncorrelated with VIMS.

Limitations

All four conditions were presented subsequently in one session in a within-subjects design. As with every within-subjects design, carry-over effects are a considerable disadvantage; however, we presented the experimental conditions in different orders to reduce such carry-over effects while minimizing the number of drop-outs. The total exposure to the stimulus was limited to 14 min to make the experimental sessions tolerable, resulting in 3.5 min per condition. We acknowledge that this rather short stimulus duration per condition may have resulted in the overall low VIMS scores. We recommend for future studies to prolong the stimulus presentation to maximize the likelihood of experiencing stronger levels of VIMS with each experimental condition administered on different days. However, we believe that it is unlikely but conceivable that longer exposures would prompt participants to make better use of the earth-stable reference cues.

After extensive piloting, we had decided on a stimulus that was just provocative enough so subjects were likely to finish the experiment. Nonetheless, eight participants reported severe simulator sickness and terminated the experiment prematurely and were excluded from the data analysis. Consequently, only those who were able to finish all four experimental conditions were included in the data analysis, which likely explains the low sickness scores found in this study. This may limit the generalizability of our findings to mildly provocative stimulations. In other words, we acknowledge that these results are limited by low overall FMS ratings ($M_{\text{PeakFMS}} = 4.64$) and should accordingly be interpreted with care. Future research could explore the possibility of an adaptive stimulus, whereby the frequency and amplitude of the random motion is altered according to participants' current FMS ratings, thereby increasing or decreasing motion to meet a target FMS-value. Analysis could incorporate this parameter as a time-varying covariate.

Would participants be able to benefit more from an earth-fixed reference cue when the task allows them to fixate this cue at all times? This may well be the case, but it is exceedingly difficult to provide such a cue and at the same time ensure that the provocative stimulus is not ignored. Our results do only speak to the case where the reference is provided next to a main task that draws most of the attentional resources.

CONCLUSION

This study adds to and qualifies the growing body of literature suggesting a beneficial effect of a visible horizon in the reduction of MS. We observed that the presence of a stationary earth-fixed horizon while performing a time-to-contact task in VR, significantly lowers VIMS, as measured by FMS-ratings. While the absolute difference in VIMS ratings between experimental groups was small, this effect could not be found for an earth-stationary fixation point, neither for a head-fixed horizontal line. Only the artificial horizontal line sufficed to provide sufficient rest-frame information. These results can be utilized when designing virtual environments.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

WH: manuscript and data analysis. BK and HH: manuscript. All authors contributed to the article and approved the submitted version.

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REVIEW
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Latency and Cybersickness: Impact, Causes, and Measures. A Review

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Latency is a key characteristic inherent to any computer system. Motion-to-Photon (MTP) latency describes the time between the movement of a tracked object and its corresponding movement rendered and depicted by computer-generated images on a graphical output screen. High MTP latency can cause a loss of performance in interactive graphics applications and, even worse, can provoke cybersickness in Virtual Reality (VR) applications. Here, cybersickness can degrade VR experiences or may render the experiences completely unusable. It can confound research findings of an otherwise sound experiment. Latency as a contributing factor to cybersickness needs to be properly understood. Its effects need to be analyzed, its sources need to be identified, good measurement methods need to be developed, and proper counter measures need to be developed in order to reduce potentially harmful impacts of latency on the usability and safety of VR systems. Research shows that latency can exhibit intricate timing patterns with various spiking and periodic behavior. These timing behaviors may vary, yet most are found to provoke cybersickness. Overall, latency can differ drastically between different systems interfering with generalization of measurement results. This review article describes the causes and effects of latency with regard to cybersickness. We report on different existing approaches to measure and report latency. Hence, the article provides readers with the knowledge to understand and report latency for their own applications, evaluations, and experiments. It should also help to measure, identify, and finally control and counteract latency and hence gain confidence into the soundness of empirical data collected by VR exposures. Low latency increases the usability and safety of VR systems.

Keywords: virtual reality, latency, cybersickness, jitter, simulator sickness

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1. INTRODUCTION

Cybersickness is a severe problem for the usage and safety of VR technology. It hinders both the broader adoption of VR technology and its overall usability. Cybersickness is closely related to simulator sickness and motion sickness. Early research describes cybersickness as a motion sickness in virtual environments (McCauley and Sharkey, 1992). Cybersickness is usually defined by a set of specific adverse symptoms in combination with the use of certain technologies, such as disorientation, apathy, fatigue, dizziness, headache, increased salivation, dry mouth, difficulty focusing, eye strain, vomiting, stomach awareness, pallor, sweating, and postural instability (LaViola, 2000; Stone Ill, 2017; McHugh, 2019). These symptoms are shared with related definitions of sickness, even though their severity might vary. Stanney et al. (1997) argues that cybersickness is connected to more symptoms in the disorientation cluster of the Simulator Sickness Questionnaire

(SSQ) (Kennedy et al., 1993) than simulator sickness. The disorientation cluster contains several symptoms which do not all carry the explicit meaning of disorientation. Gavgani et al. (2018) show that motion sickness and cybersickness show the same severity of symptoms in extreme cases. Bockelman and Lingum (2017) distinguish cybersickness from other definitions of sickness by its "cyber" source. We use the term cybersickness to describe sickness with the aforementioned symptoms induced by Virtual Reality or Augmented Reality applications that do not apply external forces on the user. External forces are motion platforms or other motor actuated methods that move a user without the user's own effort. These VR or AR applications provide stimuli predominately by visual perception.

Chang et al. (2020) review experiments that measure cybersickness. They describe the frequency of use for different subjective measurements. Out of 76 experiments, 58 ($\approx$ 76%) use the SSQ (Kennedy et al., 1993). Less often used questionnaires are the Fast Motion Sickness scale (FMS, 6 experiments $\approx$ 8%, Keshavarz and Hecht, 2011), a forced-choice question (5 experiments $\approx$ 6.5%, Chen et al., 2011), the Misery Scale (MISC, 4 experiments $\approx$ 5%, Bos et al., 2010), the Motion Sickness Assessment Questionnaire (MSAQ, 3 experiments $\approx$ 4%, Gianaros and Stern, 2010) and the Virtual Environment Performance Assessment Battery (VEPAB, 3 experiments $\approx$ 4%, Lampton et al., 1994). In contrast, Davis et al. (2014) state that the Pensacola Diagnostic Index (Graybiel et al., 1968) is the "most widely used measure in motion sickness studies"(Davis et al., 2014, p. 6). They state that another widely used questionnaire besides the SSQ is the Nausea Profile (Muth et al., 1996) and further list the Virtual Reality Symptom Questionnaire (Ames et al., 2005). Another questionnaire in use is the Motion Sickness Susceptibility Questionnaire (MSSQ) (Golding, 1998). Here again, it becomes apparent how close cybersickness is to simulator sickness and motion sickness, since questionnaires are often used for multiple sickness definitions. The listed questionnaires are in use for research on cybersickness, but care has to be taken to understand their different usage and purpose. Many, like the SSQ, report on the sickness experienced at the time of answering the questionnaire while others like the MSSQ ask for past experiences to gauge sickness susceptibility that can play into the experience. The Nausea Profile is a scale for measuring nausea due to any cause, not a motion sickness-specific scale, while the MSAQ of the same group targets motion sickness and describes subscales for further differentiating motion sickness aspects.

There are different explanations how cybersickness comes into being and there are multiple factors that influence cybersickness. Explanations for cybersickness often preceed the term cybersickness itself. They were created for motion sickness or simulator sickness and then adopted for cybersickness. Rebenitsch and Owen (2016) and LaViola (2000) list and discuss the following theories for cybersickness: the sensory mismatch theory (Reason and Brand, 1975; Oman, 1990), the poison theory (Treisman, 1977), the postural instability theory (Riccio and Stoffregen, 1991) and the rest frame theory (Virre, 1996). Oman (1990) describe their sensory mismatch theory as possibly underlying multiple different sickness definitions such as motion sickness and simulator sickness. Bles et al. (1998) adapt this statement to describe postural stability as underlying multiple different sickness definitions.

Factors that evoke cybersickness are "rendering modes, visual display systems and application design" (Rebenitsch and Owen, 2016, p. 102) as well as hardware-specific factors. Rebenitsch and Owen (2016) describe the former factors but leave hardware-specific factors such as latency open to be discussed in other publications. This review focuses on latency contributions to cybersickness. There are other hardware-specific factors such as tracking accuracy (Chang et al., 2016) that are not covered in this review. Latency describes the processing time incurred by the computer system used for the VR application. VR needs complex hard- and software to deliver the desired experience. Each part in the system contributes to the overall latency by itself and by the effects of its interaction with other parts.

Latency as an inherent property of computer system processing is easily introduced into complex architectures, and as such is subject to many evaluations. There are different angles toward research on latency in virtual environments that mutually influence each other. Effects of latency on cybersickness are found, which necessitate research into measurements and control of latency. Experiments that simulate latency are performed that gather more insight into its effects on cybersickness and user performance. And not least of all, latency in experiments performed in virtual environments needs to be reported in research articles. This review is thus organized as follows: First, we discuss experiments that show that latency contributes to cybersickness. Then, we describe ways to measure latency, which is essential for development of applications with consistent latency behavior. We then show how measured latency is reported in research articles to illustrate latency patterns in experiments.

2. EFFECTS

Table 1 shows an overview of different studies that show that latency contributes to cybersickness. The researchers conducted experiments with latency as the independent variable and cybersickness as the dependent variable. Latency is manipulated to create conditions of different motion to photon latency in the employed systems. For each condition, cybersickness is measured to compare sickness values between the conditions. Researchers measure cybersickness with subjective questionnaires or objective physiological measurements. The most often used questionnaire for the listed papers is the SSQ with six out of 11 papers (Meehan et al., 2003; Moss et al., 2011; St. Pierre et al., 2015; Kinsella et al., 2016; Stauffert et al., 2018; Caserman et al., 2019). Physiological measurements are postural stability or postural sway, heart rate, sweating and galvanic skin response. We list postural stability separate from the other physiological measurements to distinguish the different cases of usage. Frank et al. (1988) list postural stability separate from other physiological measurements. Kawamura and Kijima (2016) only observe postural stability. Postural instability often correlates with visually-induced motion sickness (Riccio and Stoffregen, 1991) and some studies have found it to be predictive of visually-induced motion sickness (Arcioni et al., 2019). Meehan et al. (2003) and Stauffert et al. (2018) only use heart rate and galvanic skin response. Their physiological measurements showed an effect of increased latency on heart rate. Gavgani et al. (2018) argue that forehead sweating is the best physiological indicator for motion sickness which shows the same symptoms as cybersickness in extreme cases. Their rollercoaster experiment only finds minor or moderate effects for heart rate and galvanic skin response. While heart rate may not be the best indicator of latency induced cybersickness, it supports the research that evaluates cybersickness with the SSQ.

Most research for latency and cybersickness tests only the effect of static latency added (Frank et al., 1988; DiZio and Lackner, 2000; Meehan et al., 2003; Moss et al., 2011; Kawamura and Kijima, 2016; Caserman et al., 2019; Palmisano et al., 2019; Kim et al., 2020). They introduce a fixed delay into the system and test different such latencies against each other. This is based on the assumption that most observed latencies are close to one mean latency, for which one fixed added latency per condition is an approximation. This simple latency model consistently shows an increase of latency in the VR simulation, leading to increased cybersickness or a more disturbed stand equilibrium.

Movement itself is important to experience latency induced cybersickness (DiZio and Lackner, 2000). Although, Moss et al. (2011) found no influence of latency in an experiment with a lot of head movement. They report that the head movement itself evoked sickness. It may be that sickness from other sources was stronger than the latency induced sickness thereby masking it. Without movement, the user might not feel the discrepancy between real world and virtual world widened by latency. An increase of head movement can increase cybersickness (Palmisano et al., 2019; Kim et al., 2020). Studies often involve a search task that requires head movement.

Taking into account that latency in measurements often shows irregular spikes, Stauffert et al. (2018) showed that not only uniform but occasional latency spikes provoke cybersickness. St. Pierre et al. (2015) and Kinsella et al. (2016) show that periodic latency like measured by Wu et al. (2013) contributes to cybersickness. They describe latency as consisting of a time-invariant and a periodic part. Periodic latency is described to follow a sine wave. St. Pierre et al. (2015) argues that the sine's amplitude has more influence than its frequency. Kinsella et al. (2016) observes the opposite.

3. MEASURING LATENCY

The contribution of latency to cybersickness necessitates controlling latency in every VR or AR application. High latency and especially latency spikes can often only be detected by measurements, which in turn provide researchers and other developers with indications if and where interventions are needed during the development process. Approaches to measure latency are numerous and distinguish themselves in the amount of instrumentation they need, and which kind of latency they measure. Most approaches measure motion to photon latency, which is the time between a movement of some tracked object, and the effect corresponding to this movement shown on a screen, conveyed by photons emitted from the screen. Different tracked objects can be used to signify movement in the measurement of motion to photon latency, such as Motion Controllers or Head-Mounted Displays (HMD). The employed screens may be computer monitors, mobile phone screens or AR/VR HMD screens. The motion to photon latency is also called end-to-end latency. **Table 2** shows an overview of approaches.

Measurements need to compare the time difference between the motion of a tracked object and a resulting response on a screen. The observed motion can be the onset of a motion (Feldstein and Ellis, 2020), special characteristics during a motion such as the peak of acceleration (Friston and Steed, 2014), the end of a motion (Chang et al., 2016) or arrival at a predetermined position (He et al., 2000) or a predetermined motion (Di Luca, 2010). A predetermined motion is usually a sinusoidal movement of a pendulum (Steed, 2008) or the circular movement of a turntable (Swindells et al., 2000). A motion can also be the passing of time in the form of timestamps (Sielhorst et al., 2007; Billeter et al., 2016; Gruen et al., 2020).

The screen shows either a copy of the motion (Roberts et al., 2009) or an encoded version of it (Becher et al., 2018). The system needs to track the tracked object, integrate it into its simulation and show a generated image on the screen (Mine, 1993; Feldstein and Ellis, 2020). The necessary processing time leads to the image on the screen always being delayed in contrast to the original, real motion. Additional steps such as Remote Graphics Rendering (Kämäräinen et al., 2017), or using additional computers to process tracking information, leads to increased latency (Roberts et al., 2009).

A straight forward approach uses a camera to observe both the real and the virtual motion and compare the delay between their chosen motion aspect. The analysis can be done by hand (Liang et al., 1991) or automated (Friston and Steed, 2014). Tracking cameras trade spatial resolution for temporal resolution. High spatial resolution is needed to better capture the real motion, but high temporal resolution is needed to determine a high precision latency value. A way around the dilemma is to fit the mathematical function of the known movement to the tracking data (Steed, 2008). This reduces uncertainty due to restricted resolution.

Camera based measurements do not work well with HMDs, because the lenses distort the image in a way that necessitates them to be very close to the lens. This way, they cannot record the real tracked object any longer. These approaches usually use a computer monitor as the observed screen. Some researchers remove the HMD lenses (Feldstein and Ellis, 2020) or use additional lenses that reverse the distortion (Becher et al., 2018).

An alternative is to observe the real motion separately from its virtual counterpart. The obvious extension is to

TABLE 1 | Research simulating latency that tested for a connection to cybersickness.

	System	Task	Measure	Latency shape	Conditions	Result	*n*
Frank et al., 1988	Driving simulator	Driving	Rod and frame, physio, postural stability	Uniform	Added 0, 170, 340 ms transport delay	Evokes sickness visual delay more important than motion delay	54 (27f 27m)
Stauffert et al., 2018	HMD Vive	Search	SSQ, physio	Jitter	Added no latency, Added latency jitter	Jitter provokes sickness	45 (36f 9m)
Kawamura and Kijima, 2016	HMD DK2	Keep balance	Pressure plate	Uniform	Absolute 1, 26, 39, 53, 66 ms	Latency disturbs human stand equilibrium	17
Caserman et al., 2019	HMD Vive Pro full bodytracking	Search	SSQ	Uniform	Absolute 0, 50, 54, 58, 63, 69, 75, 83, 92, 104, 121, 150 ms	More latency More cybersickness	21 (6f 15m)
Moss et al., 2011	HMD No HMD	Search	SSQ	Uniform	Added 0, 200 ms Added 0, 145, 300 ms	Latency unclear connection to Simulator sickness; exposure time and active head movements Evoke simulator sickness	22 (11f 11m) 29 (12f 17m)
Kinsella et al., 2016	HMD	Search	SSQ	Periodic	2 × 2 design: Added frequency 0.2/1 Hz Amplitude 100/20–100 ms	Latency frequency with Periodic latency scenario Increases sickness 0.2 Hz sickens more	120
St. Pierre et al., 2015	HMD	search	SSQ	Periodic	0, 100 ms, 100 ms 0.2 Hz added 20–100 ms 0.2 Hz	Amplitude increases sickness frequency potentially too Periodic worse than uniform	120 (64f 56m)
DiZio and Lackner, 2000	HMD	Search	Criteria of Graybiel et al., 1968	Uniform	Absolute 67, 159, 254, 355 ms 21, 39, 80, 163 ms	Lag leads to sickness, no sickness without head movement	21 8
Meehan et al., 2003	HMD	Explore Move	SSQ, Physio	Uniform	Absolute 50, 90 ms	More latency, Increased heart rate	164 (32f 132m)
Palmisano et al., 2019	HMD	Rotate head	FMS	Uniform	Absolute 5, 46, 87, 128, 169, 212 ms	More latency, Increased cybersickness	14
Kim et al., 2020	HMD	Rotate Head	FMS	Uniform	Absolute 5, 46, 87, 128, 169, 212 ms	More latency, Increased cybersickness	30

use two synchronized cameras (Kijima and Miyajima, 2016b). More often, the real motion is observed by a photodiode that gets covered (Mine, 1993) or a rotary encoder (Seo et al., 2017) that reports the orientation of the platform that the tracked object is placed on. The screen is monitored by one (Pape et al., 2020) or more photodiodes (Becher et al., 2018; Stauffert et al., 2020a). A photodiode has a high temporal resolution but can only measure one brightness value per measurement. The application to measure needs to display its tracking information in brightness levels to use photodiodes.

The chosen method determines how many latency values are measured. Sine fitting (Steed, 2008; Teather et al., 2009; Zhao et al., 2017) and cross correlation (Di Luca, 2010; Kijima and Miyajima, 2016b; Feng et al., 2019) only report one latency for one measurement run. If the latency between an event and its reaction on the screen is measured, the number of latency measurements that can be reported depends on the approach. Some methods need to provoke an event and then wait for the result, before it is possible to measure again (Liang et al., 1991; He et al., 2000; Swindells et al., 2000; Miller and Bishop, 2002; Roberts et al., 2009; Friston and Steed, 2014; Raaen and Kjellmo, 2015; Kämäräinen et al., 2017; Seo et al., 2017; Feldstein and Ellis, 2020; Pape et al., 2020). Some approaches allow to measure the latency for every frame shown on the screen (Sielhorst et al., 2007; Papadakis et al., 2011; Wu et al., 2013; Billeter et al., 2016; Kijima and Miyajima, 2016b; Becher et al., 2018; Gruen et al., 2020; Stauffert et al., 2020a). Some approaches that only measure the latency of an event are usable to measure continuously, while others are not. We distinguish methods in **Table 2** depending on the reported usage.

4. DESCRIPTION

Looking at the approaches to measure latency, we see that latency is reported in different ways. The reported values are often not comparable, as different papers use different systems

TABLE 2 | Comparison of latency measurement approaches.

Paper	Motion		Photon		Method
	Device	Capture	Device	Capture	
Becher et al., 2018	HMD	Rotary encoder	HMD	Photodiode	Continuous
Di Luca, 2010	Tracked object	Photodiode	Screen	Photodiode	Cross correlation
Billeter et al., 2016	LED timestamp	Camera	AR HMD	Same camera	Continuous
Feldstein and Ellis, 2020	HMD	Camera	HMD	Same camera	Event
Feng et al., 2019	HMD	Camera	HMD	Same camera	Cross correlation
Friston and Steed, 2014	Mouse	Camera	Monitor	Same camera	Event
Gruen et al., 2020	Sub millisecond clock	Camera	HMD	Synced camera	Continuous
He et al., 2000	Wand	Camera	Monitor	Same camera	Event
Kämäräinen et al., 2017	Touch	Switch	Mobile phone	Photodiode	Event
Kijima and Miyajima, 2016a	HMD	Camera	HMD	Synced camera	Cross correlation
Kijima and Miyajima, 2016b	HMD	Camera	HMD	Synced camera	Continuous
Liang et al., 1991	Pendulum	Camera	LED display	Same camera	Event
Miller and Bishop, 2002	HMD	CCD array	Monitor	CCD array	Event
Mine, 1993	Pendulum	Photodiode	Monitor	Photodiode	Event
Papadakis et al., 2011	Tracked object	Rotary encoder	Monitor	Photodiode	Continuous
Pape et al., 2020	Rigid body	Switch	Projection	Photodiode	Event
Raaen and Kjellmo, 2015	HMD	Photodiode	HMD	Photodiode	Event
Roberts et al., 2009	Hand	Camera	Monitor	Synced camera	Event
Seo et al., 2017	HMD	Rotary encoder	HMD	Photodiode	Event
Sielhorst et al., 2007	Timestamps	Camera	AR HMD	Same camera	Continuous
Stauffert et al., 2020a	Tracked object	Motor driver	HMD	Photodiode	Continuous
Steed, 2008	Pendulum	Camera	Monitor	Same camera	Sine fitting
Swindells et al., 2000	Turntable	Camera	Half silvered mirror	Same camera	Event
Teather et al., 2009	Tracked object	Camera	Monitor	Same camera	Sine Fitting
Wu et al., 2013	Manually Moved Bar	Camera	Monitor	Same camera	Continuous
Zhao et al., 2017	HMD	Potentiometer	HMD	Photodiode	Sine fitting

Camera based measurement has a camera that observes both the real tracked object and its virtual counterpart. Photodiode based measurements read the encoded information off a screen with a photodiode. The observation of the real object is done with a different sensor. Motion to Photon latency measurements use different devices where the motion originates from and which kind of screen emits the photon. The methods column describe how often it is possible to measure latency.

with varying complexity. A less complex system is expected to show lower and more deterministic latency than a more complex system. Newer hardware often has lower latency with reduced determinism (McKenney, 2008). Some papers report multiple measurements of different systems. **Table 3** lists only a subset of the numbers reported in the respective research papers. Interested readers are referred to the original publications.

An observation is that latency is not a constant value. Latency is different with different devices (Mine, 1993), different software configurations (Friston and Steed, 2014) or different input methods (Kämäräinen et al., 2017). Different usage patterns such as a change of the movement direction can influence latency (He et al., 2000). Even small changes in the measurement setup can make a difference. Latency measured in the upper part of a screen can be lower than latency measured in the lower part, due to the scan out sequence (Papadakis et al., 2011). The problem with latency measurements is that they are often performed "under optimized and artificial conditions that may not represent latency conditions in realistic application-oriented scenarios" (Feldstein and Ellis, 2020).

The variability is usually reported by a mean value at least. Standard deviation and minimum/maximum values provide more insight. Histograms can be used to show even more information about what latencies are to be expected. We want to focus on these visualization methods here as a basis to understand the connection between latency and cybersickness. The different ways to describe cybersickness are used in the different simulated latencies of the cybersickness experiments of **Table 1**.

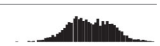
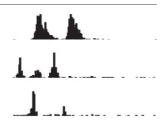
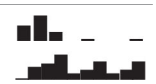
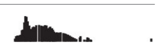
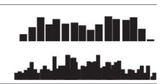
The sparklines in **Table 3** give an impression of the shape of latency. The data is stretched to take the maximum amount in x and y direction and only shows the x axis segment that contains data. Sparklines are supposed to only give a general idea of the shape (Tufte, 2001). Stauffert et al. (2016) and Stauffert et al. (2020a) use a logarithmic y axis. The other papers use a linear y axis. Every sparkline has the measured latency in x direction and its probability in y direction. We exclude Stauffert et al. (2020a) systems where there is artificial latency introduced, but include systems that have artificially high system load but mimic real world scenarios.

A key difference between representations given in publications is if they include rare outliers. Some researchers show no outliers (Wu et al., 2013; Pape et al., 2020) while others do (Sielhorst et al., 2007; Stauffert et al., 2016, 2020a). Latencies usually cluster around one or multiple values. Wu et al. (2013) system 2 and Stauffert et al. (2020a) system 1 show one cluster. Pape et al. (2020) and Sielhorst et al. (2007) system 1 and 3, Wu et al. (2013) system 1 and Stauffert et al. (2016) show two clusters. Sielhorst et al. (2007) system 2 shows 3 clusters and Stauffert et al. (2020a) system 2 shows 9 clusters, each indicated by higher probabilities surrounded by lower probabilities in the histogram.

Each cluster's distribution appears to follow a normal distribution though Sielhorst et al. (2007) system 1, Stauffert et al. (2016) and Stauffert et al. (2020a) system 2 show a more skewed distribution with a longer tail toward larger latencies, resembling more a gamma distribution. Pape et al. (2020) proposes to describe the distribution with a gaussian mixture model, i.e., an imposition of multiple normal distributions. Stauffert et al. (2018) argue to use an empirical distribution derived from the measurements. Multiple clusters presumably originate from the interplay of two or more parts running in decoupled loops in the observed system. Feldstein and Ellis (2020) list processing stages such as simulation or rendering that contribute to the final latency pattern with their runtime and communication behavior. Antoine et al. (2020) show how latency jitter emerges when input device and display sampling frequency differ.

Besides the general distribution, there may be temporal patterns. Stauffert et al. (2020a) found reoccurring latency spikes with a uniform interarrival time. Wu et al. (2013) found a sinusoidal latency pattern.

TABLE 3 | Table summarizing how latency is reported in papers that propose latency measurement approaches.

	Mean	SD	Min/Max	Histogram
Becher et al., 2018	5.1	2.7	1/10	
Billeter et al., 2016	9.8	2.1		
Di Luca, 2010	43.5	5.1		
Feldstein and Ellis, 2020	84	6.3	72/94	
Feng et al., 2019	2.3			
Friston and Steed, 2014	24		18/32	
Gruen et al., 2020	54	1.9		
He et al., 2000	58.5			
Kämäräinen et al., 2017	74.3	14.7		
Kijima and Miyajima, 2016b	16.86			
Kijima and Miyajima, 2016a	19.64			
Liang et al., 1991	85			
Miller and Bishop, 2002	100			
Mine, 1993	80.95			
Papadakis et al., 2011	50	5		
Pape et al., 2020	124.62			
Raaen and Kjellmo, 2015	4		2/5	
Roberts et al., 2009	414			
Seo et al., 2017	46.48	1.09		
Sielhorst et al., 2007				
Stauffert et al., 2020a	64.14	1.6		
Stauffert et al., 2016				
Steed, 2008	64			
Swindells et al., 2000	49			
Teather et al., 2009	73	4		
Wu et al., 2013	27.2			
Zhao et al., 2017	7.2	0.5		

All values are in milliseconds. The values are not comparable and are only for illustration because different systems or parts of systems are measured. Histograms are described with sparklines. The sparklines show only the general shape of the distribution. They are scaled to show the data range of reported values and their frequency. Some papers measure for up to three systems.

5. DISCUSSION

We have shown how latency is measured. The necessary instrumentation varies from simple observations of the VR equipment (Steed, 2008), to the need of specific software to run (Friston and Steed, 2014), to required modifications of the hardware (Stauffert et al., 2020a). The motion may be evoked manually (Wu et al., 2013) or with a pendulum (Mine, 1993) or a turntable (Chang et al., 2016). Latency is observed from one distant observer with one camera (He et al., 2000), multiple distant observers with synchronized cameras (Gruen et al., 2020) or close observers that are attached to the moved device and the screen (Di Luca, 2010).

Most researchers that measure latency report a mean latency value with an optional standard deviation. Some report a minimum and maximum value in addition. More insight is provided by histograms and plots showing the temporal behavior (Wu et al., 2013). There is research into whether latency influences cybersickness. Most compare the effect of one latency condition with another condition that has a time invariant increased latency (Frank et al., 1988; DiZio and Lackner, 2000; Meehan et al., 2003; Moss et al., 2011; Kawamura and Kijima, 2016; Caserman et al., 2019; Palmisano et al., 2019; Kim et al., 2020). This is based on the most often reported mean latency. Latency jitter as described in latency histograms and periodic latency patterns are shown to also contribute to cybersickness (Stauffert et al., 2018). All approaches to report latency find a counterpart where latency is simulated and shown to influence cybersickness.

There is more research into latency for VR systems than for AR systems, mainly because the technology is often times easier to handle. Many AR systems are simulated with VR systems until AR technology makes the simulated features possible. While less researched, AR systems show similar problems (Sielhorst et al., 2007).

5.1. Limitations on Latency Comparability

There are many factors that can influence latency and the predictability. Kijima and Miyajima (2016a) show that HMD prediction and timewarp (van Waveren, 2016) make a difference. Asynchronous timewarp uses a shortcut to update the displayed image after it was rendered, which yields different values when measured to a system that looks at motion controller movement that is only updated in the simulation of the virtual world. A sequential scan-out process leads to the eyes getting the information at different points in time so it can make a difference which screen is taken for measurement (Papadakis et al., 2011). He et al. (2000) found different latency depending on the movement direction of the tracked object. Manufacturers optimize latency with prediction that may fail (Gach, 2019).

Latency reporting depends on the observed system. The values in **Table 3** are not comparable to one another because some do not measure certain stages of computation or use other hardware. Even though the values are not comparable, they are often reported in a similar fashion with one mean value and a standard deviation.

Spatial jitter can be similar to latency jitter by offsetting tracking positions in an unexpected way. Some measurement methods can not distinguish between latency jitter and spatial jitter by their design. 2D pointing performance suffers with spatial jitter (Teather et al., 2009). Spatial jitter is likely to evoke cybersickness as well and may partially be described in the latency jitter studies already. Some measurement methods measuring related phenomena further complicates the comparison.

5.2. Latency Variability

VR and AR applications require substantial computational power to create virtual environments. Computer systems to provide the experience are optimized for performance rather than real-time, i.e., guaranteed response times (McKenney, 2008). Some applications such as robotics and space exploration require such deterministic runtime behavior of software. Modern operating systems do not provide real-time capabilities and even the Linux PREEMPT_RT patches cannot provide reliable real-time runtimes (Mayer, 2020). Without a real-time operating system, there may be unforseeable latency spikes that can harm VR experiences, even if latency was previously acceptable.

Researchers agree that “the delays vary substantially” (Kämäräinen et al., 2017) and often try to “illustrate the variations in latency of real systems” (Friston and Steed, 2014) by reporting more than one mean latency value. As a caveat, the “latency testing on isolated virtual reality systems under optimized and artificial conditions may not represent latency conditions in realistic application-oriented scenarios” (Feldstein and Ellis, 2020). Care must be taken to measure as close to the use case as possible to best represent the expected latencies. The best case would be to measure during exposure.

Rare latency outliers show latencies much larger than the average (Stauffert et al., 2020a). Networked applications often only look at the 95th, 99th, and 99.9th percentile (Vulimiri et al., 2013) to estimate response times. Teather et al. (2009) use the 95th percentile to describe their motion-to-photon latency measurements. Stauffert et al. (2018) provide a first study with latency spiking behavior including the top one percent but more research is needed to understand if regarding only the 95th or 99th percentile is sufficient. Some web applications found the need to include the remaining one percent of latencies in their analyses (Hsu, 2015).

Latency jitter can be reduced with prediction (Jung et al., 2000). Incorporating latency jitter in the prediction model increases the prediction performance (Tumanov et al., 2007). Prediction, however, introduces its own side effects such as over anticipation (Nancel et al., 2016).

5.3. Desirable Latency Values

How much latency is tolerable for a good VR experience? Carmack (2013) says that it should be below 50 ms to feel responsive and recommends less than 20 ms. Attig et al. (2017) look at HCI experiments without VR that report no impact on usability when latency is below 100 ms. Humans can detect visual variations at 500 Hz (Davis et al., 2015) and latency below 17 ms (Ellis et al., 1999, 2004; Adelstein et al., 2003). Although, Feldstein and Ellis (2020) indicate that perceivable latency does not necessarily cause cybersickness. Jerald (2010) measures a minimum latency threshold of 3.2 ms in one of the participants, but adds that the exact perceivable latency may depend on the virtual environment.

5.4. Need to Measure Latency

Measuring latency helps to become aware of bottlenecks in employed hard- and software (Swindells et al., 2000; Di Luca, 2010). Without measuring, those problems may never be detected and may influence an otherwise sound experiment. Many researchers, however, do not report latency. The 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) saw 104 published papers. 85 papers conducted a user study in virtual reality. Only 6 reported the latency of the employed VR system. Although a reported mean latency strengthens trust that the systems performed as expected, latency jitter may still have occurred during experiments and may have impaired individual measurements.

Which approach to use depends on the application and possibilities of the researchers. A detailed analysis helps to judge the application's performance but everything is better than not measuring at all. Every researcher should be able to do manual frame counting (He et al., 2000) as shown in Feldstein and Ellis (2020) that compare the results of different evaluators. Sine fitting (Steed, 2008) reduces imprecisions in the video analysis. Even though it is more involved than manual frame counting, software can help with the analysis (Stauffert et al., 2020b). Beyond these basic approaches, the choice of how to measure latency depends on the specific hard- and software used. Design your measurement system to fit your VR system guided by the approaches in **Table 2**. Research should strive toward measuring latency for every frame shown on the employed screen to assure validity of observations and to maximize insight. Measuring latency can hint at problems, latency values then have to be interpreted to find an intervention if need be.

6. CONCLUSION

Latency is one of the characteristics of a computer system that is often discussed to have a major impact on the system's usability. Research shows that larger latencies and latency jitter can influence well-being in a negative way in the form of cybersickness. Yet little research of VR experiences check and report the latency behavior of their employed computer system. Only 7% of the papers published at the 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) conducting user studies in virtual reality reported their motion to photon latency. Latency may introduce unwanted effects that are not obvious to the researchers and reviewers if a latency value is not reported.

Latency is not restricted to one value but changes over time and with the VR system usage pattern. More elaborated test setups are required to capture these dynamics. Research is only beginning to understand the implications of time-invariant latency. Even the occasional latency spike will contribute to cybersickness. Measuring latency is of importance to understand better the influence on cybersickness and to understand where latency might not be the main cause for cybersickness.

AUTHOR CONTRIBUTIONS

J-PS conducted the literature review and took the lead in writing the manuscript, he collectively discussed, and developed concepts to measure and report latency. FN worked on the manuscript and supervised the project. ML conceived the original idea, collectively discussed and developed concepts of own research on latency, and supervised the project. All authors provided critical feedback and helped shape the research, analysis, and manuscript.

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The Psychometrics of Cybersickness in Augmented Reality

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Augmented reality (AR) is rapidly being adopted by industry leaders and militaries around the globe. With the Defense Health Agency pushing AR as a solution to the distributed learning problem, along with AR applications being explored within primary care and operational medical settings, it is crucial for these immersive platforms to have a standardized, scientifically based paradigm on which they are designed and used. One area of particular concern is the potential for physiological maladaptation following prolonged AR exposure, which is expected to vary from that associated with virtual reality exposure. Such maladaptation is potentially driven by limitations that exist with regard to the types and extent of perceptual issues characteristic of AR head-worn displays (e.g., mismatches between visually displayed information and other senses, restricted field of view, mismatched interpupillary distance). Associated perceptual limitations can reduce training effectiveness or impose patient and/or trainee safety concerns. Thus, while AR technology has the potential to advance simulation training, there is a need to approach AR-based research—particularly that which relates to long-exposure-duration scenarios—from a bottom-up perspective, where its physiological impact is more fully understood. In the hopes of assisting this process, this study presents a comparison of cybersickness between two common forms of AR displays. Specifically, by comparing the Microsoft HoloLens, a head-worn display that has seen rapid adoption by the scientific community, with an AR Tablet–based platform within the context of long-duration AR training exposure, it will be possible to determine what differences, if any, exist between the two display platforms in terms of their physiological impact as measured via cybersickness severity and symptom profile. Results from this psychometric assessment will be used to evaluate the physiological impact of AR exposure and develop usage protocols to ensure AR is safe and effective to use for military medical training.

Keywords: augmented reality, cybersickness, virtual reality, HoloLens, AR tablet

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INTRODUCTION

Over the last several years, there have been vast improvements in virtual reality (VR) and augmented reality (AR) technology, and yet, many people still report experiencing cybersickness symptoms from their use (Rebenitsch and Owen, 2016; Gavgani et al., 2017; Duzmanska et al., 2018; AR: Vovk et al., 2018; Guna et al., 2019; VR: Saredakis et al., 2020). Cybersickness is defined as the cluster of symptoms that a user experiences during or after exposure to an immersive environment (McCauley and Sharkey, 1992). It is characterized as a physiological response to an unusual sensory stimulus, similar to motion sickness (Bouchard et al., 2007). The reported incidence and degree of intensity vary based on exposure duration and nature of virtual content and display technology; more than half of participants are expected to experience at least some degree of discomfort upon initial exposure (Lawson, 2014; Garcia-Agundez et al., 2019), although most users adapt to the environment after a few uses (Stanney et al., 2020b).

Currently the standard method for self-reporting cybersickness symptoms is the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). This questionnaire assesses symptoms on a scale of 0 (none) to 3 (severe) and then subdivides the symptoms into three symptomatic subcategories: nausea (N), oculomotor (O), and disorientation (D). The scores for nausea relate to gastrointestinal distress (i.e., nausea, stomach awareness, salivation, and burping); scores for oculomotor relate to visual distress (i.e., eyestrain, difficulty focusing, blurred vision, and headache); and scores for disorientation relate to vestibular distress (i.e., dizziness and vertigo; Kennedy et al., 2001). These three subcategories have been used to build symptom profiles (N vs. O vs. D) associated with specific VR systems, as well as to characterize the psychometrics of cybersickness associated with VR exposure (Kennedy and Stanney, 1996; Stanney and Kennedy, 1997; Hale and Stanney, 2006; Garcia-Agundez et al., 2019; Stanney et al., 2020a).

While the typical symptom profile of D > N > O for VR has been well-characterized by previous research (Kennedy and Stanney, 1996; Stanney and Kennedy, 1997; Hale and Stanney, 2006; Garcia-Agundez et al., 2019; Stanney et al., 2020a), the same cannot be said for the adverse physiological effects of AR systems. AR devices have their own set of design challenges and potential physiological maladaptation that may differ from those associated with VR systems and even within AR systems the symptoms may not be the same across devices; thus, the psychometrics of cybersickness in AR need to be fully characterized. The limited evidence available suggests that AR systems pose the greatest burden on the oculomotor system, specifically visual discomfort/fatigue, difficulty focusing, and headaches (Vovk et al., 2018). While studies are few, the most common symptom profile found for AR exposure is greater oculomotor disturbances (O), and at times high disorientation (D), with little nausea (N). Thus, O > D > N is the expected adverse symptom profile for AR exposure; however, further study is needed to validate that this is indeed the typical AR symptom profile. As this differs from the typical symptom profile of VR, the physiological impact of AR is expected to be distinguishable from VR systems. It is important, however, to emphasize that cybersickness is an individual problem. Each person has his/her own genetic predisposition, health history, and physical and mental attributes that influence the physiological impact of extended AR exposure. Thus, it will be important to ultimately determine an individual's AR risk estimate, not a generalized "one size fits all" recommendation and define personalized mitigation strategies.

Physiological disturbances are expected to be compounded when an AR headset is donned for extended periods of time, as the severity of physiological maladaptation associated with VR exposure has been demonstrated to be proportional to exposure duration (Kennedy et al., 2000). Unlike VR exposure, which is oftentimes self-limiting (i.e., dropouts; Stanney et al., 1999) due to high levels of nausea and malaise, the potentially high level of oculomotor disturbance associated with AR is not expected to lead to self-cessation of exposure, as it will likely manifest as headache and eyestrain, with which people who regularly use screen-based technology are accustomed. Thus, because users will likely not self-limit exposure with AR, exposure duration could be prolonged. If AR technology poses any substantial maladaptation [e.g., prolonged adverse physiological aftereffects (AEs) such as altered visual functioning, degraded hand–eye coordination, postural instability], this could present safety risks post-exposure. It is thus of critical importance to assess the physiological impact of AR exposure and its implications to training effectiveness, patient/trainee safety, and operational advantages on the battlefield.

TECHNOLOGY CONCERNS

When studying physiological maladaptation possible within AR, one of the most important aspects is the technology being used for consumption. Each AR device, and even each development platform, comes with its own technology challenges that may contribute to potential for maladaptation. In general, such maladaptation is caused by some degree of mismatch between the information displayed visually within the AR display and a user's other senses, which may be driven by low frame rate, mismatches in interpupillary distance (IPD), lag time between a user's movement and spatial mapping of displayed information, among other factors (Fang et al., 2017). Two particularly difficult technology challenges in AR displays are vergence–accommodation conflicts and restricted field of view (FOV). Differences between a trainee's natural depth perception and the depth planes simulated by AR may pose a particularly difficult challenge for users. Depending on the development platform used for AR generation, trainees may be forced into viewing content at specific focal distances, which may or may not match what is natively supported by the AR device, particularly those that are head-worn displays (HWDs), like the MS HoloLens. This mismatch in visual depth planes may result in a trainee perceiving depth beyond those planes that are artificially calculated and rendered (Padmanaban et al., 2017). It is likely that this process will result in physiological symptoms in the form of eyestrain, particularly related to a trainee's natural saccadic eye movement and eye movements that occur at forced visual depth planes in an AR HWD (Fidopiastis et al., 2010). Further, when a trainee is forced to focus on depth planes optimized by the display, vergence–accommodation conflict is likely to occur. As presented depth planes approach optical infinity—which begins at approximately 6 m and is indicated by light rays being viewed as parallel by the eyes—it becomes exponentially more difficult for HWDs to replicate shifts in focus that accompany natural vision (Padmanaban et al., 2017). Such maladaptation may not be as problematic in AR-capable tablet displays.

FOV has a significant impact on the optics of HWDs (Weech et al., 2019). Humans have an FOV of ∼200 degrees horizontal and ∼140 degrees vertical (Mazuryk and Gervautz, 1999). Considering that human–computer interaction principles recommend a 1:1 (Buie, 1999) system of interaction as ideal, any system that constrains FOV <200 × 140 degrees will undoubtedly result in some degree of perceptual issues (Lin et al., 2002). In VR, a low FOV has been found to correlate to cybersickness (Duzmanska et al., 2018; Weech et al., 2019). While most AR HWDs have low FOV, it is unclear if the physiological impact of low FOV is as direct in AR, particularly because in AR users always have view of the real world. Specifically, as AR provides continuous viewing of real-world rest frames (e.g., walls, furniture, etc.), this may help to disambiguate virtual motion cues presented in AR HWD with vestibular cues from real-world motion or lack thereof, which should minimize cybersickness and associated adverse AEs (Chang et al., 2003). Thus, even though the HoloLens, with an FOV of 34 degrees, is significantly smaller than even the smallest VR HWD, the instantiation of virtual elements overlaid onto reality instead of directly replacing them may have a reduced maladaptive impact on users (Drascic and Milgram, 1996). Unfortunately, a wide FOV may also cause higher cybersickness levels if the FOV is paired with display stutter or similar issues (Lin et al., 2002). Thus, even as the FOV of AR displays is enlarged (Ochanji, 2020), cybersickness may persist.

There is tremendous potential to increase training efficiency with the use of AR by providing a contextually rich, embodied immersive learning environment, which allows trainees to get up to proficiency at an accelerated rate (Stanney et al., 2013; Garzón and Acevedo, 2019; Claypoole et al., 2020). However, if limitations exist regarding the type and extent of physiological maladaptation one may experience in AR-based training solutions, training effectiveness may be impeded (Lee, 2012; Fang et al., 2017) and, depending on the training task, pose safety risks should the training experience negatively impact real-world performance post-exposure (Wann et al., 2014).

TACTICAL COMBAT CASUALTY CARE USE CASE

In the process of updating the training curriculum for Tactical Combat Casualty Care (TCCC), the Defense Health Agency has been considering AR as a potential solution to distributed learning. TCCC is the curriculum by which the U.S. Army, Navy Corpsmen, Special Forces, Marines, and Air Force train their Combat Lifesavers (CLS). This program focuses on potentially survivable injuries that occur most often on the battlefield: the leading causes of preventable deaths being massive hemorrhage and tension pneumothorax [Bellamy, 1984; Champion et al., 2003; Butler, 2017 as cited in Kotwal et al. (2011)]. CLS provide battlefield care for these injuries while executing their unit's mission and working to prevent further injury (National Association of Emergency Medical Technicians [NAEMT]., 2018). Effective CLS training, which transfers knowledge directly and accurately to the field, is essential to decreasing preventable combat casualty deaths.

Training Efficacy

The potential for optimal learning training efficacy for skills such as TCCC is one of the main drivers for Department of Defense (DoD) interest in adopting AR training solutions. Currently, the standard CLS class runs over a 4-day period at most Medical Simulation and Training Centers and is required for all service members once per year. If an AR solution could increase skill retention or learning efficiency, such that the time-to-train or number of competency recertifications could be reduced, that solution would be ideal. However, if that same AR solution is causing trainees to experience cybersickness because correct design guidelines and usage protocols are not understood and in place, AR could potentially reduce training efficacy and decrease the unit's ability to complete other required training due to adverse AEs.

One of the primary skills that all military medical providers are expected to learn is the application of a tourniquet to a casualty's limb to treat massive hemorrhage. Tourniquets, such as the Combat Application Tourniquet favored by the military forces, are designed to stop external bleeding from a limb injury and to stabilize casualties until they can be transported to a more advanced treatment facility. Training of this skill within current AR display hardware, specifically the MS HoloLens and its presentation of depth planes, could potentially cause physiological AEs in terms of displaced hand–eye coordination that could lead to a differential of potentially several centimeters (cm) between the holographic tourniquet and real-world counterpart if the trainee were to perform the task in the real world immediately after exiting AR training. Depending on the location of the injury, this might result in the CLS provider incorrectly applying the tourniquet (i.e., negative transfer of training). In this situation, anatomic accuracy could well be the difference between life and death, as placing the tourniquet over a joint would fail to stop bleeding, likely resulting in death of a soldier.

Safety Concerns

Another consideration is the potential for safety risks that might arise from using AR to train TCCC medical tasks. One potential risk arises from the use of AR overlays with medical manikins. Even with recent advancements in the field, anchoring AR content to real-world objects is still challenging. A marker-based approach is generally most effective, but it requires a special marker to be aligned with the AR display device FOV at all times. Within the TCCC context, this issue could translate to one of negative training and, in turn, safety. Consider needle decompression of the chest, a treatment for tension pneumothorax. This medical intervention requires a provider to insert a needle into one of the casualty's intercostal spaces, which is ∼19.7 mm wide (Kim et al., 2014). If a three-dimensional model of a ribcage were shown to a CLS trainee as an AR overlay, and that overlay was not correctly superimposed and aligned to the medical manikin, maladaptation in hand–eye coordination could occur. The result of such negative

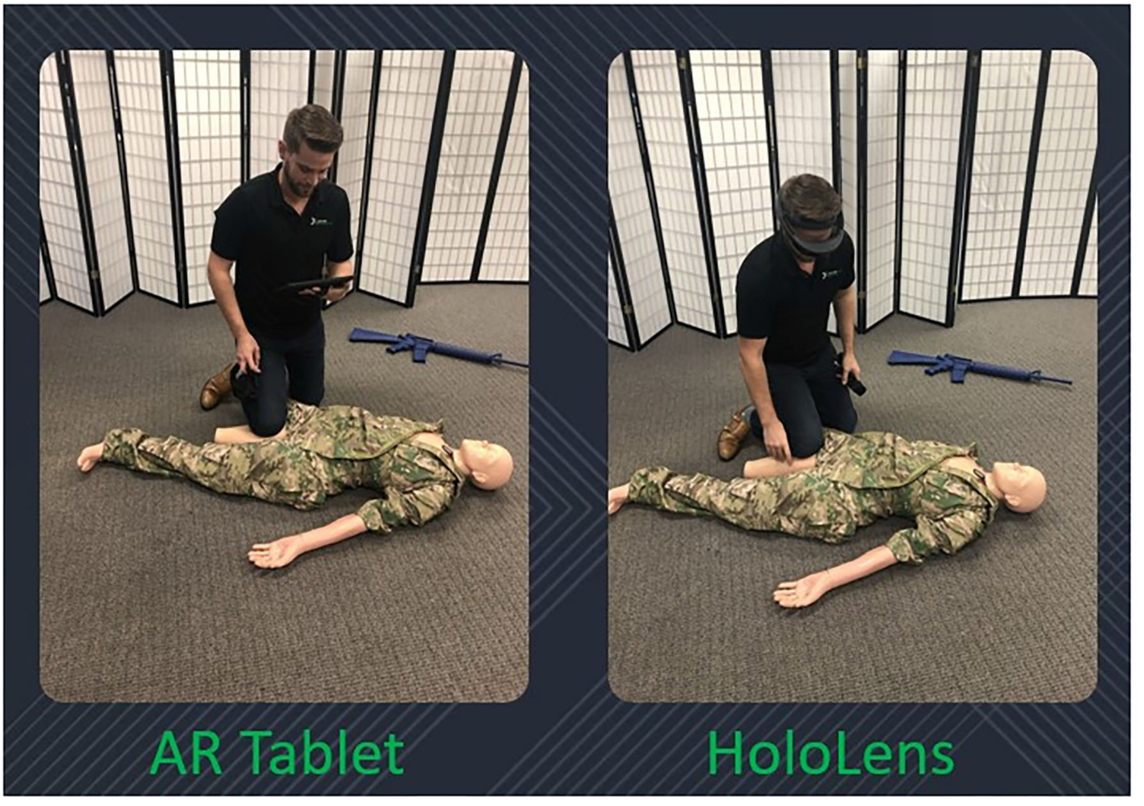

FIGURE 1 | Display type, HoloLens vs. AR Tablet.

training might be that CLS providers who have learned to place the needle in an improper location may experience a shift in their kinesthetic position sense (Wann et al., 2014) and may perform this intervention incorrectly in the field, potentially worsening their casualty's prospect for recovery. It is vital that when considering AR for use in training, particularly medical training, such physiological impacts on trainees be well-characterized. A study was thus conducted to characterize the psychometrics of cybersickness associated with AR exposure.

METHODS

The purpose of this study was to determine differences in cybersickness between AR HWD vs. AR Tablet training during two different exposure protocols. It was anticipated that cybersickness levels, as measured by the SSQ, would be higher in immersive HWD AR as compared to tablet-based AR and would lead to an O > D > N symptom profile in immersive AR and very low-level symptoms within the AR Tablet.

Participants

Adults aged 19–55 years (mean = 25.88, SD = 7.80), of both sexes (11 females, 23 males) participated in this study. The age and sex spread were as follows: 23 participants ≤25 years of age (7 females, 16 males); 9 participants 26–40 years of age (4 females, 5 males), and 2 participants 41–55 years of age (0 females, 2 males). This research complied with the American Psychological Association Code of Ethics and was approved by Copernicus Institutional Review Board and the Human Research Protection Office at U.S. Army Medical Research and Development Command. Informed consent was obtained from each participant, and all participants were compensated for their time in the experiment.

Equipment

The following devices were used in this study: Microsoft HoloLens 1, Samsung S5e AR-capable tablet, and a Rescue Randy medical manikin (**Figure 1**).

- The HoloLens 1 has 2.3-megapixel widescreen see-through holographic lenses (waveguides), a resolution of 1,280 × 720 per eye, a holographic density >2.5 K radiants, an FOV of 34 degrees with a single depth plane, and weight of 579 g (1.28 lb).
- The Samsung AR Tablet has a 10.5″ WQXGA Super AMOLED display, a resolution of 2,560 × 1,600, and weight of 400 g (0.88 lb).
- A male Rescue Randy was used, which is a life-like 5′5″ medical manikin with articulated joints weighing 55 lb with weight distribution according to human weight distribution chart.

Display Content

Unity game engine was used to develop immersive display content, which was focused on TCCC training. Specifically, two scenarios were developed: one focused on massive hemorrhage, and the other focused on respiration. Each scenario had timed subtasks; if a participant took the full time to complete each subtask, then the overall scenario would take 20 min to complete. However, participants could complete subtasks before the timer ran out.

- The massive hemorrhage scenario required participants to perform a tourniquet application on the manikin. During this scenario, virtual massive hemorrhage–related overlays were projected onto the physical manikin in the form of a traumatic amputation of the right leg with pulsating bleeding and pooling blood below the amputated limb.
- The respiration scenario required participants to perform a chest seal application on the manikin followed by a needle decompression of the chest after development of tension pneumothorax. During this scenario, virtual respiration related overlays were projected onto the physical manikin in the form of a left lateral open chest wound, which over time progressed to tension pneumothorax.
- Both scenarios contained training on the completion of a DD1380 Field Medical Card and the procedure for calling in a medical evacuation.

The AR display platforms allowed for physical embodiment (e.g., participants had to physically apply a tourniquet, insert a needle during chest decompression, etc.) and contextualization (e.g., scenarios placed participants in the context of the battlefield). Such physical embodiment engenders copious head and body movements, which have oftentimes been associated with motion sickness (Walker et al., 2010), whereas contextualization can add stress to training scenarios (Cohen et al., 2015).

Unity game engine was used to ensure the development of the content was as similar as possible across both AR platforms with respect to interactions and identical with respect to content. Individual differences in viewability were accounted for in the design of the TCCC experience through personalized settings, such as IPD device sizing or adjustment where necessary. A cue fidelity analysis conducted early in the effort was used to determine the optimal placement of holographic content within the real-world space. Even though Unity interacts poorly at times with FOV parameters for differing AR display types, the cue fidelity analysis allowed for control to be maintained with respect to optimal viewing of training content across the devices.

Procedure

The experiment involved five phases—prescreening, screening, pretesting, immersive exposure, and posttesting. In the prescreening phase, potential participants were referred to a weblink to take a screening survey. Any participants reporting any exclusion criteria (neurological impairments; musculoskeletal problems of the knee, ankle, shoulder, and/or elbow; loss in depth perception; <20/20 corrected visual acuity; inner-ear anomalies; or history of seizures) were informed they did not qualify for participation. Participants who met prescreening eligibility went on to on-site screening, which involved informed consent and additional screening, including assessment of fitness, visual and stereo acuity, illness, alcohol, and medication consumption; participants who did not meet the criteria were excluded from the study. Participants who met screening eligibility proceeded to pretesting to complete a demographics questionnaire, have their IPD measured via a digital pupilometer, have their weight and height measured to assess body mass index, and complete surveys to assess individual demographics. During the immersive exposure phase, participants were randomized to a control (i.e., AR Tablet) or experimental group (i.e., HoloLens). Participants' IPDs in the HoloLens group were entered into the headset software and adjusted appropriately. No participants had an IPD smaller or larger than the HoloLens range (50–80 mm). Next, marker detection was used to align virtual augmented content to the physical manikin. Once aligned, participants were exposed to the TCCC display content according to their assigned exposure protocol [three 40- (3–40 min) or six 20-min sessions (6–20 min)]. Participants commenced with their assigned starting scenario (either massive hemorrhage or respiration, counterbalanced across participants) and then alternated between the two scenarios throughout the 2-h exposure period. During the posttesting phase, SSQ total score was assessed immediately following immersive exposure (AE 0 min), and in 15-min increments for a total of 60 min (AE 15 min–AE 60 min) post-exposure, for a total of five AE measurement time periods. Participants were then debriefed, thanked, and paid for participation.

Experimental Design

The experiment was a mixed design, with 2 (exposure protocol) × 2 (display type) between factors and a 5 (AE time period) within factor. The display types between factor conditions were HoloLens headset and AR Tablet. The exposure protocol between factor conditions were 3–40 min sessions or 6–20 min sessions, both with 30-min breaks between sessions. Total AR exposure duration for each exposure protocol condition was thus 2 h. Participants were randomized to a display type (HoloLens $n = 19$ or AR Tablet $n = 15$) and an exposure protocol (3–40 min sessions $n = 13$ or 6–20 min sessions $n = 21$). The AE time period within factor included five post-exposure SSQ measurements, which were conducted at 0, 15, 30, 45, and 60 min post-exposure.

Dependent Measure

The dependent measure was cybersickness as measured by the SSQ (Kennedy et al., 1993) at pre-exposure baseline (BL), 0, 15, 30, 45, and 60 min post-exposure. The time component after AR exposure is critical to understanding sustained negative AEs of exposure on an individual (Stanney and Hash, 1998). To be compared appropriately, post-exposure SSQ scores were adjusted using BL pre-exposure SSQ scores. Given a total AR exposure duration of 2- and 1-h post-exposure measurement periods, participants would be expected to have "recovered" to BL SSQ levels for D, O, N, and Total SSQ scores at the conclusion of the experiment. In addition, TCCC performance measures

TABLE 1 | Total simulator sickness questionnaire total scores.

		Display type			
		HoloLens		AR Tablet	
		Mean	SD	Mean	SD
Exposure protocol					
6–20 min	Aftereffects time period				
	Baseline	0.37	1.18	0.68	2.26
	AE_0 min	15.71	10.40	9.18	13.83
	AE_15 min	18.70	12.21	11.90	18.23
	AE_30 min	22.81	16.95	17.34	21.11
	AE_45 min	19.45	13.63	13.26	16.67
	AE_60 min	19.45	13.52	17.00	17.49
3–40 min	Baseline	1.25	2.64	0.00	0.00
	AE_0 min	23.69	21.73	3.74	7.48
	AE_15 min	19.53	17.62	8.42	8.29
	AE_30 min	21.19	26.11	6.55	10.74
	AE_45 min	22.02	33.21	11.22	11.01
	AE_60 min	20.78	32.29	10.29	9.35

included number of training scenarios completed and number of correct responses.

RESULTS

As **Table 1** shows, for the AR Tablet conditions, all but two post-exposure Total SSQ scores were <15.5, which puts AR Tablet in the "low" range for subjective symptomatology as compared to VR systems [see Stanney et al. (2014) for ranges]. On the other hand, the HoloLens 3–40 min condition elicited SSQ scores >20.1 but <27.9 over the duration of all AE measurement periods, which puts the HoloLens in the "medium" range for subjective symptomatology as compared to VR systems. The fact that AEs stayed elevated >30 min post-exposure places this condition in the lower 25th percentile of virtual environment systems in terms of persistence of AEs [∼75% of VR systems have AEs lasting <30 min; see Stanney et al. (2014) for ranges]. Stanney et al. (2014) found that if a given VR system is of medium to extreme intensity (75th percentile, with a Total SSQ score of 20.1 or higher) and is associated with persistent AEs, significant dropouts can be expected. In VR studies, dropout rates of 20% or more are common, with about 50% of attrition occurring within the first 20 min of exposure due to sickness or general malaise (Stanney et al., 1999; Reed et al., 2007). In the current study, even with SSQ > 20.1 and persistent AEs with the HoloLens 3–40 min condition, there were no dropouts. This may be due to differences in symptom profiles, which is discussed below.

A non-parametric Friedman test demonstrated that there was a significant difference for the following conditions: HoloLens, 6–20 min condition ${\chi^2}_r(5) = 22.75$, $p = 0.001$, HoloLens, 3–40 min condition ${\chi^2}_r(5) = 18.28$, $p = 0.002$, AR Tablet, 6–20min condition ${\chi^2}_r(5) = 24.54$, $p = 0.001$, and AR Tablet, 3–40min condition ${\chi^2}_r(5) = 11.81$, $p = 0.04$. A Wilcoxon signed-rank test with a Bonferroni correction showed that these differences were between the BL and AE Total SSQ scores ($p < 0.01$). A between-display-type evaluation was conducted for each respective exposure protocol. While Total SSQ mean scores were highest for HoloLens 3–40 min condition at the 0-min AE condition (mean = 23.69, SD = 21.73), this result was not significantly different from the AR Tablet. The confidence intervals in **Figure 2** suggest that there is a potential for moderate (Total SSQ score > 15.5–20.1) to even extreme [Total SSQ scores > 33.3–53.1; see Stanney et al. (2014) for ranges] symptomatology for the HoloLens 3–40 min condition even 45 min after exposure. By 60 min post-exposure, between-participant variability in symptoms in this condition substantially contracted. The AR Tablet 6–20 min condition also has potential to reach medium cybersickness levels (Total SSQ score >20.1–27.9) but not more extreme levels. The lesser cybersickness with 6–20 vs. 3–40 min exposures suggests that participants may have experienced a mild form of inoculation to cybersickness with more (6 vs. 3) repeat exposures due to a sensory reweighting process in which they "learned" to ignore conflicts associated with AR HWDs, such as the vergence–accommodation conflict (Stanney et al., 2020b). It is interesting that the adverse AEs persisted for >60 min post-exposure with the 3–40 min condition, which suggests that the longer exposure duration may have inhibited the inoculation process. A question-by-question analysis was conducted along with a sickness profile assessment to better understand drivers of participants' cybersickness reports.

SSQ Subscores Symptom Profiles

Table 2 shows that the SSQ symptom profile for AR, both immersive HWD and non-immersive tablet, follows an O > D > N symptom profile, as expected. This suggests that long-duration AR exposure is associated with eyestrain, difficulty focusing, blurred vision, and headache, with lesser dizziness and vertigo, and limited nausea, stomach awareness, salivation, and burping. A one-way analysis of variance (ANOVA), $F_{(2,3)} = 19.04$, $p = 0.049$ showed that HoloLens Oculomotor SSQ scores were significantly higher than for AR Tablet for both exposure protocols. There were no other significant differences in SSQ subscores.

Comparison of Symptom Profile Results

The SSQ questionnaire scale is interval, with a maximum value of 3 designating a severe participant response to the associated question. Weighting of subscores places more weight on Nausea (9.54) and Disorientation (13.2) than on Oculomotor (7.58) symptoms. There are also shared ratings, such as "general discomfort," which is shared between Oculomotor and Nausea. **Figure 3** shows that fatigue and eyestrain are the dominant symptoms reported with HoloLens use regardless of exposure protocol (SSQ O subscore). Eyestrain is also dominant for the AR Tablet 3–40 min exposure condition. Oculomotor subscores were rated significantly worse for the HoloLens conditions, $X_{\text{HoloLens6-20min}} = 23.65$, SD = 3.10; $X_{\text{HoloLens3-40min}} = 25.27$, SD = 1.58, as compared to the AR Tablet conditions, $X_{\text{ARTablet6-20min}} = 16.26$, SD = 3.86; $X_{\text{ARTablet3-40min}} = 11.75$, SD = 4.11. The AR Tablet 3–40 min condition was comparable

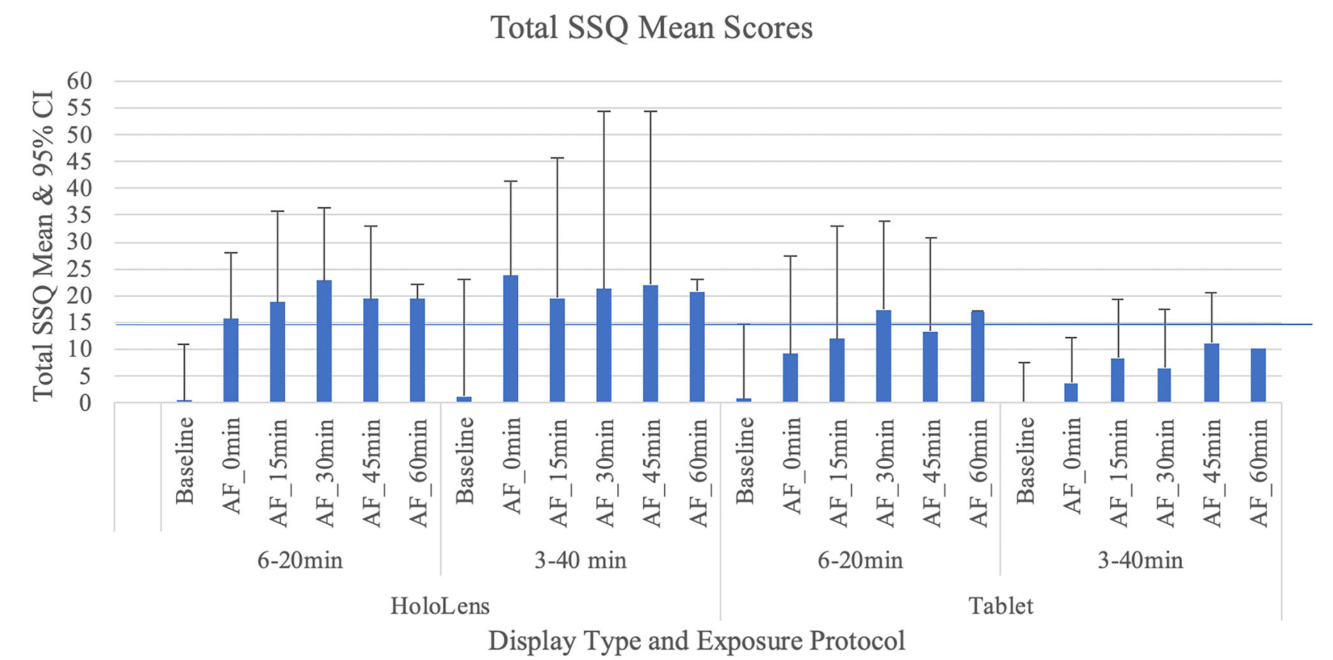

FIGURE 2 | Total SSQ mean scores and 95% confidence interval.

TABLE 2 | Simulator sickness questionnaire subscores.

		Display type			
		HoloLens		AR Tablet	
		Mean	SD	Mean	SD
Exposure protocol					
6 - 20min					
SSQ subscores	Oculomotor	23.65*	3.10	16.26*	3.86
	Disorientation	14.76	2.11	12.15	3.86
	Nausea	9.16	1.45	6.24	2.41
3 - 40min					
SSQ subscores	Oculomotor	25.27*	1.58	11.75*	4.11
	Disorientation	15.16	3.69	7.66	2.91
	Nausea	12.51	2.53	0.48	1.07

$p < 0.05$, HoloLens significantly greater than AR Tablet.

to the HoloLens for reports of eyestrain; however, unlike the HoloLens, these symptoms were not accompanied by other adverse outcomes.

Participants in the HoloLens 3–40 min condition reported difficulty focusing, blurred vision, and dizziness with eye closed, with some fullness of the head and nausea (SSQ D subscore; **Figure 4**). For the HoloLens and AR Tablet or 6–20 min conditions, participants reported low scores on most physical indicators of disorientation. Those in the AR Tablet 3–40 min condition experienced some blurred vision and fullness of the head. **Figure 4** shows that participants reported difficulty focusing as their highest symptom for both HoloLens and AR Tablet 6–20 min conditions, with lesser blurred vision dizziness and fullness of the head.

Figure 5 shows that participants reported general discomfort and difficulty concentrating, as well as some stomach awareness and nausea in the HoloLens 3–40 min condition, which was the only condition to report any nausea (SSQ N subscore). The HoloLens and AR Tablet 6–20 min conditions experienced some general discomfort and difficulty concentrating.

TCCC Performance Data

Tables 3, **4** present the results of TCCC performance data, which evaluated the number of scenarios completed and number of correct responses over the cumulative exposure duration. A two-way ANOVA $F_{(1, 28)} = 17.11$, $p = 0.000$, showed a significant main effect of technology for both scenarios completed and correct responses. There was also a significant main effect of exposure protocol, $F_{(1, 28)} = 11.39$, $p = 0.002$, on scenarios completed, with more scenarios completed in the 3–40min condition. While there was no significant interaction effect for scenarios completed or correct responses, there was a trend toward significance for correct responses, $F_{(1, 28)} = 3.57$, $p = 0.069$. An increased sample size may increase the significance. The results indicate that while those participants assigned to the AR Tablet condition completed more scenarios (∼30% more) than those in the HoloLens group, the HoloLens group scored more correct answers than those in the AR Tablet conditions (∼9% more in the 6–20 min condition; ∼30% more in the 3–40 min condition). It is possible that the

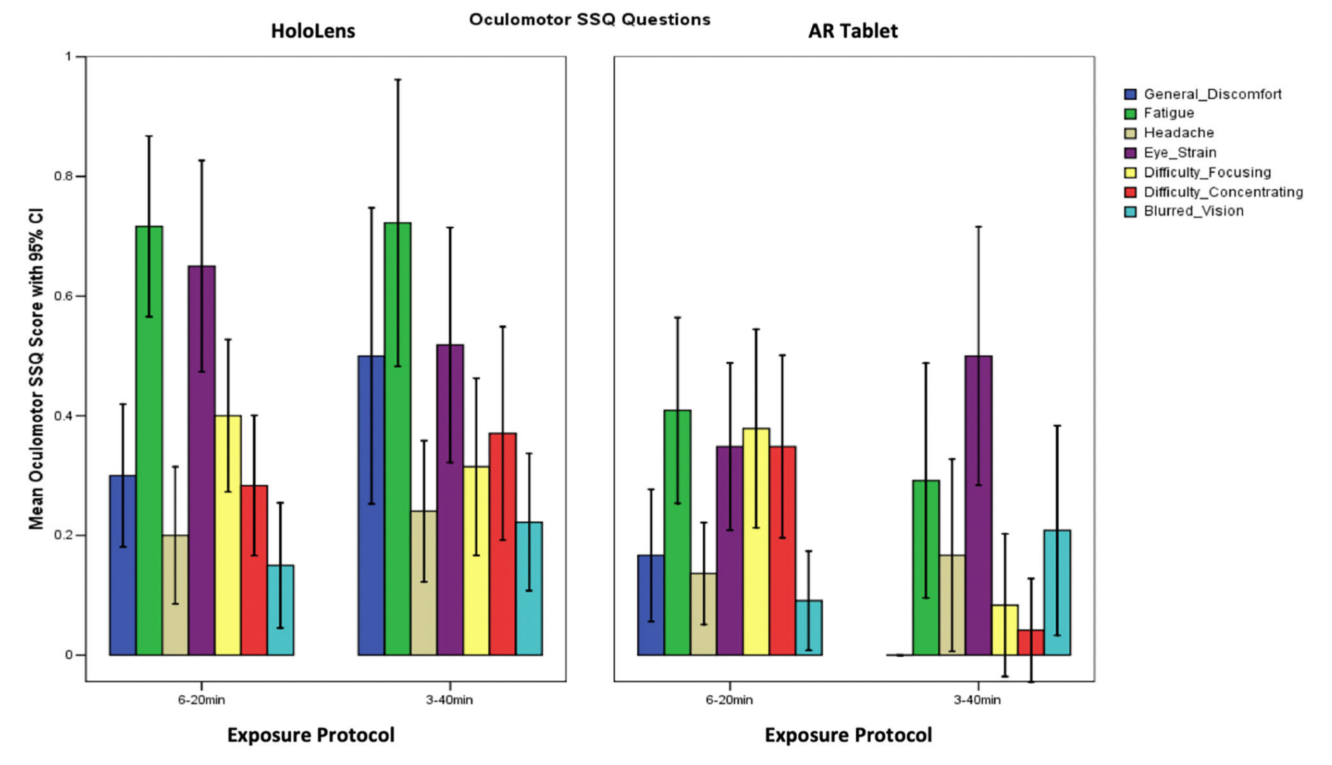

FIGURE 3 | Mean oculomotor SSQ question scores with 95% CI.

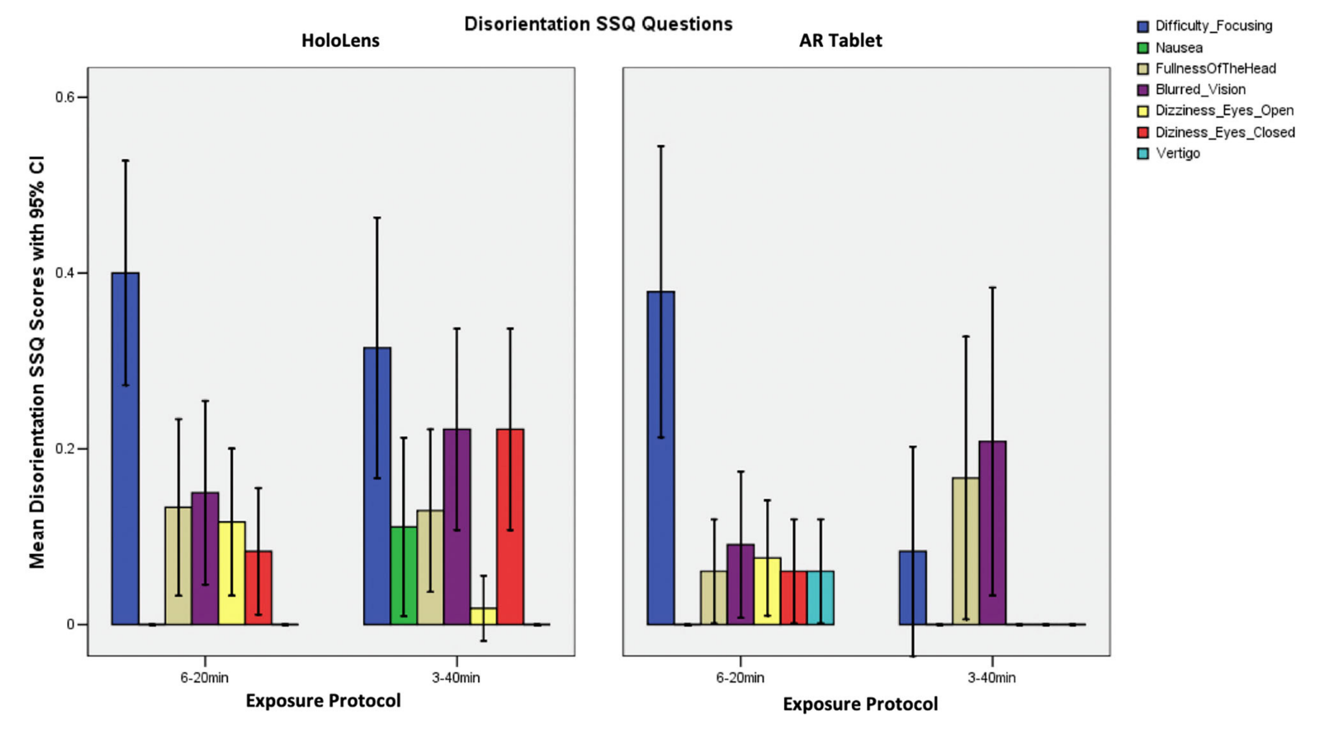

FIGURE 4 | Mean disorientation SSQ question scores with 95% CI.

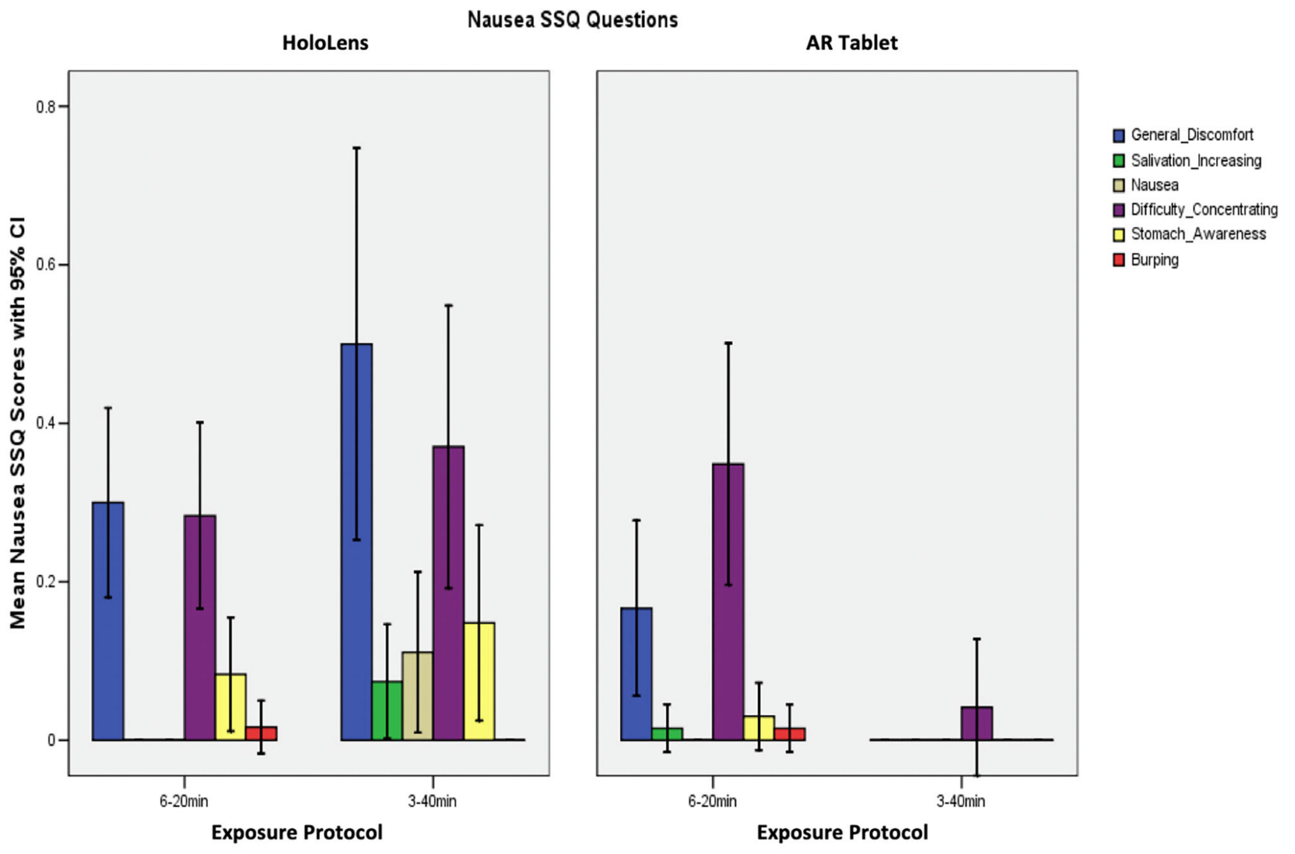

FIGURE 5 | Mean nausea SSQ question scores with 95% CI.

TABLE 3 | TCCC performance scenarios completed.

	Display type			
	HoloLens		AR Tablet	
	Mean	SD	Mean	SD
Exposure protocol				
6 - 20min	3.88*	0.64	6.00*	0.89
3 - 40min	5.56*	0.73	8.25*	4.11

**p < 0.05, AR Tablet significantly greater than HoloLens.*

TABLE 4 | TCCC performance correct responses.

	Display type			
	HoloLens		AR Tablet	
	Mean	SD	Mean	SD
Exposure protocol				
6 - 20min	100.13*	6.96	91.73*	18.91
3 - 40min	105.44*	20.25	69.25*	33.18

**p < 0.05, HoloLens significantly greater than AR Tablet.*

significantly greater oculomotor disturbances in the HoloLens condition as compared to the AR Tablet may have slowed down performance, or perhaps the novelty of the HoloLens form factor may have slowed performance. At the same time, even though less overall training content was consumed, the HoloLens condition yielded significantly better performance outcomes. The 3–40 min condition results are of particular interest, as participants in this condition who donned the HoloLens had substantially more oculomotor disturbances (mean = 25.27, SD = 1.58) as compared to the AR Tablet (mean = 11.75, SD = 4.11) but still managed to achieve substantially better performance outcomes (∼30% more accurate). These results suggest that individuals may be able to overcome the adverse physiological impact of HWD AR, still concentrate on training content, and benefit from the more contextualized, embodied training afforded by this immersive form factor in order to realize deeper learning and more resilient training outcomes.

USAGE GUIDELINES

The SSQ results (**Figures 3**, **4**) suggest that the burden on the visual system through eyestrain, difficulty focusing, blurred vision, and headache is relatively pronounced in immersive HWD AR systems while performing complex, close (personal space within <2 m) training tasks such as TCCC training. Further, low levels of nausea were experienced in the HoloLens 3–40 min, but not the HoloLens 6–20 min condition (**Figure 5**). Given that the TCCC training scenarios were identical across these conditions, these results suggest that the adverse physiological impacts of AR exposure may be able to be moderated through usage protocols that carefully specify appropriate exposure duration in immersive AR systems; however, it is important to note that these protocols may be differentially effective based on individual differences. For example, for the immersive AR TCCC training used in this study, the 6–20 min protocol posed less of a physiological impact than the 3–40 min exposure protocol (**Table 1**, **Figure 2**). The 6–20 min condition with 30-min breaks between sessions HoloLens condition led to a Total SSQ score of 15.71 (SD = 10.4) on average immediately post-exposure, which is approaching the "low" range (25th percentile) as compared to VR systems (Stanney et al., 2014). This condition also led to strong performance outcomes in terms of correct responses (mean = 100.12, SD = 6.96). In comparison, the 3–40 min condition with 30-min breaks between sessions HoloLens condition led to a Total SSQ score of 23.69 (SD = 21.73) on average immediately post-exposure, which is firmly in the "medium" range (75th percentile) as compared to VR systems. Further, the AEs persisted in the latter condition, which would be expected to compromise post-exposure human performance and safety. However, one must also consider that the 3–40 min HoloLens condition led to strong training outcomes in terms of percent correct (mean = 105.44, SD = 20.25), and thus, participants appeared to be able to overcome the cybersickness they were experiencing and concentrate on the training content. Nonetheless, limiting exposure duration in immersive HWD AR systems to 20 min with at least 30-min breaks in between is one potential way of minimizing the adverse physiological impact of AR exposure, while still achieving strong performance outcomes. Finally, as the AR Tablet conditions had, on average, low levels of adverse symptomatology and led to substantially more training content consumed, the results suggest that complex training of longer duration may benefit from a dual technology usage protocol, where AR Tablet–based training delivers longer duration training content that is less demanding of embodied psychomotor skills and the importance of contextualization (e.g., declarative knowledge), while immersive AR headsets are used to deliver shorter-duration, fully contextualized, and embodied training experiences. An initial set of suggested AR usage guidelines thus includes the following:

- When post-exposure dexterity is important, until personalized, real-time assessment of adverse physiological effects is widely available, consider limiting exposure duration in immersive HWD AR systems to 20 min with at least 30-min breaks between exposures.
- For immersive HWD AR exposures longer than 20 min, expect dropouts and higher levels of adverse effects, such as prolonged headaches and eyestrain post-exposure, which should be measured for their severity; however, expect that trainees can overcome these adverse physiological impact and still derive substantial value from HWD AR training.
- Until adaptive AR-based training solutions are adopted, which personalize the training experience based on trainee proficiency and physiological well-being, consider adopting a dual technology usage protocol, where AR Tablet–based training delivers declarative knowledge of longer duration and immersive AR headset-based training is used to deliver shorter-duration, fully contextualized, and embodied training experiences focused on procedural and conditional (strategic) knowledge.

CONCLUSION

Immersive AR applications have the potential to significantly accelerate training expertise given the capability to present training content in a more realistic and embodied context. Understanding the potential for cybersickness and associated symptom profiles can assist in the design and development of optimal AR-based individual training protocols, such as those being developed for TCCC training. This study demonstrated an O > D > N adverse symptom profile for both immersive and tablet-based AR training systems. The oculomotor symptomology sustained across a 60-min post-exposure assessment period for longer exposure durations (3–40 min vs. 6–20 min exposure sessions). These cybersickness indicators were, on average, of moderate to medium effects and, for oculomotor symptoms, were significantly higher and persisted longer for HoloLens conditions, as compared to AR Tablet, regardless of exposure protocol. Nonetheless, HoloLens conditions led to better performance outcomes, which suggests trainees can overcome adverse physiological impacts and still derive substantial value from HWD AR training. Thus, this preliminary research suggests that time within immersive AR training systems may need, at least initially, to be dispersed across multiple shorter exposure (∼20 min) sessions with an intersession break of at least 30 min to minimize adverse symptomatology and prolonged adverse AEs, as well as foster inoculation. It was surprising to find that the persistence of adverse AEs in the long-duration immersive AR exposure condition was found to be as severe as some of the worst VR systems. Thus, even though the symptom profile for AR is loaded on oculomotor symptoms, which are less overtly incapacitating than the nausea symptoms typically associated with VR systems, the adverse symptoms can linger for long periods of time post–AR exposure, just as they do after VR exposure. More research is needed to confirm these results. Objective physiological measures of cybersickness during AR exposure, such as electrogastrography and HWD embedded eye tracking, as well as objective measures of negative adaptation effects (e.g., shifts in visual functioning, degraded hand–eye coordination, ataxia) post-exposure, should be included in future studies to quantify the extent of the effects of cybersickness associated with HWD AR exposure, especially on human performance.

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 Copernicus IRB and Human Research Protections Office at USAMRDC. The patients/participants provided their written informed consent to participate in this study. Consent has been obtained from the relevant individuals for the publication of any identifiable images in this article.

AUTHOR CONTRIBUTIONS

CH assisted with the literature review, directed the study, and was the lead author of the paper. CF led the data analytics. KS designed the experiment, contributed to, reviewed, and provided feedback on all aspects of this paper. PB and ER assisted with the literature review, collected the data, reviewed, and provided feedback on the paper. All authors contributed to the article and approved the submitted version.

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Postural Activity During Use of a Head-Mounted Display: Sex Differences in the "Driver–Passenger" Effect

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Motion sickness is common in virtual environments. The risk of motion sickness varies widely between individuals and across situations. The subjective experience of motion sickness often is preceded by distinctive patterns of movement in the control of head and body posture. Previous research has documented reliable sex differences in the kinematics of postural activity, as well as reliable differences in postural activity between participants who were in control of a virtual vehicle and participants who were not. We asked whether postural precursors of motion sickness would simultaneously be influenced by individual and situational factors. We analyzed movement of the head and torso while seated participants were exposed to a driving video game presented through a head-mounted display. Half of the participants were women, and half were men. Using a yoked-control design, half of the participants controlled the virtual vehicle (*Drivers*), whereas half watched previously recorded vehicle trajectories (*Passengers*). The maximum exposure duration was 15 min, but participants were instructed to discontinue participation immediately if they experienced any symptoms of motion sickness, however mild. We analyzed movement kinematics not only in terms of sex and vehicle control but also in terms of participants who did or did not report motion sickness. Movement differed between Drivers and Passengers, in terms of both the spatial magnitude and multifractality of movement. The spatial magnitude of movement was simultaneously influenced by sex (men vs. women) and vehicle control (Drivers vs. Passengers). In addition, in statistically significant interactions, we identified postural precursors of motion sickness that differed between Drivers and Passengers and, separately, between Drivers and Passengers as a function of sex. The results are consistent with a prediction of the postural instability theory of motion sickness etiology and shed new light on the multifactorial origins of postural precursors of motion sickness in virtual environments.

Keywords: motion sickness, cybersickness, virtual reality, head-mounted display, posture, sex differences

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INTRODUCTION

Among users of interactive technologies, motion sickness is widely reported. For head-mounted displays (HMDs), this type of motion sickness is often referred to as cybersickness. Typically, the risk of motion sickness is greater during applications that feature virtual locomotion (i.e., movement of the observer relative to a virtual world) and is less common in applications that do not include virtual locomotion (e.g., Bruder et al., 2012; Munafo et al., 2017; Nilsson et al., 2018).

A common example of virtual locomotion is virtual driving. In many cases, users control virtual vehicles: they are drivers. In other cases, users merely observe the motion of virtual vehicles; in effect, they are passengers. Both physical and virtual vehicles are associated with the *Driver–Passenger effect*, in which the risk of motion sickness typically is greater for passengers than for drivers (e.g., Rolnick and Lubow, 1991; Dong et al., 2011). In this article, we report the final component of a larger study of sex differences in the driver–passenger effect in HMDs. Earlier reports presented data on the incidence and severity of motion sickness (Curry et al., 2020a) and on standing body sway prior to HMD exposure (Curry et al., 2020b). In the present article, our focus was on seated postural activity during exposure to a virtual vehicle presented through an HMD.

Postural Precursors of Motion Sickness During Exposure

The postural instability theory of motion sickness predicts that the quantitative kinematics of postural activity will differ between persons who state that they are motion sick and persons who state that they are not motion sick, and that these differences should exist before the onset of motion sickness (Riccio and Stoffregen, 1991). In the empirical literature, this prediction has been operationalized in terms of relations between quantitative measures of postural activity (i.e., continuous variables) and the incidence of motion sickness. In most tests, motion sickness incidence has been a dichotomous variable, with individual participants being classified as being either well or sick. Several studies have investigated the kinematics of postural activity during exposure to potentially nauseogenic motion. Most have used a method in which participants were instructed to discontinue immediately if they experienced any symptoms of motion sickness, however mild. This instruction is given repeatedly (e.g., during the consent process and before each exposure trial). In addition, participants are informed that they may discontinue participation at any time for any reason, and that there is no penalty for early discontinuation. These aspects of the design remove motivation for false positives (i.e., feigning motion sickness as an excuse to discontinue) and ensure that all postural data precede the onset of any subjective symptoms of motion sickness (e.g., Stoffregen and Smart, 1998; Dong et al., 2011; Stoffregen et al., 2017).

Using this method, researchers have identified postural precursors of visually induced motion sickness in laboratory devices (e.g., Stoffregen et al., 2010; Koslucher et al., 2014, 2016a; Li et al., 2018; Walter et al., 2019), in desktop virtual environments (e.g., Stoffregen et al., 2008, 2017; Dong et al., 2011; Chang et al., 2017), in handheld devices (Stoffregen et al., 2014), in projection video systems (e.g., Villard et al., 2008; Palmisano et al., 2018), and in HMDs (e.g., Merhi et al., 2007).

During exposure to virtual environments, postural activity evolves; that is, it changes over time. This effect has been documented in a wide variety of studies (e.g., Stanney et al., 1998; Stoffregen et al., 2010; Koslucher et al., 2016a). In a logically distinct effect, some studies have identified statistically significant interactions between the duration of virtual environment (VE) exposure and the subsequent development of motion sickness (e.g., Villard et al., 2008; Stoffregen et al., 2010, 2014; Koslucher et al., 2016a). We expected to replicate these empirical effects.

Sex Differences in Postural Precursors of Motion Sickness

A common observation is that susceptibility to motion sickness differs between the sexes. In both field research and in the laboratory, women typically are more susceptible than men (e.g., Lawther and Griffin, 1988; Koslucher et al., 2015). Separately, both laboratory and population studies have found that the kinematics of standing body sway differ between the sexes (e.g., Era et al., 2006; Kim et al., 2010). Recent research has revealed that these two effects are related; that is, that postural precursors of motion sickness are different for women and men, with differences that often are qualitative. Several studies have found sex-specific postural precursors of motion sickness in standing body sway prior to exposure to any motion stimuli (e.g., Koslucher et al., 2016a; Munafo et al., 2017; Curry et al., 2020b). Koslucher et al. (2016a) found this to be the case *during* exposure to nauseogenic motion. In the present study, we conducted the first assessment of possible sex differences in postural precursors of motion sickness during seated exposure to virtual locomotion in an HMD.

Postural Precursors and the Driver–Passenger Effect

Arcioni et al. (2018; see also Risi and Palmisano, 2019) exposed participants to a virtual environment through an HMD. All participants controlled their own motion within the virtual environment. The authors measured standing body sway before HMD exposure, and in these data, they identified postural precursors of (subsequent) motion sickness. Arcioni et al. and Risi and Palmisano included both women and men, but the authors did not analyze for possible sex differences in postural precursors of motion sickness. Munafo et al. (2017) compared women and men, but measured postural activity only prior to exposure to the virtual environment. In addition, in their study, all participants controlled virtual locomotion.

Dong et al. (2011) examined the Driver–Passenger effect in virtual vehicles as presented to seated participants through a desktop video monitor. Using a yoked-control design (cf. Rolnick and Lubow, 1991), one member of each pair of participants (the Driver) drove a virtual vehicle (i.e., played the driving video game), while their performance was recorded. This recording was replayed and viewed by the other member of the pair (the Passenger). This design ensured that visual motion stimuli were identical for the two members of each pair: exposure to the game differed only in that one participant controlled the virtual vehicle, whereas the other did not. The results revealed that the incidence of motion sickness was greater among Passengers than among Drivers, consistent with the Driver–Passenger effect. Dong et al. also recorded the kinematics of the head and torso as seated participants were exposed to the video game.

Patterns of postural activity were found to differ between Drivers and Passengers and, separately, between participants who later reported motion sickness, and those who did not. In the present study, we asked new questions about relations between postural precursors of motion sickness, the Driver–Passenger effect, and sex differences.

The Present Study

The present study was modeled on Dong et al. (2011), in terms of our focus on head and torso movement of seated participants during exposure to a driving video game, either as drivers or as passengers. Like Dong et al., we used a yoked-control design in which one member of each pair of participants played a driving game (i.e., drove a virtual automobile). A recording of that performance was viewed (in a separate session) by the other member of the pair. Thus, the two members of each pair were exposed to identical vehicle trajectories, but the risk of behavioral contagion was minimized. The present study differed from Dong et al. in several respects. First, we used a different driving video game. Second, the game was presented through an HMD, rather than being presented through a desktop interface. Third, we crossed our manipulation of vehicle control (i.e., Drivers vs. Passengers) with a manipulation of sex: half of our participants were men, whereas half were women. Independent measures of motion sickness incidence and symptom severity from our sample were reported by Curry et al. (2020a), who found that the incidence of motion sickness did not differ between Drivers and Passengers or between women and men. That is, they did not replicate either the classical Driver–Passenger effect or commonly reported sex differences in susceptibility. The study by Curry et al. (2020a) was the first assessment of the Driver–Passenger effect in an HMD, as well as being the first study of sex differences in the control of virtual vehicles. It is possible that unique characteristics of HMDs may minimize the Driver–Passenger effect, while the dynamics of virtual vehicles may tend to suppress sex differences in the incidence of motion sickness (for a discussion, see Curry et al. (2020a). In the present study, we investigated the kinematics of head and torso movement as seated participants were exposed to the driving video game in the study by Curry et al. (2020a). Previous studies have found differences in postural precursors of motion sickness between groups (e.g., people with vs. without experience driving physical vehicles) even when groups did not differ in motion sickness incidence or severity (e.g., Stoffregen et al., 2017).

Postural activity typically changes over time during exposure to virtual environments, and postural precursors of motion sickness often vary as a function of exposure duration (e.g., Dong et al., 2011; Chang et al., 2017; Stoffregen et al., 2017). Following these studies, we separated data on postural kinematics into three non-overlapping Time Windows, which allowed us to evaluate possible changes in postural activity as a function of exposure duration.

We predicted that postural activity would differ between Drivers and Passengers and between women and men. Our primary prediction was that differences in postural precursors of motion sickness between Drivers and Passengers would, themselves, be modulated by sex. Within these interactions, we did not make predictions about specific contrasts. For this reason, we do not report *post-hoc* contrasts on statistically significant effects.

METHOD

Participants

Curry et al. (2020a) reported data on 79 participants. Some of those participants were not included in the present study (see the Results section for details). The present analysis included data from 65 individuals (32 women and 33 men), who participated in exchange for course credit. Participants ranged in age from 18 to 36 years (mean = 21.55 years, SD = 3.04 years), in height from 1.51 to 1.94 m (mean = 1.73 m, SD = 0.10 m), and in weight from 47.63 to 104.33 kg (mean = 72.19 kg, SD = 12.22 kg). The research protocol (STUDY00001875) was approved in advance by the IRB of the University of Minnesota.

Apparatus

Participants wore the Oculus Rift CV1. The device comprised a lightweight (0.360 kg) headset that completely covered the field of view. The headset included separate displays for each eye, each with 1,080 × 1,020 resolution, yielding a 100° horizontal field of view. A lens located in front of each display rendered display content at optical infinity.

We used a magnetic tracking system (Fastrak; Polhemus, Colchester, VT) to record postural activity. Sensors were worn at the head and torso (as described below), and each was sampled at 60 Hz. For each sensor, we collected data on movement in the anterior–posterior (AP) and mediolateral (ML) axes.

Procedure

We obtained informed consent from each participant. We informed participants that they could discontinue at any time, for any reason, without penalty. Following previous studies (e.g., Stoffregen and Smart, 1998; Merhi et al., 2007; Stoffregen et al., 2008, 2010; Dong et al., 2011; Koslucher et al., 2015), we used independent assessments of the incidence of motion sickness and the severity of symptoms (for details, see Curry et al., 2020a). To assess motion sickness incidence, participants answered a forced-choice, yes/no question, *Are you motion sick?* Participants were instructed (both verbally and on the consent form) to discontinue the experiment immediately if they experienced any motion sickness symptoms, however mild. After completion of the consent process, we conducted a pre-exposure assessment of motion sickness incidence and severity, after which we measured standing body sway while participants performed some simple visual tasks, as reported by Curry et al. (2020b).

Following our assessment of standing posture, participants sat on a stool that did not rotate and had no wheels and were fitted with a sensor from the magnetic tracking system, which was attached, using cloth medical tape, between the shoulder blades, at the base of the neck. Another sensor was attached to the Oculus headset. Participants donned the Oculus headset and were exposed to *Assetto Corsa*, a commercial driving game. Each Driver drove a Ferrari 458 Italia on the Highlands Long Track (**Figure 1**). Details of the driving game were reported

FIGURE 1 | Overhead representation of the racetrack. The length of the simulated track was 12.19 km.

in Curry et al. (2020a). During exposure to the video game, we used a between-participants, yoked-control design, with individual Passengers yoked to individual Drivers. Participant pairs were sex-matched: men with men and women with women. Participants played or viewed the game for up to 15 min. Data on head and torso motion were collected continuously. Additional details of the yoked-control procedure are reported in Curry et al. (2020a).

After completing the 15-min game exposure, or after discontinuation (whichever came first), we again assessed motion sickness incidence and severity. Participants who answered yes to the forced-choice, yes/no question, *Are you motion sick?* were assigned to the sick group. All others were assigned to the well group.

Analysis of Head and Torso Movement

Postural activity can be characterized in terms of spatial magnitude (i.e., spatial structure), but it can also be characterized in terms of temporal dynamics (i.e., temporal structure). Recent years have seen the development of a wide array of dependent variables that assess different aspects of the temporal dynamics of the kinematics of human movement. Many widely used parameters are derived from general physical processes and do not have an *a priori* or intrinsic relation to animate movement. For example, stabilogram diffusion analysis (e.g., Collins and De Luca, 1993) is derived from models of the movement of gas molecules and has no intrinsic relation to the physical structure of the body. One relatively new parameter is the multifractality of movement. Several scholars have argued that multifractality may be a fundamental property of animate movement, and that, as such, measures of multifractality may be more meaningful than measures of other aspects of temporal dynamics (Kelty-Stephen et al., 2013; Palatinus et al., 2014). Several studies have documented the existence of multifractality in standing body sway (Thurner et al., 2000; Shimizu et al., 2002; Ihlen et al., 2013; Munafo et al., 2016). Other studies have shown that postural precursors of motion sickness can occur in the multifractality of postural activity (e.g., Koslucher et al., 2016a; Munafo et al., 2017; Curry et al., 2020b).

We conducted separate evaluations of the spatial magnitude and multifractality of movement. We evaluated the spatial magnitude of postural activity in terms of positional variability, which we defined operationally as the standard deviation of position. We used multifractal detrended fluctuation analysis, or *MF-DFA*, to evaluate the multifractality of postural activity (e.g., Kantelhardt et al., 2002; Ihlen et al., 2013; Munafo et al., 2016). MF-DFA is an extension of detrended fluctuation analysis, or *DFA* (Lin et al., 2008). MF-DFA has been used in the assessment of postural sway in a variety of contexts (e.g., Munafo et al., 2016). Detrended fluctuation analysis assumes that fluctuations in a time series are homogeneous (Ihlen and Vereijken, 2010), but this assumption typical is not met in data on human movement: multifractal fluctuations are interdependent and heterogeneous. The heterogeneous nature of multifractal fluctuations can be revealed in the range of the singularity exponent, $h(q)$ (Ihlen, 2012). The width of this range is an index of the degree (or amount) of multifractality in a time series. The range of $h(q)$ values is known as the *singularity spectrum* or the *spectrum*. The wider the spectrum, the more multifractal is the movement (Kelty-Stephen et al., 2013). For each trial, we conducted inferential statistics on the width of the singularity spectrum. We obtained the width of the spectrum using open source code for MATLAB (MFDFA1; Ihlen, 2012). Following Munafo et al. (2016), we selected a minimum scaling range of 16 data points with 19 evenly spaced increasing segment sizes to a maximum of the length of the time series. This range was the same for each time series.

Exposure duration varied between participants, as reflected in variations in discontinuation time, and in the fact that some participants completed the 15-min protocol. We conducted separate repeated measures ANOVAs on positional variability and the width of the multifractal spectrum. For each ANOVA, the factors were Time Windows (W1, W2, W3), Segment (head vs. torso), Body Axis (AP vs. ML), Sex (women vs. men), Control (drivers vs. passengers), and Sickness Groups (well vs. sick). Time Windows, Segment, and Body Axis were within-participants factors, whereas Sex, Control, and Sickness Groups were between-participants factors.

RESULTS

As reported by Curry et al. (2020a), the overall incidence of motion sickness was 43% (34/79). Data on symptom severity were also reported by Curry et al. (2020a).

We excluded the kinematic data from three participants (one well, two sick) because of technological difficulties. Of the remaining 32 participants in the sick group, 11 discontinued after <6 min of game play. For this reason, these three participants were excluded from movement analysis. For the remaining 21 participants in the sick group, the mean exposure to the game was 620.64 ± 190.01 s. Following Chang et al. (2017), we defined time windows for the well groups based on the mean exposure time of

TABLE 1 | Statistically significant effects from analysis of variance.

	Positional variability		
	F	***p***	***Partial η^2***
Segments	(1, 57) = 74.53	<0.001	0.57
Time windows	(2, 114) = 3.99	0.021	0.07
Segment × Time windows	(2, 114) = 6.49	0.002	0.10
Body axis × Time windows	(2, 114) = 9.55	<0.001	0.14
Body axis × Time windows × Control × Sex	(2, 114) = 5.07	0.008	0.08
Body axis × Time windows × Control × Sickness groups	(2, 114) = 3.41	0.036	0.06
Segment × Control	(1, 57) = 5.99	0.018	0.10
Body axis × Segment	(1, 57) = 19.29	<0.001	0.25
Body axis × Segment × Sex × Sickness groups	(1, 57) = 6.25	0.015	0.10
Body axis × Segment × Control × Sex × Sickness groups	(1, 57) = 4.40	0.04	0.07
	Width of the multifractal spectrum		
	F	***p***	***Partial η^2***
Control	(1, 57) = 7.24	0.009	−0.11
Body axis × Segment	(1, 57) = 4.80	0.033	0.08

The factors are Segments (head vs. torso), Time Windows (W1, W2, W3), Body Axis (anterior–posterior vs. mediolateral), Control (drivers vs. passengers), Sex (women vs. men), and Sickness Groups (well vs. sick).

participants in the sick group. Accordingly, Window 1 comprised the first 120 s of game play, Window 2 ran from 251 to 371 s, and Window 3 ran from 501 to 621 s.

Positional Variability

The results are summarized in **Table 1**, which details Factors, F-values, p-values, and values of partial η^2. For positional variability, the main effect of Segments was significant. Positional variability for the head ($M = 1.17$ cm, $SE = 0.08$ cm) was greater than that for the torso ($M = 0.76$ cm, $SE = 0.06$ cm). The main effect of Time Windows was significant (Window 1 mean = 1.06 cm, $SE = 0.07$ cm; Window 2 mean = 0.91 cm, $SE = 0.08$ cm; Window 3 mean = 0.93 cm, $SE = 0.07$ cm).

There were several significant interactions involving the Time Windows factor. A stand-alone effect was the significant Segment × Time Windows interaction. As shown in **Figure 2**, motion of the head and torso changed differently over time (i.e., across Time Windows). For the torso, changes across Time Windows were not significant. The Body Axis × Time Windows interaction was significant. This interaction was subsumed in two higher-order interactions. The Body Axis × Time Windows × Control × Sex interaction was significant (**Figure 3**). In addition, the Body Axis × Time Windows × Control × Sickness Groups interaction was significant (**Figure 4**).

Several significant interactions did not include the Time Windows factor. The Segment × Control interaction was significant, as was the Body Axis × Segment interaction was significant. In addition, the Body Axis × Segment ×

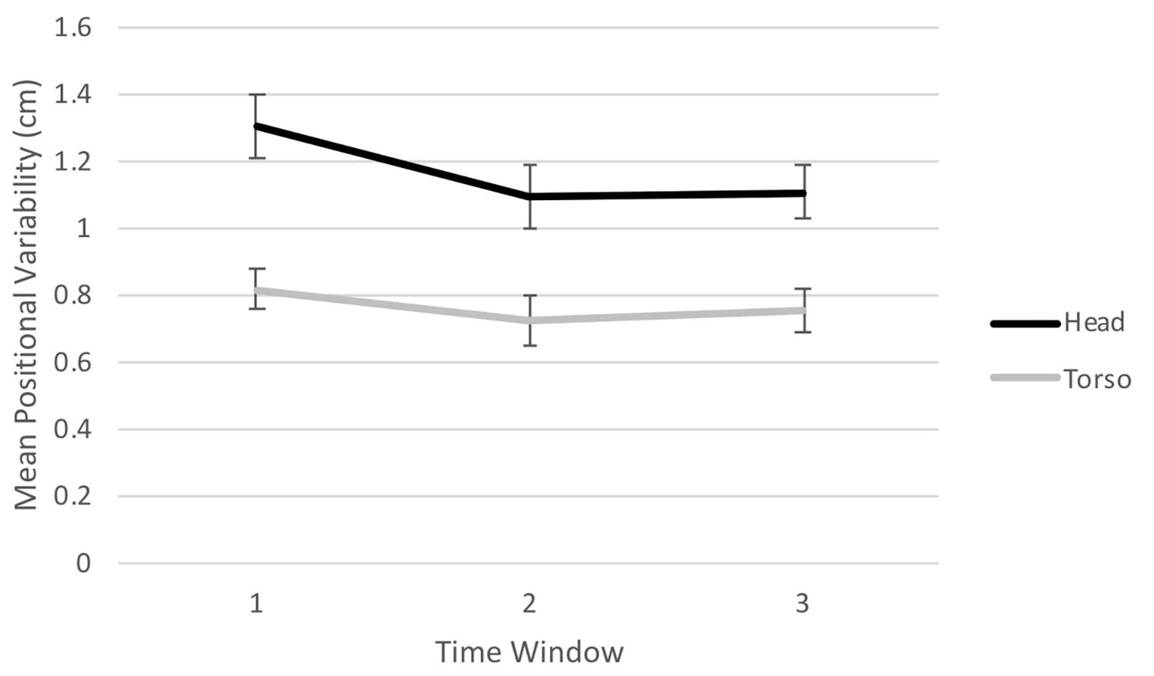

FIGURE 2 | Positional variability, illustrating the statistically significant interaction between Body Segment (head, torso) and Time Windows.

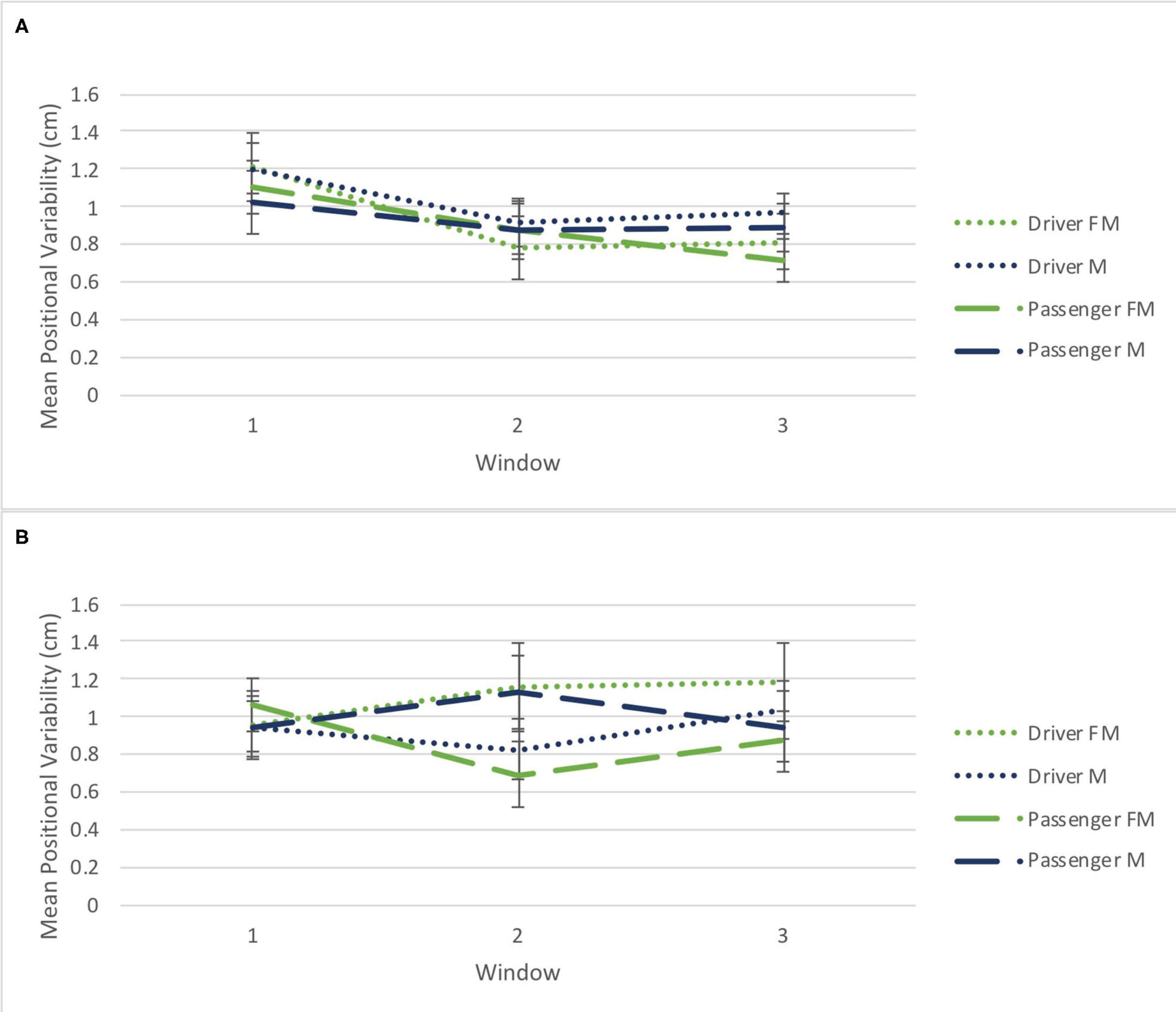

FIGURE 3 | Positional variability, illustrating the statistically significant interaction between Body Axis (anterior–posterior, mediolateral), Sex, Control (drivers, passengers), and Time Windows. **(A)** Movement in the mediolateral axis. **(B)** Movement in the anterior–posterior axis.

Sex × Sickness Groups interaction was significant. These interactions were subsumed in a statistically significant 5-way interaction between Body Axis, Segment, Control, Sex, and Sickness Groups (**Figure 5**). There were no other significant differences.

Width of the Multifractal Spectrum

The results are summarized in **Table 1**. For the width of the multifractal spectrum, the main effect of Control was significant. The multifractal spectrum was wider among Passengers ($M = 0.36$, $SE = 0.02$) than among Drivers ($M = 0.30$, $SE = 0.02$). In addition, the Body Axis × Segment interaction was significant (head AP $M = 0.31$, $SE = 0.01$; head ML $M = 0.32$, $SE = 0.014$; torso AP $M = 0.36$, $SE = 0.02$; torso ML $M = 0.32$, $SE = 0.02$). There were no other significant effects.

DISCUSSION

We exposed seated participants to a virtual vehicle in a driving video game that was presented through an HMD. We covaried sex (women vs. men) control of the virtual vehicle (drivers vs. passengers) and motion sickness status (well vs. sick, as reported by Curry et al., 2020a). In the present study, we examined movement of the head and torso during game exposure. We found several effects that were independent of motion sickness status. Some of these replicated common findings in the

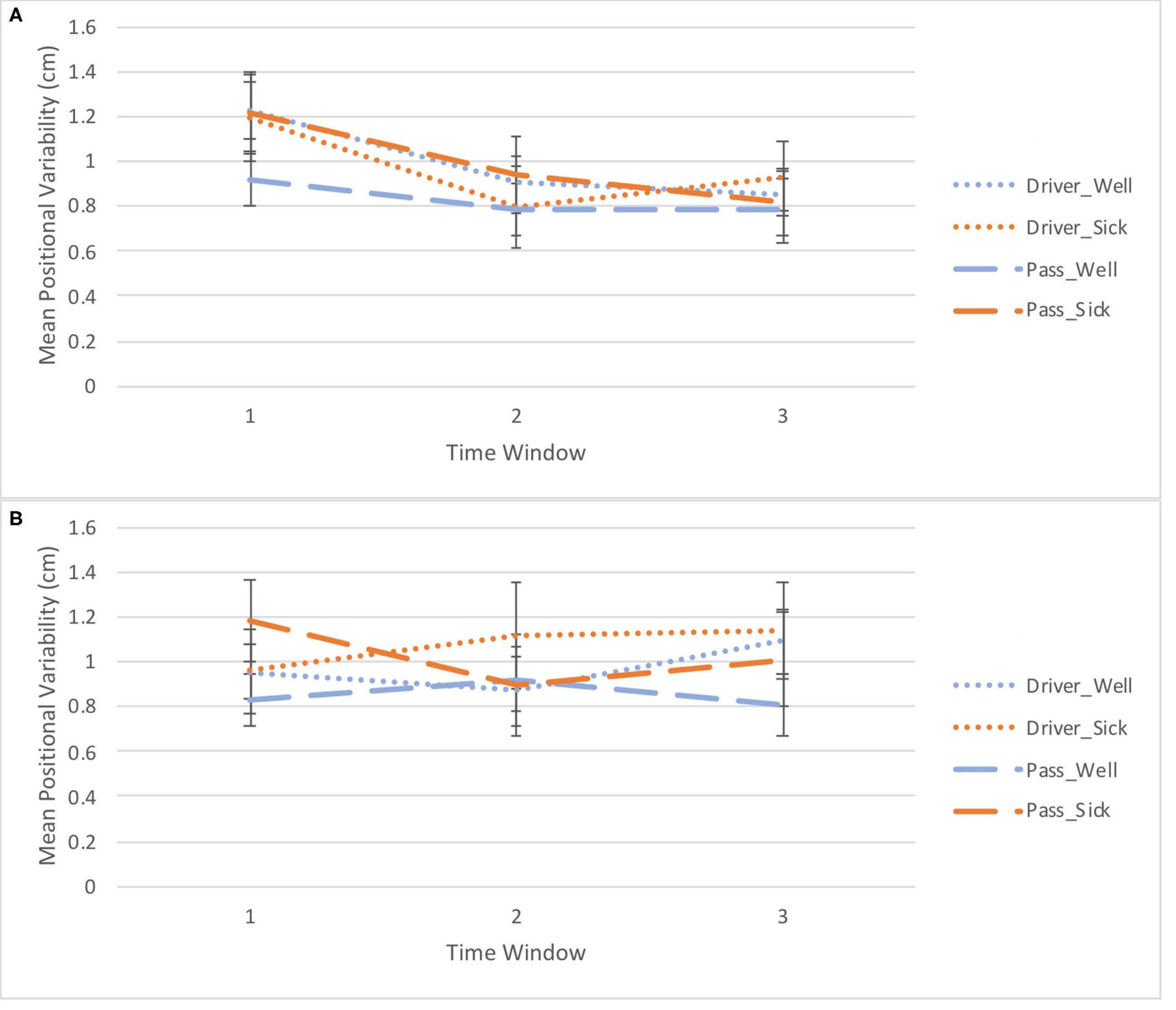

FIGURE 4 | Positional variability, illustrating the statistically significant interaction between Body Axis (anterior–posterior, mediolateral), Control (drivers, passengers), Time Windows, and Sickness Groups. **(A)** Movement in the mediolateral axis. **(B)** Movement in the anterior–posterior axis.

literature, whereas others were novel. The principal result of the study was our identification of postural precursors of motion sickness. Two statistically significant interactions revealed that postural precursors of motion sickness differed between drivers and passengers and between women and men. We discuss these results in turn.

Movement Independent of Motion Sickness

The main effect of Segment was significant for the positional variability of postural activity, but this effect was subsumed in the significant Segment × Time Windows interaction (**Figure 2**). The nature of the interaction was unusual, in that movement of both the head and torso declined across Time Windows. This pattern contrasts with previous studies, in which postural activity has tended to increase over time (e.g., Merhi et al., 2007; Villard et al., 2008; Dong et al., 2011). The Segment × Body Axis interaction was also significant for the width of the multifractal spectrum. That is, relations between body segments and body axes influenced the orthogonal variables of positional variability and movement multifractality. A similar effect was reported by Walter et al. (2019) who exposed standing participants to oscillation of the visual environment along the line of sight.

For positional variability, the Body Axis × Time Windows interaction was significant; however, this interaction was subsumed in the significant Body Axis × Sex × Control × Time Windows interaction (**Figure 3**). Sex differences are a common feature of the kinematics of standing body sway (e.g., Era et al.,

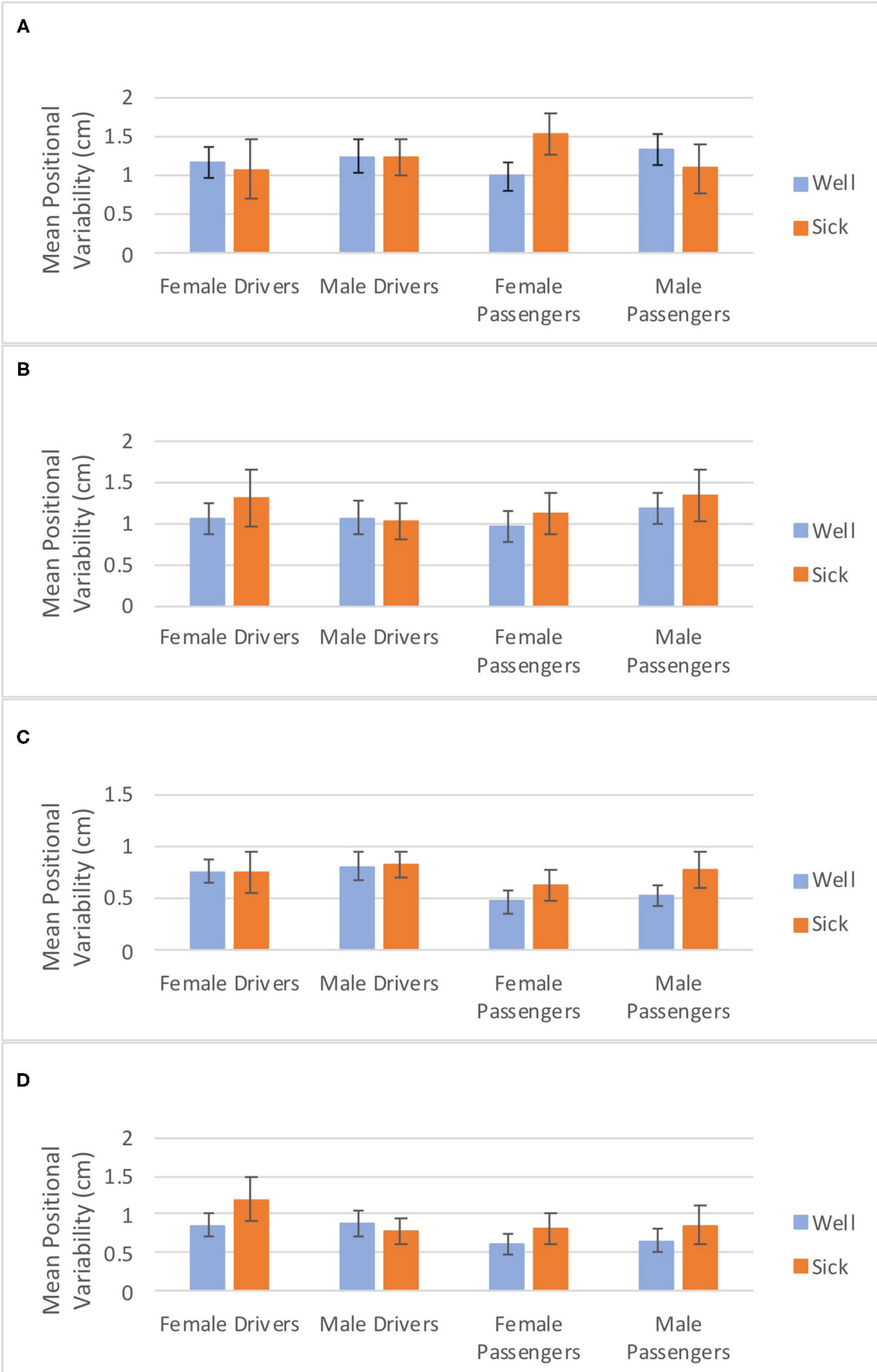

FIGURE 5 | Positional variability, illustrating the statistically significant interaction between Body Axis (anterior–posterior, mediolateral), Segment (Head, Torso), Sex, Control (drivers, passengers), and Sickness Groups. **(A)** Head movement in the mediolateral axis. **(B)** Head movement in the anterior–posterior axis. **(C)** Torso movement in the mediolateral axis. **(D)** Torso movement in the anterior–posterior axis.

2006; Kim et al., 2010). In the present study, participants were seated, which made it possible for us to evaluate the possibility that there might be sex differences in the control of seated postural sway. We are not aware of any previous research on sex differences in seated postural activity. Accordingly, the effect illustrated in **Figure 3** appears to be novel.

The main effect of Control was significant for the width of the multifractal spectrum, confirming our prediction. The multifractal spectrum was wider (that is, postural activity exhibited a greater degree of multifractality) for Passengers than for Drivers. Differences in postural activity between seated Drivers and Passengers in virtual vehicles have been reported in previous studies in which virtual vehicles were presented *via* a desktop monitor. Dong et al. (2011) found that postural activity of Drivers and Passengers differed in terms of both the positional variability and temporal dynamics of the head and the torso. A similar effect has been reported for seated participants who controlled the gait of a virtual avatar vs. participants who merely watched recorded locomotion of the avatar (Chen et al., 2012). Chen et al. also found control-related differences in the positional variability of the torso and the temporal dynamics of the head. That movement might differ between Drivers and Passengers is not surprising. Because Drivers control the virtual vehicle, their postural adjustments related to vehicle motion can be anticipatory. For Passengers, postural adjustments for motion of the virtual vehicle must be compensatory (Dong et al.; Stoffregen et al., 2017).

Postural Precursors of Motion Sickness

We identified postural precursors of motion sickness in the positional variability of the head and torso. One such effect was a statistically significant Body Axis × Time Windows × Control × Sickness Groups interaction (**Figure 4**). This interaction reveals that the temporal evolution of postural precursors of motion sickness differed between Drivers and Passengers. This finding is novel. Dong et al. (2011) found that the temporal evolution of movement differed over time (i.e., across Time Windows) between Drivers and Passengers. In a separate effect, they found that the temporal evolution of movement differed between the well and sick groups; however, they found no evidence of any interaction between these factors. In the present study, our novel identification of this interaction may be related to the fact that our driving game was presented *via* an HMD, whereas in Dong et al., the driving video game was presented on a desktop monitor.

Our primary prediction was that there would be statistically significant interactions that would include the factors Sickness Groups, Sex, and Control. This prediction was confirmed in the statistically significant Body Axis × Segment × Control × Sex × Sickness Groups interaction (**Figure 5**). This effect reveals, for the first time, that sex can interact with vehicle control in determining postural precursors of motion sickness.

To summarize, in two statistically significant interactions, postural precursors of motion sickness differed between Drivers and Passengers (**Figures 4**, **5**). In one of these interactions, postural precursors of motion sickness that differed between Drivers and Passengers also differed between women and men (**Figure 5**). Several studies have identified sex differences in postural precursors of motion sickness (Koslucher et al., 2016a,b; Munafo et al., 2017), but this is the first demonstration that sex differences in postural precursors of motion sickness can differ between drivers and passengers. These effects confirm a prediction of the postural instability theory of motion sickness (Riccio and Stoffregen, 1991) that the kinematics of movement should differ between individuals who (later) report motion sickness and those who do not, and that these differences should exist before the onset of any subjective symptoms of motion sickness. The postural instability theory predicts that any factor that influences the control of posture can modulate postural precursors of motion sickness. The present results demonstrate that such individual differences can be situational, or task related (i.e., Drivers vs. Passengers; cf. Slobounov and Newell, 1994; Stoffregen et al., 1999), or structural (i.e., women vs. men). Our results are consistent with broader developments in the study of human movement, such as the claim that the subtle kinematics of movement may be unique to each individual (e.g., Slowinski et al., 2016). Other theories of motion sickness etiology (e.g., Reason, 1978; Oman, 1982) make no predictions about how postural precursors of motion sickness might be modulated by either situational or structural factors.

Interpupillary Distance: Cause or Correlate?

The Oculus Rift system fits persons with interpupillary distance (IPD) in the range 58–71 mm. Most adults fall within this range; however, 30% of adult women have IPD $<$59 mm (Stanney et al., 2020). Stanney et al. (2020) found that cybersickness was correlated with the "goodness" of IPD fit. However, based on this correlational finding, they did not claim that IPD played a causal role in cybersickness. If IPD were a causal factor in motion sickness among HMD users, then we would expect to see higher rates of sickness among populations that tend to have smaller IPD. One such population is children, who often are enthusiastic users of HMD systems. Thus, if motion sickness is caused by inappropriate matching between HMD design capabilities and users' IPD, then we would expect that HMD-related motion sickness would be especially common among children. We know of no evidence for differential rates of HMD-related sickness between children and adults. There is also an issue of etiology. A correlation between IPD and motion sickness susceptibility does not, by itself, imply any particular etiological interpretation. On the one hand, the discrepancy might be interpreted as a source of sensory conflict, such that the correlation between IPD and cybersickness might have a causal link through the sensory conflict theory of motion sickness (Reason, 1978; Oman, 1982). However, an interpretation in terms of sensory conflict is not mandatory. Different causal linkages can be proposed. It might be, for example, that improper fit of HMD headsets can undermine stable control of the body, which is more likely to have a causal relation to cybersickness. We predict that correlations should be stronger between motion sickness and postural kinematics than between motion sickness and IPD.

CONCLUSION

We examined the postural activity of seated participants during exposure to a driving video game presented through an HMD. We covaried sex (women vs. men), vehicle control (Drivers vs. Passengers), and motion sickness status (as reported by Curry et al., 2020a). Analysis of the positional variability of head and torso movement revealed differences between Drivers and Passengers in the temporal evolution of postural precursors of motion sickness. In a separate effect, postural precursors of motion sickness that differed between Drivers and Passengers co-varied as a function of sex. These results are in agreement with the general hypothesis that motion sickness is preceded by patterns of postural activity that differ between individuals who (later) report motion sickness and those who do not. In addition, these results reveal that the nature of postural precursors of motion sickness can differ between the sexes and between Drivers and Passengers. In general, the results are consistent with predictions derived from the postural instability theory of motion sickness (Riccio and Stoffregen, 1991).

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://doi.org/10.13020/a9w0-8k04.

ETHICS STATEMENT

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

AUTHOR CONTRIBUTIONS

CC, RL, and TS developed the study concept and design. CC, NP, and RL performed the testing and data collection. CC, NP, and TS contributed to the manuscript draft. RL contributed to the study concept and design. All authors approved the final version of the manuscript for submission and performed the data analysis and interpretation.

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frontiers in Virtual Reality

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Static Rest Frame to Improve Postural Stability in Virtual and Augmented Reality

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Many users have shown increased postural instability while using Head-Mounted Displays (HMDs) as HMDs block their real-world vision. People with balance impairments are especially more affected by this as they depend more on their visual cues to maintain their balance. In addition, balance is a good indication of cybersickness according to postural instability theory. In this research, we have investigated how to use additional visual cues to improve postural stability. Through conducting one user study in Virtual Reality (VR) and Augmented Reality (AR), we have studied the effect of a Static Rest Frame (SRF) on postural stability in persons with balance impairments due to Multiple Sclerosis (MS). Results indicate that an SRF significantly improves postural stability in VR and AR for users with MS. Based on these results, we propose guidelines for designing more accessible VR and AR systems for persons with balance impairments.

Keywords: balance, postural stability, accessibility, multiple sclerosis, cybersickness, virtual reality, augmented reality, head-mounted display

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1 INTRODUCTION

Many consumer-level head-mounted displays (HMDs) are currently available and/or in development used by a diverse population, including users with balance impairments. Previous research has shown that HMDs (e.g., the Oculus, 2020) can potentially hinder the balance of users with balance impairments while standing or walking as HMDs blocks peripheral vision (Guo et al., 2014). However, there is not enough research targeted to solve this problem. We aim to improve the postural stability in Virtual Reality (VR) and Augmented Reality (AR) for persons with balance impairments in this research.

Many rehabilitation programs use VR to improve balance for people with balance impairments (Sveistrup et al., 2003; Fulk, 2005; Lozano-Quilis et al., 2013; Nilsagård et al., 2013). However, VR that uses HMDs often negatively affects the balance of users with balance impairments. Therefore, HMDs are not popular in rehabilitation programs. Instead, projectors or large screens are mostly used as display media in these programs. Previous research shows that HMDs are more immersive than projectors and users may experience a higher presence (Moreno and Mayer, 2002).

Abbreviations: ABC, Activities-Specific Balance Confidence; AR, Augmented Reality; EC, Eyes Closed; EO, Eyes Open; EDSS, Expanded Disability Status Scale; FB, Functional Balance; QSB, Quiet Stance Balance; SRF, Static Rest Frame; SSQ, Simulator Sickness Questionnaire; VE, Virtual Environment; VR, Virtual Reality.

Hypothetically, HMDs could engage participants more effectively. Therefore, the imbalance problems of users with balance impairments while wearing HMDs need to be addressed.

Previous research shows that users have decreased postural stability in an immersive Virtual Environment (VE) that uses an HMD. Samaraweera et al. (Samaraweera et al., 2015) reported that participants have increased near falls and stumbles in VR. In other researches, positive effects of SRF were observed to improve presence (Prothero, 1998) and depth perception (Jones et al., 2013) and reduce cybersickness (Prothero, 1998; Chang E et al., 2013; LaViola, 2000). Based on these previous researches, we hypothesize that a Static Rest Frame (SRF), a subtle yet effective visual feedback, can improve postural stability. Baram et al. successfully demonstrated the positive effect of visual feedback on improving gait (i.e., walking patterns) for persons with balance impairments (Baram and Miller, 2006). Their research used a virtual grid on the floor to show that an additional visual cue, rendered from the perspective of the users' view, improved gait in persons with Multiple Sclerosis (MS). The reason can be that persons with vestibular (i.e., balance perception in the inner ear) impairments and neuropathy (e.g., numbness) depend more on their visual feedback to maintain balance (Corporaal et al., 2013). Therefore, additional visual cues may improve a user's postural stability. Being inspired by the previous work on the perceptual benefits of SRFs, our first study investigates how an SRF in an HMD affects postural stability for persons with balance impairments in VR.

To ensure undisturbed interaction in the VR, we wanted to use an SRF that minimally blocks the VE. Therefore, our SRF consists of five small static frames (one cross-hair in the middle and four L-shaped frames in four corners). **Figure 1** shows the static positioning of the SRF regardless of participants' left or right rotation. **Figure 1** also shows a dodgeball game used to analyze the effects of an SRF on the postural stability of persons with balance impairments.

In this article, we presented two studies to improve postural stability in VR and AR for persons with balance impairments, such as users with MS (see **Section 3.2.1**). The results of the VR study were published in a previous conference (Ferdous et al., 2016). The AR study data and results and the comparison between AR and VR study data are the unique contributions of this article. The VR study and results are also described in this article to provide the whole context. That is, **Section 4** extends the published work described in **Section 3**. For the first study, we recruited seven users without impairment and seven users with balance impairments caused by MS to examine the effect of SRF in VR. We analyzed their Quiet Stance Balance (QSB) and Functional Balance (FB) while in the VE. QSB is defined as standing balance on a stable support surface. It is inspired by the Romberg test (Khasnis and Gokula, 2003). In the Romberg test, participants have to stand still with their eyes closed, feet together, and arms at the side while their balances are measured. FB is inspired by the multidirectional reach test (Newton, 2001). In a multidirectional reach test, a participant has to reach the front and back and lean side to side to their maximum reach with his feet flat on the floor. In our study, we only investigated participants' FB for leaning side to side, which was proven to be an effective means of balance training (Bisson et al., 2007). Our first study results suggest that participants with balance impairments have a significantly improved balance in VR, while there is an SRF in the VE.

After discovering an SRF's benefits to balance in consumer-level VR HMDs, we hypothesized that an SRF might also have similar benefits in the latest consumer-level augmented reality HMDs, such as the Microsoft HoloLens. AR HMDs do not block the periphery as the VR HMDs do. Therefore, the participants will get an additional cue from their peripheral vision to maintain balance in AR HMDs. We ran a follow-up study to determine SRF's effect in AR. Additional visual feedback in augmented reality was useful in improving functional mobility for people with Parkinson's disease (Kaminsky et al., 2007). There are augmented reality cueing devices available for improving gait in patients with Parkinson's disease (Espay et al., 2010). Therefore, our result from the VR study and previous literature on using visual cues in augmented reality motivated us to investigate the effect of SRFs in AR. We found that the SRF improved balance in AR.

2 BACKGROUND AND RELATED WORK

2.1 Balance and Multiple Sclerosis

People rely on three inputs for maintaining balance: proprioception, vestibular organ information, and the major contributing factor, which is vision (Hansson et al., 2010). When the vision is limited, postural sway is increased in people with MS more than people without MS (Van Emmerik et al., 2010). Moreover, when vision is compromised, people rely more on proprioceptive feedback, and proprioceptive impairments often affect balance in patients with MS (Rougier et al., 2007). Therefore, altering the major contributing factor (i.e., vision) can potentially affect balance for people with MS. This also opens the possibility of providing additional visual cues to improve balance, where visual information is altered or insufficient.

2.2 Virtual Reality and Rehabilitation

VR is becoming popular in the rehabilitation of balance impairments. Fulk et al. used VR to improve gait speed, gait endurance, and balance improvement (Fulk, 2005). Lozano-Quilis et al. developed REOVIEM, a system that uses VR and natural user interfaces for motor rehabilitation exercises (Lozano-Quilis et al., 2013). Nilsagård et al. proved the usability of Nintendo Wii games for balance and gait rehabilitation (Nilsagård et al., 2013). Sveistrup et al. showed a comparison of a VR-delivered exercise program to a conventional exercise program for the rehabilitation of shoulder joint range of motion in patients with chronic frozen shoulder and discussed the possibility of using VR in rehabilitation (Sveistrup et al., 2003).

2.3 Balance in Immersive VR

It is unknown what causes an imbalance in HMDs or how to mitigate these effects, but it is known that many users often experience an increased imbalance in immersive VR with HMDs.

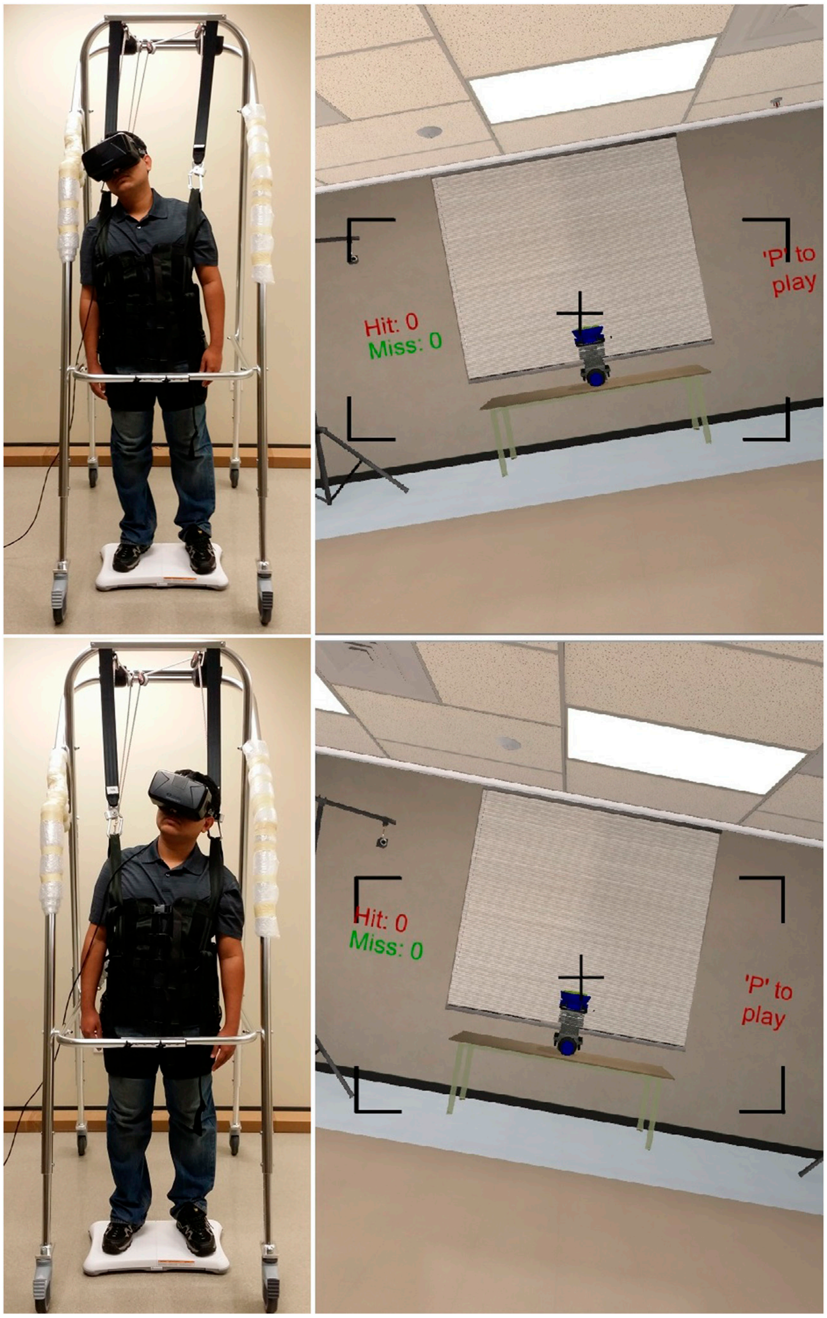

FIGURE 1 | A participant playing the dodge ball game and his view in VR with a static rest frame as he shifts his balance to the right or left. The figure shows an author who is posing as a participant. He gave consent to publish this image.

For example, for both persons without impairments and persons with balance impairments (Guo et al., 2014), Samaraweera et al. (Samaraweera et al., 2013) found that most users experienced reduced gait (i.e., walking patterns) performance; for example, they walked slower and took shorter strides in VR compared to the real environment. This could be indicative of more cautious behavior due to increased imbalance. Kennedy et al. showed that postural instability due to VR exposure is similar to alcohol-induced ataxia (Kennedy and Stanney, 1996). They developed an objective measurement of postural stability based on head movement to certify a VR system's safety. Horlings et al. reported that VR causes an increase in postural sway in amplitude similar to that caused by closing the eyes (Horlings et al., 2009). The postural instability can linger even after the completion of VR exposure (Champney et al., 2007).

2.4 Cybersickness and Balance

The postural instability theory is a widely cited theory that describes postural instability as a cause of cybersickness (Riccio and Stoffregen, 1991). Riccio et al. categorized the environmental situations responsible for postural instability into four categories: low-frequency vibration, weightlessness, changing relationships between the gravitoinertial force vector and the surface of support, and altered specificity. LaViola et al. suggested altered specificity to be the cause of cybersickness (LaViola, 2000). In an altered specificity situation, Riccio et al. described that a person might exert muscular efforts to resist an optically specified acceleration. Moreover, overall body posture is strongly influenced by optical stimulation (Lee and Lishman, 1975). Persons with MS face more difficulty in muscular movement than persons without impairment (Bakshi, 2003) and have worse balance in VR. Thus, persons with MS may be more prone to cybersickness than persons without impairment.

Kennedy et al. developed the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993), which is widely used to measure cybersickness. SSQ measures cybersickness using three subscales: *Nausea*, *Oculomotor*, and *Disorientation*. Kennedy et al. reported that disorientation is strongly correlated with postural stability (Kenney et al., 1997).

2.5 SRF to Reduce Cybersickness

Prothero showed that SRFs could improve persons' presence and reduce cybersickness in VEs (Prothero, 1998). He argued that humans have a strong perception of stationary things (e.g., we perceive the earth as stationary). He asserted that humans interpret relative motion to find if an object is moving. Therefore, humans need a rest frame to imply if the object in question is moving. In real life, the earth's surface works as a rest frame, and we perceive relative motion with respect to the earth's surface. Therefore, we hypothesize that additional static rest visual cues may aid in persons' balance. Results from Prothero's study support the hypothesis that the inclusion of an SRF improves presence and reduces cybersickness. His findings of improved presence motivated us to research the balance of persons in VEs.

Chang et al. demonstrated that an SRF consisting of one or several frames can be beneficial to lessen cybersickness indications (Chang E et al., 2013). They presented that the presence of an SRF changes one's perception of the VE, and this change of perception may be the cause of reduced cybersickness. Therefore, with the change of perception, the SRF may impact the balance of a person.

2.6 SRF to Improve Depth Perception

Jones et al. showed that applying static white light at the periphery of the VE display improves a person's ability to judge distance (Jones et al., 2013). The static light was also useful when a person estimates virtual space size using a visual scale task. Distance judgment ability or depth perception plays an essential role in a person's balance (Lord, 2006). Therefore, the finding of Jones et al. in improving depth perception using a static light may also be applicable to improve balance. A similar effect may be achieved using an SRF as it is also static though it uses frames instead of lights.

All of the works described before in this section successfully used an SRF in different aspects of VR (e.g., presence, cybersickness, and depth perception). However, none of these previous researches focused on the balance of users in VR. Therefore, the success of previous researches leads us to the primary research goal of our first study, that is, investigating the effect of an SRF in VR on QSB and FB of users, primarily focusing on users with MS.

2.7 Augmented Reality and Rehabilitation

In general, showing additional visual cues in AR can help improve the mobility of people with mobility impairments. For example, AR was found to be useful in improving functional mobility for people with Parkinson's disease (Kaminsky et al., 2007). The authors used virtual cueing spectacles to mimic kinesia paradoxa—a sudden, brief period of mobility under certain circumstances (Banou, 2015). Kaminsky et al. used spectacles that consist of a light-emitting diode that generates a series of horizontal lines, and the lights are reflected off a lens into the wearer's eye. Other types of AR cueing devices have also been used to improve gait in people with Parkinson's disease (Espay et al., 2010). These authors used visual cues that mimic a life-size virtual checkerboard-tiled floor. These checkerboards have a similar impact as earth-stationary cues (i.e., a real tiled floor) for improving gait. Rather than gait, our research specifically investigates balance in AR and the effects of SRFs.

3 EFFECT OF STATIC REST FRAME IN VIRTUAL REALITY

As the first step of our investigation, we focus on improving accessibility in VR. Inspired by the background works described in **Section 2**, we aimed to investigate our hypotheses with the help of a game we designed. The following subsections will describe our VR study in detail.

3.1 Hypotheses

The goal of this research is to improve the postural stability in VR and AR for persons with balance impairments. We broke down our research goal into two parts and conducted two studies: a VR study and an AR study. As a part of the VR study, we need to analyze each person's QSB and FB in VR and find out the effect of the SRF on balance. Based on the known advantages of SRFs from the literature, the following hypotheses are to investigate the effects of SRFs on balance in VR:

H1: An SRF will significantly improve balance in VR for users with balance impairments.
H2: The balance of persons with balance impairment will be more affected by VE than that of persons without balance impairments.
H3: Persons with balance impairment experience different levels of severity of cybersickness compared to persons without impairments.

TABLE 1 | Descriptive statistics for participants' information.

Participant group	No. of males	No. of females	Age (Years)	Weight (lbs.)	EDSS
			Mean (SD)	Mean (SD)	Mean (SD)
Participants with MS	0	7	51 (6.1)	187 (74.4)	4.43 (0.19)
Participants without impairment	2	5	56 (9.9)	193 (39)	

3.2 Methods

3.2.1 Participants and Selection Criteria

For the first study, we recruited seven participants without impairment and seven participants with MS to investigate the effect of the SRF while in VR on their QSB and FB. All participants were informed of the study procedure, and they provided written consent in accordance with the Institutional Review Board of the University of Texas at San Antonio (UTSA IRB #14–095). The experimental group consisted of persons with MS, and the control group was comprised of persons without any balance impairment. The participants without impairment came from a similar demographic background and had similar height and weight to the participants with MS. Every participant had a normal or corrected to normal vision. To keep the level of disability for the persons with MS homogeneous, we recruited persons who had an Expanded Disability Status Scale (EDSS) (Kurtzke, 1983) between 3 and 4.5. EDSS is measured from 0 to 10, where 0 means normal neurological state and 10 means death due to MS. Any person with severely blurred vision, vestibular diseases (non-MS related), psychiatric disorders, cognitive impairment, or cardiovascular and respiratory disorders were excluded from the study. **Table 1** shows the mean (SD) age, EDSS, and other detailed information about the participants.

3.2.2 Study Conditions

QSB and FB in VR are the conditions that we examined in this study. QSB data were assessed with the SRF (QSB-SRF) and without the SRF (QSB-NoSRF) in the VE (see **Section 3.2.4**). FB data were also measured with the SRF (FB-SRF) and without the SRF (FB-NoSRF). The order of the subconditions (with or without the SRF) was counterbalanced and assigned randomly among the participants. In addition to these conditions, there were two baseline conditions in our study: Eyes Open (EO) balance and Eyes Closed (EC) balance. We compared the data from QSB-SRF and QSB-NoSRF conditions with the baseline conditions. Berg Balance Scale (Berg et al., 1989) and Tinetti Performance-Oriented Mobility Assessment (Tinetti, 1986) showed that EO and EC are effective measurements of balance.

We developed a virtual representation of the physical room where the experiment took place. Participants experienced the virtual representation in QSB-SRF and QSB-NoSRF conditions while their balances were being measured. In FB-SRF and FB-NoSRF conditions, they played a VR game where a virtual bowling machine shot tennis balls toward their heads and they dodged the balls by moving their head from side to side.

3.2.3 System Description

We designed a system with a Nintendo Wii Fit Balance Board to measure the participants' balance in different study conditions as described earlier (see **Section 3.2.2**). Many studies showed the validity and reliability of the Wii balance board as an effective tool to measure balance (Clark et al., 2010; Chang WD et al., 2013). We supported all the participants with a harness attached to a partial weight-bearing support system to prevent them from sudden falls as half of our participants have mobility impairments. Both the harness and the suspension system were from (Kaye Products Inc, 2020).

The VR system was designed using Unity 5, a multiplatform game development system from Unity Technologies. The fully immersive VEs were rendered using an Oculus Rift DK2, an HMD developed by Oculus VR. The Oculus Rift DK2 has a resolution of 960 × 1,080 pixels per eye with a refresh rate of 60 Hz and a 100° field of view (FoV). Microsoft Kinect ^{2}V tracked the movement of the participants using the depth sensor. Kinect ^{2}V has a depth resolution of 512 × 424 pixels with a 30 Hz refresh rate and 70 × 60 FoV.

A high-performance computer generated the VEs and recorded the data of the experiment. The system was equipped with Intel Core i7 processor (2.50 GHz), 16 GB DDR3 RAM, NVIDIA GeForce GTX 860M graphics card with 2 GB of dedicated video memory, and a Windows 8.1 Pro operating system.

3.2.4 Virtual Environment

We developed a VE that was a virtual representation of the room where the experiment took place. According to previous studies, participants feel a higher presence in a VE if the VE is similar to the surrounding physical room (Bouchard et al., 2006). **Figure 2** shows the VE with the SRF. In our VR system, participants moved their upper body to move an avatar's upper body in the VE. Participants' joints from the hips up were tracked by a Kinect depth sensor, and the avatar's respective joints replicated the participants' movement. As the participant's lower body remained in a fixed position during the game and the Kinect joint data for the lower body were less accurate, the lower body from the hips down was not tracked. **Figure 3** shows a participant's view when he looks down to see his body and extends his arm to experience the responsiveness of the avatar's hand movement.

In FB-SRF and FB-NoSRF conditions, participants played a dodgeball game. There was a virtual bowling machine that shot virtual tennis balls toward a participant's head. Participants lean on left or right while maintaining their balance to avoid the balls from hitting them in the face. The virtual bowling machine shot one ball every 1.5 s, and the ball took 1 s to travel from the bowling machine to the participant's head. The game determined the position of the participant's head using Kinect at the time of

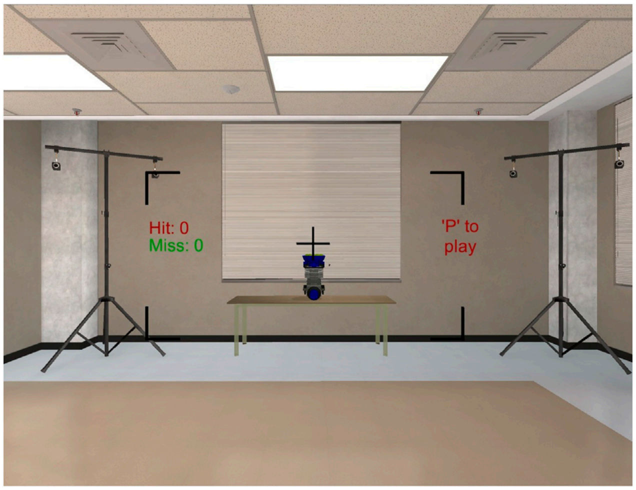

FIGURE 2 | The VE observed by the participants through HMD with an SRF.

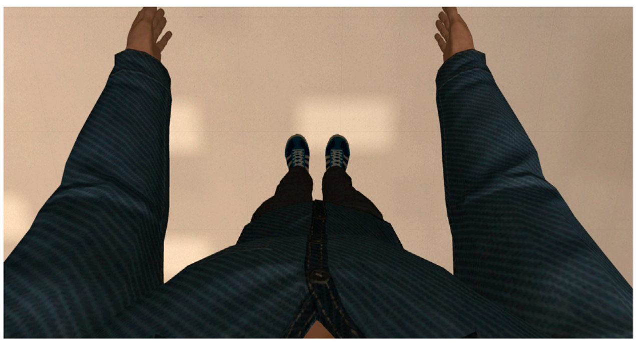

FIGURE 3 | Participants' view of their avatar when they look down and extend their arms to experience responsiveness of the avatar arms with the movement of their arms.

the shooting and shot the ball in the direction of the participant's head. As the participant just dodged the previous ball by leaning on one side (left or right), the next ball will go toward that side (left or right). Therefore, the participant had to move to the other side to dodge the next ball. To break this rhythm, after shooting ten balls, the virtual machine paused for 1 s before shooting another set of ten balls. Participants heard different auditory feedback based on *hit* or *miss*. **Figure 1** shows a participant playing the game. The game showed the scores (e.g., number of *hits* and *misses*) and information about the game on the wall of the virtual room. The total duration of the game was 120 balls. We used tennis balls that were well-textured, randomly rotated around their own axis, and illuminated using spotlights. This was done to facilitate depth perception in the game. A real-time reflection probe in the VE also increased depth perception by changing the lighting of the floor with the movement of participants. Participants played the game in two conditions, with the SRF and without the SRF. **Figure 4** shows a virtual bowling machine, which is shooting tennis balls in a VE without the SRF condition. The frame rate of the game was approximately 60 FPS.

3.2.5 Study Procedure

The study procedure consisted of the following five consecutive steps.

3.2.5.1 Consent and Prestudy Questionnaire

A participant started the study by signing a consent form, filling out an Activities-Specific Balance Confidence (ABC) (Powell and Myers, 1995) and a SSQ.

3.2.5.2 Baseline Data Measurement

We measured two baseline balance data conditions in the study: EO and EC. Participants stood quietly on a Wii Fit Balance Board, gazed straight ahead with eyes open. Their balance data were measured for 40 s. The same process was repeated for the EC condition. Participants were supported by a harness the whole time. The order of the EO and EC was counterbalanced. Between the two conditions, participants were released from the harness, and they sat for at least 1 min to rest.

3.2.5.3 Quiet Stance Balance Measurement

The process for measuring the QSB is the same as the EO balance. Instead of observing the real room, participants observed the virtual representation of the room using an HMD. This process was repeated with and without the SRF, and their order is counterbalanced. In these conditions, their balance data were measured with the Wii balance board for 40 s. Again, they rested for at least 1 min between the conditions.

3.2.5.4 Functional Balance Measurement

To measure FB, we instructed the participants to play the virtual dodge ball game (see **Section 3.2.2**). First, there was a 1 min training mode for the game. The purpose of the game is to make

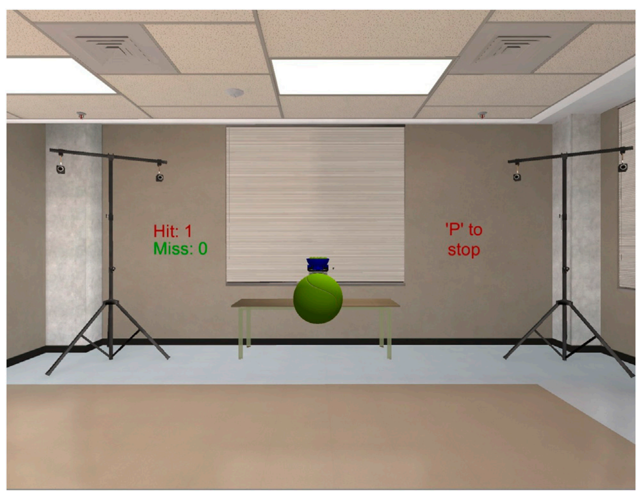

FIGURE 4 | Bowling machine is shooting balls toward the head of the participants. This VE does not have the SRF.

the participants comfortable with the gameplay. Once they were comfortable with the game, data measurement began while they played the game for 3 min. This process was repeated with and without the SRF, and their order is counterbalanced. One-minute rest was given between the conditions.

3.2.5.5 Poststudy Questionnaire

Participants ended the study by filling out an SSQ followed by an ABC. They received a payment of $50 after that. The average duration of the whole study for a single participant was 45 min.

3.3 Metrics

3.3.1 Imbalance Count

Previous studies have shown that to get valid balance data from a Wii balance board, we should sample the data at 10 Hz (Salavati et al., 2009). Following this guideline, we obtained pressure data from four pressure sensors of the Wii balance board at a 10 Hz sample rate. Calculating the average of these pressure sensors' data, we got the participants' weight distribution data. As participants were instructed to maintain their balance, their weight in any sample is expected to be within three standard deviations from the mean, assuming that their weight data are normally distributed. Moreover, 99.7 percent of the data were within three standard deviations away from the mean in a normal distribution. Therefore, if the weight data in any sample are more than three standard deviations away from the mean, we consider the participant to be imbalanced. However, if two or more consecutive sample data points show imbalance (e.g., balance data are three standard deviations away in both samples from 10.1 s to 10.2 s), we count it as one *imbalance* as the participant did not get their balance back in the meantime. The following equation shows us how to find an *imbalance*:

$$Imbalance(i) = \begin{cases} 1 & \textbf{if } Weight(i) \text{ is 3 SD away from Mean} \\ & \textbf{AND } Imbalance(i-1) \neq 1 \\ 0 & otherwise \end{cases} \qquad (1)$$

The total count of these imbalances gives us a measurement of a participant's balance in VR. The following equation shows how to calculate an *imbalance count* for a participant:

$$Imbalance\ Count = \sum_{t=15}^{165} Imbalance(t) \qquad (2)$$

The imbalances were counted for 150 s (from 15th second to 165th second). The first 15 s and last 15 s of each session were excluded from the result as data can be more error-prone at the beginning and the end of the study. Participants were fit enough to work for a full day and rested well between conditions. Therefore, the imbalance count was minimally affected by fatigue.

3.3.2 Center of Pressure Path

Center of Pressure (COP) was calculated from four weight sensors in the Wii board using the following equation developed by Young et al. (2011):

$$COP(X, Y) = \frac{\sum_{i=1}^{4} Weight_i * (x_i, y_i)}{\sum_{i=1}^{4} Weight_i}, \qquad (3)$$

where (x_i, y_i) is the coordinates of the pressure sensor *i*, $Weight_i$ is the weight or pressure data on *i*th sensor, and $COP(X, Y)$ is the coordinates of the *COP*.

COP was sampled at 10 Hz, and it may change from one sample to the next consecutive sample. The Euclidean distance between one sample's *COP* to the next sample's *COP* is called a *path*. Taking the summation of all of these paths derived from all of the samples gives us the *COP path*. *COP Path* is calculated using the following equation:

$$COP\ Path = \sum_{i=1}^{n-1} \sqrt{(COP_{i+1}X - COP_iX)^2 + (COP_{i+1}Y - COP_iY)^2}, \qquad (4)$$

where COP_iX and COP_iY are the *X* coordinate and *Y* coordinate of COP at *i*th second, respectively.

3.3.3 Simulator Sickness Questionnaire

Simulator Sickness Questionnaire (SSQ) is a sixteen-item questionnaire where each item asks about participants' different physiological discomfort (Kennedy et al., 1993). Each item can be rated from *None* to *Severe*, where *None* quantifies as 0 and *Severe* quantifies as 3 toward the calculation of *SSQ*. *SSQ* has three subscales of scores: *Nausea*, *Oculomotor*, and *Disorientation*. This *SSQ score* is calculated from these three subscales. The following equations are used to calculate the *SSQ score* (Kennedy et al., 1993):

$$Nausea\ Sum = Q1 + Q6 + Q7 + Q8 + Q9 + Q15 + Q16 \qquad (5)$$

$$Nausea\ Score = Nausea\ Sum * 9.54 \qquad (6)$$

$$Oculomotor\ Sum = Q1 + Q2 + Q3 + Q4 + Q5 + Q9 + Q11 \qquad (7)$$

$$Oculomotor\ Score = Oculomotor\ Sum * 7.58 \qquad (8)$$

$$Disorient^n\ Sum = Q5 + Q8 + Q10 + Q11 + Q12 + Q13 + Q14 \qquad (9)$$

$$Disorient^n\ Score = Disorient^n\ Sum * 13.92 \qquad (10)$$

$$SSQ\ Sum = Nausea\ Sum + Oculomotor\ Sum + Disorient^n\ Sum \qquad (11)$$

$$SSQ\ Score = SSQ\ Sum * 3.74, \qquad (12)$$

where *Q*1 is the score of question 1.

3.3.4 Activities-Specific Balance Confidence Scale

Activities-Specific Balance Confidence Scale (ABC) is a sixteen-item questionnaire where each item asks about participants' confidence in doing a specific daily life activity (Powell and Myers, 1995). Each item can be rated from 0% to 100%, where 0% is *no confidence* and 100% is *complete confidence*. The average of the ratings of these sixteen questions generates the total *ABC score*.

3.3.5 Hit Count (Game Performance)

Hit count denotes how many times any participant failed to dodge the ball while they were playing the game.

3.4 Statistical Analysis

We compared the FB-NoSRF data with the FB-SRF data of both groups. We also compared both groups' QSB-SRF and QSB-NoSRF data with EO baseline data. For FB data, we only

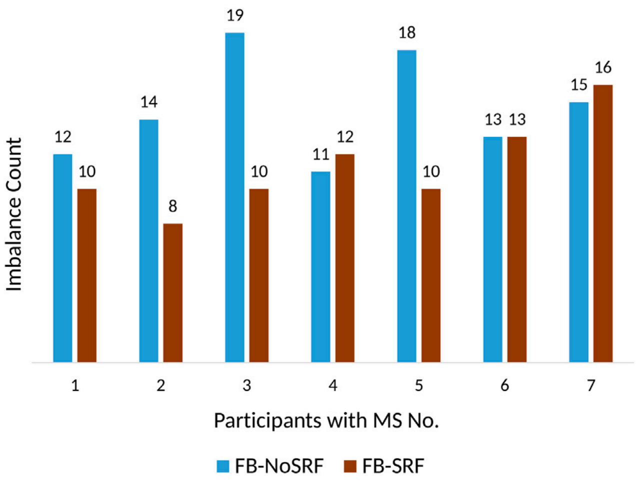

FIGURE 5 | Imbalance count of participants with MS in FB-NoSRF and FB-SRF condition in the VR study.

considered the data for 150 s (from 15th second to 165th second), whereas for QSB data, we considered the data for 30 s (from the 5th second to 35th second). All the statistical analyses were performed using *IBM SPSS version 19*. We used a Mixed Model ANOVA and then used one-tailed paired sample *t*-tests with *p* values adjusted with Bonferroni correction as needed for *post hoc* analysis of within-group comparisons. For between-group comparisons, we used independent sample *t*-tests.

3.5 Results

3.5.1 Imbalance Count

We ran a paired sample *t*-test between the *Imbalance Count* of FB-SRF and FB-NoSRF conditions for both participants with MS and participants without impairments. For participants with MS, the result shows a significantly improved balance in FB-SRF ($M = 11.28$, $SD = 2.62$) to FB-NoSRF ($M = 14.57$, $SD = 2.99$) condition; $t(6) = 2.02$, $p = 0.045$. However, for participants without impairment, there is no significant difference between FB-SRF ($M = 14.57$, $SD = 4.85$) and FB-NoSRF ($M = 12.42$, $SD = 3.90$) conditions; $t(6) = 1.205$, $p = 0.137$. It is worth mentioning that the *imbalance count* of participants without impairment is not negligible as all of them are elderly persons, and postural instability increases with age (Abrahamova and Hlavacka, 2008).

Figure 5 shows the change of *imbalance count* of participants with MS in FB-SRF and FB-NoSRF conditions. Most of the participants with MS showed improvement in their balance in the FB-SRF condition.

3.5.2 Center of Pressure Path

We ran an independent sample *t*-test on participants' QSB-NoSRF *COP path* and baseline EO *COP path*. The between-group results show that participants with MS ($M = 36.83$, $SD = 16.79$) do not have a significantly different EO COP path compared to the participants without impairment ($M = 24.37$, $SD = 6.63$) ($t(12) = 1.82$, $p = 0.093$). However, participants with MS ($M = 42.87$, $SD = 21.56$) have a significantly more deficient QSB-NoSRF than that of participants without impairment ($M = 23.69$, $SD = 5.93$) ($t(12) = 2.27$, $p = 0.043$).

Figure 6 shows that the mean *COP path* of QSB-NoSRF is larger in participants with MS than that of participants without impairment. However, the mean *COP path* from EO to QSB-NoSRF increased more for the participants with MS compared to the participants without impairment.

3.5.3 Simulator Sickness Questionnaire

We ran an independent sample *t*-test on different *SSQ* subscales and total *SSQ* scores between groups. The results show that only the postexposure *disorientation* score is significantly higher ($t(12) = 2.34$, $p = 0.04$) in participants with MS than that of participants without impairment. **Table 2** shows the mean (SD) and the significance level of pre- and postexposure *SSQ* subscales and total score for participants with MS and participants without impairment.

3.5.4 ABC Questionnaire

For participants with MS, the paired sample *t*-test shows a significant improvement from preexposure *ABC* ($M = 67.27$, $SD = 19.57$) to postexposure *ABC* score ($M = 70.71$, $SD = 19.93$) ($t(6) = 2.81$, $p = 0.015$). However, for participants without impairment, we did not notice any significant difference from preexposure *ABC* ($M = 96.25$, $SD = 3.49$) to postexposure *ABC* score ($M = 96.07$, $SD = 3.65$) ($t(6) = 1.55$, $p = 0.086$).

3.5.5 Hit Count (Game Performance)

Paired sample *t*-test between the *hit count* with the SRF and without the SRF in the VE shows that hit counts do not have a significant difference between with the SRF and without the SRF conditions for both participants with MS ($t(6) = 0.927$, $p = 0.39$) and participants without impairment ($t(6) = 0.717$, $p = 0.5$). **Table 3** shows the mean (SD) and the significance level of *hit count* with the SRF and without the SRF conditions for participants with MS and participants without impairment.

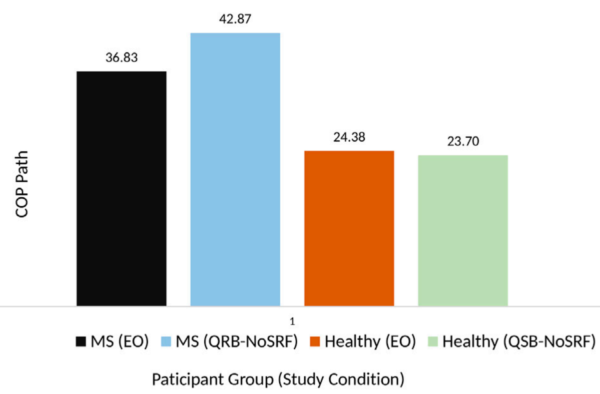

FIGURE 6 | COP path (EO and QSB) comparison between participant groups in VR.

TABLE 2 | Descriptive statistics for SSQ.

Subscale	Participants with MS	Participants without impairment	Significance level
	Mean (SD)	Mean (SD)	
Nausea (pre)	19.08 (18.26)	4.08 (7.50)	0.07
Nausea (post)	13.62 (13.33)	4.08 (7.50)	0.12
Oculomotor (pre)	37.90 (25.89)	14.07 (22.06)	0.09
Oculomotor (post)	30.32 (17.50)	16.24 (22.92)	0.22
Disorientation (pre)	29.40 (27.22)	7.95 (13.58)	0.09
Disorientation (post)	37.87 (29.76)	7.95 (15.78)	0.04
Total (pre)	34.19 (26.03)	10.68 (17.06)	0.07
Total (post)	30.45 (20.64)	11.75 (18.12)	0.10

TABLE 3 | Descriptive statistics for hit count.

Participant group	Hit count without SRF	Hit count with SRF	Significance level
	Mean (SD)	Mean (SD)	
Participants with MS	15.43 (11.14)	11.28 (8.24)	0.39
Participants without impairment	14.00 (13.76)	10.14 (8.36)	0.5

3.6 Discussion

3.6.1 Effect of SRF on Balance

Results from *imbalance count* suggest that including an SRF in a VE can improve the balance of persons with MS while they are immersed in a VE. Therefore, we can accept hypothesis 1. One reason for this could be that the SRF improves the depth perception of some individuals (Jones et al., 2013). Moreover, some individuals need SRF to make proper judgments of object movement (Prothero, 1998). Therefore, the presence of an SRF helps the participants with MS to complement their need for visual feedback to maintain their balance. However, the SRF may not improve the balance of the participants without impairment. The reason for this could be that persons without impairment rely less on their visual cues than persons with MS to maintain their balance (Corporaal et al., 2013). Therefore, persons without impairment may not benefit from additional visual cues. Adding an SRF that assists the balance of a person with MS may not affect the functionality of the VE as results from *hit count* (game performance) show that there is no significant difference. This is likely because the SRF takes a tiny portion of the VE and minimally obstructs participants' views in the VE (**Figure 2**).

3.6.2 Balance Comparison Between the Virtual and Real World

Our results from the *COP path* show that the participants with MS have worse QSB-NoSRF than participants without impairment in VR. The reason for this could be that when persons with balance impairments wear an HMD, they lose the visual cues that help them to maintain their balance. Persons with MS rely more on their visual cues than persons without impairment to maintain their balance (Corporaal et al., 2013). Therefore, with the absence of visual feedback, persons without impairment can maintain their balance using somatosensory and vestibular feedback that compensate for visual feedback, whereas persons with MS fail to do so. Therefore, we can accept hypothesis 2. This finding supports related works' previous results (Samaraweera et al., 2013; Guo et al., 2014). However, the previous works analyzed the gait of participants as balance measurement, where we analyzed the QSB and FB. Therefore, our finding provides contributions that complement previous findings.

3.6.3 Cybersickness

We did not find any significant differences in *SSQ* result other than for postexposure disorientation. The participants with MS had a little high preexposure SSQ (34.19 out of 235.62). It is not surprising since they are older adults (average age 51) with MS. For all the participants, the postexposure SSQ is very close to preexposure SSQ, and the difference is nonsignificant. The reason behind this could be that the SRF helps to reduce cybersickness in VR (Prothero, 1998; Chang E et al., 2013). In half of the time of the exposure, the VE had an SRF and did not generate any cybersickness. Therefore, this study setup was not suitable to find the effect of MS on cybersickness, and we cannot accept hypothesis 3. We plan to investigate hypothesis three in the future with a VE that induces more cybersickness by producing more sensory conflicts.

3.6.4 Confidence in Balance from VR Game

We have an interesting finding of the significant improvement of confidence in balance, based on the results from the *ABC* questionnaire. Note that this improvement results from playing the VR game only for 7–8 min. This is a very short time for actual improvement in balance. This raises the question of whether their confidence in balance is actually improved or this is just a temporary improvement after playing the game. A VR game with 30 min duration has been shown to be effective in improving short-term balance for persons with MS (Kalron and Frid, 2012). However, the minimum time required for an improvement in short-term balance is still unknown. We plan to investigate this in the future.

TABLE 4 | Descriptive statistics for participants' information.

Participant group	No. of males	No. of females	Age (Years)	Weight (lbs.)	EDSS
			Mean (SD)	Mean (SD)	Mean (SD)
Participants with MS	0	7	53 (5.6)	185 (69.1)	4.64 (0.51)

3.6.5 Effect of SRF on Game Performance

We did not find any significant difference in the *hit counts* between with the SRF and without the SRF conditions for both participants with MS and participants without impairment. This suggests that adding an SRF does not affect the game performance significantly.

4 EFFECT OF STATIC REST FRAME IN AUGMENTED REALITY

After getting positive results from our SRF in the VR study, we conducted a follow-up study to investigate the effects of an SRF in AR. The following subsections describe our AR study in detail.

4.1 Hypotheses

The goal of this study is to investigate the effect of an SRF on balance in AR. Based on the results we obtained from the previous VR study and the known advantages of SRFs from the literature, the following hypotheses are to investigate the effects of SRFs on balance in AR:

H1: An SRF will significantly improve balance in AR for users with balance impairments.
H2: Users with balance impairment will have a better balance in AR than VR.
H3: Persons with balance impairment experience less cybersickness in AR than VR.

4.2 Methods

4.2.1 Participants and Selection Criteria

We recruited the same seven participants with MS that we recruited for the VR study described in **Section 3.2.1**. However, the AR study was done after the VR study, and some of the participants had a slightly increased EDSS (Kurtzke, 1983) score. Therefore, the EDSS range was from 4.0 to 6.0. No participant had any problem in participating in the study, and nobody reported any fatigue. **Table 4** shows the mean, standard deviation (SD), weight, EDSS, and other detailed information about the participants.

4.2.2 Study Conditions

The study conditions were similar to the VR study described in **Section 3.2.2**. The only difference is that in QSB and FB conditions, the virtual model of the physical room is removed from the scene as participants can see the physical room in the AR simulation. The virtual bowling machine (see **Section 3.2.4**) was present in the environment.

4.2.3 System Description

To keep the studies comparable, we used the same hardware that we used for balance measurement, Nintendo Wii Fit Balance Board. We also used the same harness that we used in the earlier study to support the participants. The game was designed using the same version of Unity. The only difference was instead of Oculus Rift DK2, we used (Microsoft, 2020) to provide the augmented reality experience. Microsoft HoloLens has a 30 × 17.5° FoV (Kreylos, 2017). It has a refresh rate of 60 Hz and a maximum supported resolution of 1,268 × 720 pixels per eye. The same configuration computer was used to record the data.

4.2.4 Augmented Environment

The augmented environment is similar to the VE described in **Section 3.2.4**. However, as the participant can see the physical room, the virtual model of the room was not a part of the augmented environment. There was no avatar in the augmented environment as participants can see their own bodies in AR. In short, the only augmented components were the bowling machine parts, the scores, and the SRF (depending on the study conditions). **Figure 7** shows the augmented environment with the SRF. It may appear that the FoV in **Figure 7** is much smaller than the FoV in **Figure 2**. For the VR study (**Figure 2**), the picture was taken from a screenshot from Unity, and for the AR study (**Figure 7**), the picture was a screenshot from a video recording using HoloLens. However, the ball machine's distance, size, and ball's speed were the same if looked through the headsets.

In FB conditions, participants played the same dodge ball game where they dodge virtual tennis balls coming toward their heads. **Figure 8** shows a participant playing the game in AR. The size and speed of the balls, the distance from where the balls are coming from, the interval between two balls, and the pause between sets of ten balls were the same as in the VR study. The scores were shown in a similar fashion to the previous study. The audio feedback for hit or miss was similar to the VR study. **Figure 8** shows the virtual machine shooting virtual tennis balls in AR.

4.2.5 Study Procedure

The study procedure for the AR study was identical to the VR study with the following five steps:

1. Consent and Prestudy Questionnaire
2. Baseline Data Measurement
3. Quiet Stance Balance Measurement
4. Functional Balance Measurement
5. Poststudy Questionnaire

Please see **Section 3.2.5** for more details.

4.3 Metrics

We have used four metrics that are the same as the metrics we used for the VR study. Please see **Section 3.3** for more details. The metrics that are the same as the VR study are as follows:

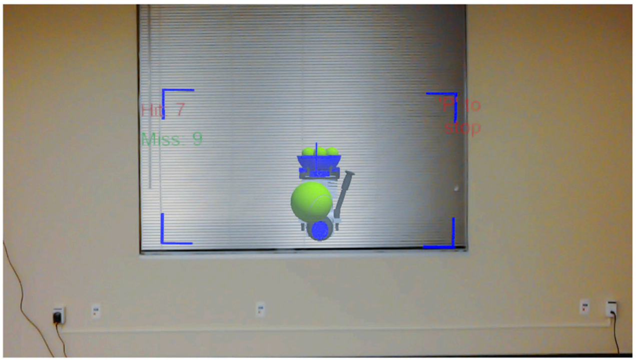

FIGURE 7 | Bowling machine is shooting balls toward the head of the participants. This augmented environment has SRF.

1. Imbalance Count
2. Center of Pressure path
3. Simulator Sickness Questionnaire
4. Activities-Specific Balance Confidence Scale

In addition to these metrics mentioned above, we have added the following metrics to compare the impact of VR and AR on balance:

5. Impact Ratio: *Impact Ratio* is the quotient between QSB and EO balance. It is motivated by Romberg ratio, where the quotient between EO and EC balance is taken as a measurement of visual dependency of balance (Kalron, 2017). For our study, we have taken the quotient between QSB-NoSRF and EO balance to normalize the effect of EO balance on QSB-NoSRF. The equation for calculating the *impact ratio* is as follows:

$$Impact\ Ratio = \frac{QSB - NoSRF\ COP\ Path}{EO\ COP\ Path}. \tag{13}$$

4.4 Statistical Analysis

We compared the FB-NoSRF data of participants with MS with FB-SRF data. We also compared their QSB-NoSRF and QSB-SRF data with their baseline EO data. Furthermore, to compare between studies (VR vs. AR), we compared the impact ratio, SSQ, and ABC data. All the statistical analyses were performed using IBM SPSS version 19. We used a Mixed Model ANOVA and then used one-tailed paired sample *t*-tests with *p* values adjusted with Bonferroni correction as needed for *post hoc* analysis of within-group comparisons. For between-study comparisons, we used independent sample *t*-tests.

4.5 Results

4.5.1. Imbalance Count

We ran a paired sample *t*-test and found out that there is a significant difference in *imbalance count* for *FB-NoSRF* ($M = 13.71$, $SD = 6.77$) and *FB-SRF* conditions ($M = 10.28$, $SD = 5.79$); $t(6) = 2.58$, $p = 0.02$. **Figure 9** shows the change of *imbalance count* of participants in FB-NoSRF and FB-SRF conditions. Most of the participants showed improvement in their balance with the presence of the SRF.

4.5.2 Center of Pressure Path

We ran a paired sample *t*-test and discovered no significant difference in *COP path* for *QSB-NoSRF* ($M = 36.17$, $SD = 16.60$) and *EO* ($M = 44.26$, $SD = 16.60$); $t(6) = 1.502$, $p = 0.092$. Similarly, we did not find any significant difference in paired sample *t*-test in *COP path* for *QSB-SRF* ($M = 31.85$, $SD = 10.75$) and *EO* ($M = 44.26$, $SD = 16.60$); $t(6) = 1.481$, $p = 0.094$. **Figure 10** shows how mean COP path changes in different study conditions in augmented reality.

For the between-study comparison, we compared their *impact ratio* as we have conducted the study at two different times and the participants had different EO balances. The impact ratio normalizes the effect of EO

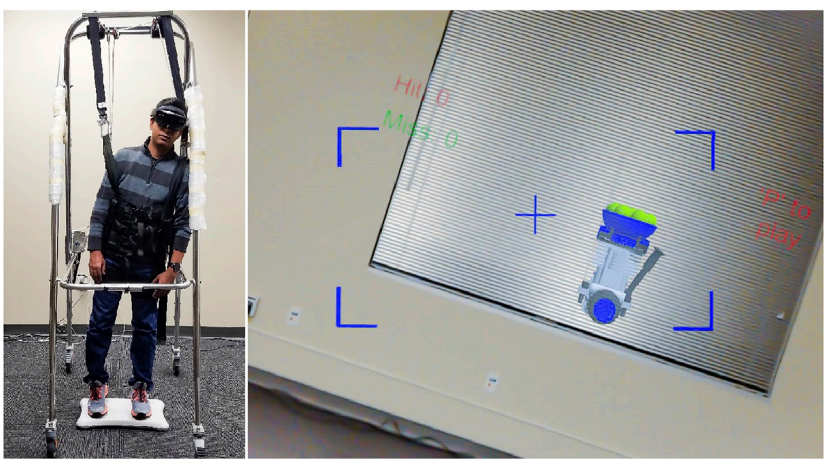

FIGURE 8 | A participant playing the dodge ball game and his view in the AR with an SRF as he shifts his balance to the left. The figure shows an author who is posing as a participant. He gave consent to publish this image.

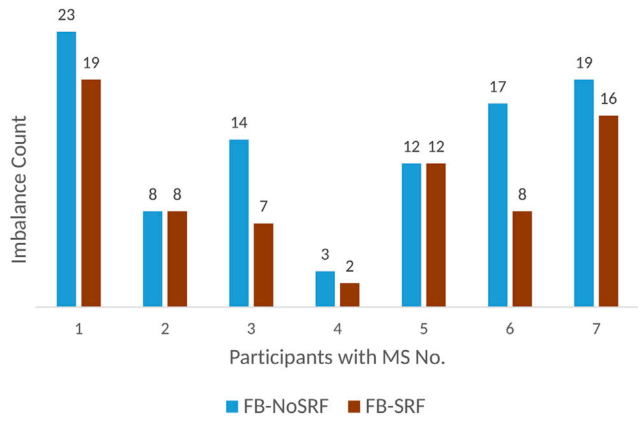

FIGURE 9 | Imbalance count of participants with MS in FB-NoSRF and FB-SRF conditions in the AR study.

balance on QSB. We conducted a paired sample *t*-test between the impact ratio of VR and AR study and discovered significant differences in impact ratio between VR ($M = 1.18$, $SD = 0.29$) and AR ($M = 0.85$, $SD = 0.25$) study; $t(6) = 2.5$, $p = 0.023$. **Figure 11** shows the comparison of the *impact ratio* of participants between VR and AR study.

4.5.3 Simulator Sickness Questionnaire

We ran a paired sample *t*-test on different SSQ subscales and total SSQ scores with before and after AR study data. We also ran an independent sample *t*-test between VR study and AR study data. However, there is no significant difference in any of the subscales or total SSQ scores in any test.

4.5.4 ABC Questionnaire

We ran a paired sample *t*-test on ABC score with before and after AR study data. We also ran an independent sample *t*-test between VR study and AR study data. However, there is no significant difference in ABC score within or between study data.

4.6. Discussion

4.6.1. Effect of SRF on Balance

Statistical results from *imbalance count* also suggest that SRF is beneficial to improve balance in AR as well as in VR. Therefore, we can accept hypothesis 1: a SRF will significantly improve balance in AR for users with balance impairments. The reason may be similar to the reason for balance improvement in VR that a person needs an SRF to make proper judgments of object movement (Prothero, 1998).

4.6.2 Balance Comparison Between Augmented and Virtual Reality

Unlike VR, participants' peripheral vision is not blocked in AR. Therefore, they can see the real world as well as the ball machine in the scene. The ball machine provides extra visual feedback to maintain their balance. The reason may be that vision is the most contributing factor in balance and AR is not blocking the periphery (Hansson et al., 2010). Moreover, optical see-through AR does not introduce latency for the real objects.

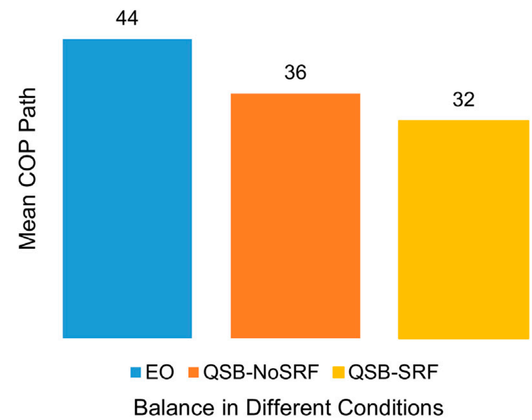

FIGURE 10 | COP path comparison between conditions in AR study.

QSB-SRF is also smaller than EO for all six of the participants who showed decreased COP path in QSB. However, there were no significant differences found in this comparison, possibly due to

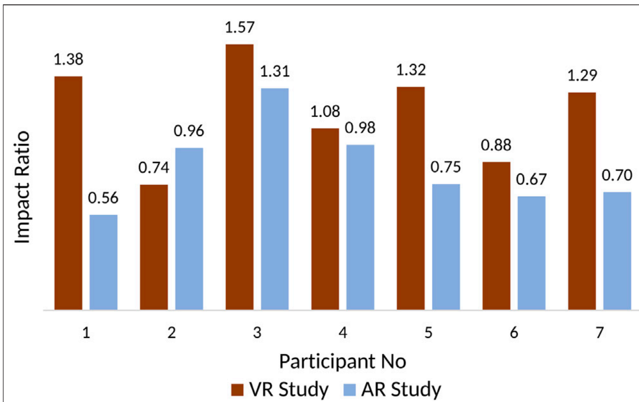

FIGURE 11 | Impact ratio of participants in VR and AR study.

our small sample size. Future studies with larger samples are needed to investigate this.

There is a significant difference observed between the impact ratio of VR and AR. Therefore, we can accept hypothesis 2: users with balance impairment will have a better balance in AR than VR. The reason could be the presence of peripheral vision feedback from the real world in AR—vision is the most contributing factor in balance (Hansson et al., 2010). Unlike VR, participants' peripheral vision is not blocked in AR. Therefore, they can see the real world as well as the ball machine in the scene. Their balances were not affected by the presence of the ball machine. Their balance is further improved in the QSB-SRF condition. Therefore, it is possible that the ball machine and the SRF provided them with more references that they already had in the real world to improve their balance.

4.6.3 Cybersickness

There were no significant differences observed in any of the subscales or the total SSQ score between VR and AR conditions. One reason can be the VE was simple, and there were not many changes in the visual information. Another reason can be that the duration of the VR exposure was short, and it was under the recommended time of 20 min (Kennedy et al., 2000). Therefore, for the lack of enough evidence, we cannot remark on cybersickness, and we cannot accept hypothesis 3: persons with balance impairment experience less cybersickness in AR than VR.

4.7 Study Limitations

There are some limitations to our study. There is a difference in the FoV between Oculus and HoloLens (see **Section 3.2.3** and **Section 4.2.3** for more details). The reason for our limitations is that there was no optical see-through AR display available that had a comparable FoV to the popular VR HMDs. In the future, similar studies can be conducted with video see-through HMDs that have been improving recently.

Another limitation of our study is that all of the participants with MS were females. The reason for this is that MS is three times more common in women than in men (MS-Society, 2020). We can expect to see similar results if we had male participants since postural stability does not depend on gender (Hageman et al., 1995).

We have some nonsignificant results, especially in SSQ. This can possibly be due to the small sample size. However, the main objective of this study is focused on postural stability, not cybersickness. Since our sample size achieved significant results for postural stability comparison, we did not increase our sample size. Another reason can be that SSQ is a subjective measurement and often can be affected by personal preference. That is, two persons with similar cybersickness may report differently in their SSQ questionnaire. We plan to include objective measures (e.g., heart rate variability (Zużewicz et al., 2011) and galvanic skin response (Kennedy et al., 2010)), in addition to SSQ, to have a comprehensive set of metrics for cybersickness analysis in our future studies.

5 CONCLUSION

The objective of our research is to improve the postural stability in VR and AR for users with balance impairments. To obtain a feasible solution, we investigated the effect of an SRF on the QSB and the FB of persons with MS in VR and AR. Our results suggest that the inclusion of an SRF will improve the balance for persons with balance impairments, while it has no significant impact on the balance of persons without impairment. Therefore, an option for adding an SRF will make VR that uses fully immersive HMDs more accessible. Our results show both VR and AR benefit from an SRF.

In the future, we plan to investigate how different types of visual feedback can affect balance and gait in VR and AR. The scope of this study was to analyze standing balance and functional balance while standing, as many of the rehabilitation games (e.g., Wii games) involve playing while you are standing in the same place. However, some games involve real walking. In the future, we also plan to investigate the effect of SRF on persons' gait and how it differs in persons with MS. As the SRF blocks a subtle portion of the environment, it may have some effect on presence. Thus, we also plan to investigate the SRF's impact on presence in the future. There are many VR-based rehabilitation exercises that are proved to be improving balance (Fulk, 2005; Nilsagård et al., 2013). It would be interesting to study in the future if adding an SRF in the VE can make VR rehabilitation more effective by reducing rehabilitation time.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

SF is the primary author of this article. He designed, developed the system, ran human subject studies, analyzed the data, and wrote the manuscript. TC and IA worked on the development and testing of the system as well as running human subject studies. JQ is their supervisory author who helped to edit the manuscript.

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Predicting Individual Susceptibility to Visually Induced Motion Sickness by Questionnaire

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Background: The introduction of new visual technologies increases the risk of visually induced motion sickness (VIMS). The aim was to evaluate the 6-item Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ; also known as the VIMSSQ-short) and other predictors for individual susceptibility to VIMS.

Methods: Healthy participants (10M + 20F), mean age 22.9 (SD 5.0) years, viewed a 360° panoramic city scene projected in the visual equivalent to the situation of rotating about an axis tilted from the vertical. The scene rotated at 0.2 Hz (72° s^{-1}), with a 'wobble' produced by superimposed 18° tilt on the rotational axis, with a field of view of 83.5°. Exposure was 10 min or until moderate nausea was reported. Simulator Sickness Questionnaire (SSQ) was the index of VIMS. Predictors/correlates were VIMSSQ, Motion Sickness Susceptibility Questionnaire (MSSQ), migraine (scale), syncope, Social & Work Impact of Dizziness (SWID), sleep quality/disturbance, personality ("Big Five" TIPI), a prior multisensory Stepping-Vection test, and vection during exposure.

Results: The VIMSSQ had good scale reliability (Cronbach's alpha = 0.84) and correlated significantly with the SSQ (r = 0.58). Higher MSSQ, migraine, syncope, and SWID also correlated significantly with SSQ. Other variables had no significant relationships with SSQ. Regression models showed that the VIMSSQ predicted 34% of the individual variation of VIMS, increasing to 56% as MSSQ, migraine, syncope, and SWID were incorporated as additional predictors.

Conclusion: The VIMSSQ is a useful adjunct to the MSSQ in predicting VIMS. Other predictors included migraine, syncope, and SWID. No significant relationship was observed between vection and VIMS.

Keywords: motion sickness (simulator sickness), migraines, optokinetic, vection, personality, anxiety, syncope, sleep

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INTRODUCTION

Visually induced motion sickness (VIMS) is a phenomenon similar to traditional motion sickness that is often observed in users of visual technologies such as simulators or Virtual Reality (VR) glasses. The widespread introduction of new visual technologies increases the risk of VIMS to the general population. The primary signs and symptoms of traditional motion sickness are nausea and vomiting, together with a host of other related symptoms including stomach awareness, sweating and facial pallor (sometimes called "cold sweating"), increased salivation, sensations of bodily warmth, dizziness, drowsiness (also denoted as the "sopite syndrome"), sometimes headache, loss of appetite, and increased sensitivity to odors (Reason and Brand, 1975). As opposed to traditional motion sickness due to whole-body accelerative stimuli such as during ship motion, the occurrence of oculomotor and central symptoms is relatively higher in VIMS where the provoking stimulus is of visual nature such as in simulators and VR systems. For example, headache is provoked more by visual than real motion, despite the fact that real motion is twice as provocative as equivalent visual motion in terms of nausea potential (Bijveld et al., 2008).

Individuals vary widely in their motion sickness susceptibility, and some general characteristics appear to influence individual differences in motion sickness susceptibility. A caveat is that most of the evidence concerns real motion stimuli rather than purely visual stimuli. For instance, twin studies on motion sickness suggest that a large proportion of variation in susceptibility is accounted for by genetic factors, with heritability estimates of 55–70% (Reavley et al., 2006). Multiple genes are involved and 35 single-nucleotide polymorphisms associated with motion sickness susceptibility have been identified (Hromatka et al., 2015). Age is another important factor, with infants and very young children being seemingly immune to motion sickness, while motion sickness susceptibility begins from around 6–7 years of age (Reason and Brand, 1975) and peaks around 9–10 years (Turner and Griffin, 1999). There is a subsequent decline of susceptibility during the teenage years towards adulthood around 20 years, doubtlessly reflecting habituation. However, for VIMS specifically, a second peak in susceptibility has been reported later in life, with older adults sometimes experiencing more VIMS than younger adults (Brooks et al., 2010; Keshavarz et al., 2018). Biological sex seems to play a role as well, as women appear somewhat more susceptible to motion sickness than men, although this is a much weaker effect than age (Kennedy et al., 1995). This increased susceptibility is likely to be objective and not subjective because women also vomit more than men as a response to motion stimuli; surveys of passengers at sea indicate a five-to-three female-to-male risk ratio for vomiting (Lawther and Griffin, 1988). With regard to VIMS, women have sometimes (but not always) been found to be more susceptible to visual stimulation (Flanagan et al., 2005; Klosterhalfen et al., 2006), and for VR headsets nonfit of interpupillary distance in females may contribute (Stanney et al., 2020). There is some evidence that several preexisting medical conditions that have an impact on quality of life are associated with raised motion sickness susceptibility, including dizziness (Bronstein et al., 2010; Golding and Patel, 2017), proneness to syncope (i.e., feeling of faintness; Bosser et al., 2006), worse sleep quality (Kaplan et al., 2017), and personality factors such as trait anxiety or neuroticism (although often weak effects; Reason and Brand, 1975). Some special groups have reduced or heightened risk: Individuals who have complete bilateral loss of labyrinthine (vestibular apparatus) function are largely immune to motion sickness (Kennedy et al., 1968; Cheung et al., 1991). But this may not be true under all circumstances, since there is evidence that a small minority of bilateral labyrinthine defective individuals are still susceptible to motion sickness provoked by visual stimuli designed to induce self-motion (vection) during pseudo-Coriolis stimulation (i.e., pitching head movements in a rotating visual field) (Johnson et al., 1999). However, it cannot be excluded that some residual vestibular peripheral function remained. Additionally, certain groups of patients with vestibular pathology and vertigo can be especially sensitive to any type of motion. For instance, patients with Meniere's disease or with vestibular migraine are especially susceptible to motion sickness (Bronstein et al., 2020). Migraineurs (nonvestibular migraine) report greater susceptibility to motion sickness provoked by real physical motion and provoked by visual stimuli (Golding and Patel, 2017). There may be individual variation among migraineurs as to their relative degree of sensitivity to these two classes of stimuli (Drummond, 2005).

A rapid estimate of an individual's susceptibility to traditional motion sickness can be made using the Motion Sickness Susceptibility Questionnaires (sometimes called Motion History Questionnaires). One of the best validated is the MSSQ (Golding, 2006). The MSSQ was developed mainly to predict the risk of motion sickness to real motion (e.g., translational motion, cross-coupled motion, seasickness, airsickness, etc.) although it was also validated to predict sickness provoked by a visual-vestibular conflict simulator. During the MSSQ development phase a range of items concerning provocative visual stimuli were tested in the item bank. However, as noted in the paper, "…excluded were visual/optokinetic items (Cinerama, Virtual Reality, etc.) … but could become important in the future." (Golding, 2006). In the intervening years, the importance of visual stimuli as a source of motion sickness has grown considerably. Therefore, work was undertaken to develop a questionnaire which might improve the predictive power for VIMS (Golding and Keshavarz, 2017). The prototype Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ) was 67 items long (Keshavarz et al., 2019), and, in the present study, this was reduced to short form consisting of six items.

The primary aim of this experiment was to evaluate the predictive efficiency of the new 6-item Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ) for individual susceptibility to VIMS. The Simulator Sickness Questionnaire (SSQ) of Kennedy et al. (1993) was employed as the metric of VIMS. Additional aims were to evaluate other questionnaire predictors (including MSSQ, migraine, dizziness, syncope, trait anxiety) for individual susceptibility to VIMS and, lastly, to investigate the possibility that individual differences in multisensory recalibration (the "Stepping-Vection test") might prove of some use as a possible predictor.

METHODS

Participants

Participants were healthy unpaid volunteers with normal or corrected-to-normal vision, had intact vestibular function, and were not on any current medication. They were fully briefed, gave informed consent, and were free to withdraw at any time. Ethical approval was granted by the Psychology Ethics Committee of the University of Westminster, London. Thirty participants (20 females, 10 males) with a mean age of 22.9 years (SD = 5.0 years) were recruited. They were all undergraduate and

TABLE 1 | Visually induced motion sickness susceptibility questionnaire (VIMSSQ). Also known as the VIMSSQ-short.

Q1. How often have you experienced each of the following symptoms when using any of these devices? (circle your response)				
Nausea	*Never*	*Rarely*	*Sometimes*	*Often*
Headache	*Never*	*Rarely*	*Sometimes*	*Often*
Dizziness	*Never*	*Rarely*	*Sometimes*	*Often*
Fatigue	*Never*	*Rarely*	*Sometimes*	*Often*
Eye-strain	*Never*	*Rarely*	*Sometimes*	*Often*
Q2. Have any of these symptoms **stopped** you using any of these devices or made you **avoid** viewing such displays? (circle your response)				
	Never	*Rarely*	*Sometimes*	*Often*
Q3. If you have answered stopped or avoided, please list the devices or displays that you avoid				

This questionnaire is designed to measure your experience with different visual display or entertainment devices and if they ever caused discomfort. Visual display or entertainment devices include Movie Theatre or Cinema, Smartphones and Tablets with movies or games, Video games, Virtual Reality Glasses or Head Mounted Displays, Simulators, Large Public Moving Display Advertising or Information Screens. Please answer these questions solely with respect to your experiences during adulthood (older than 18 years) and ignore childhood experiences.

postgraduate students, their gender ratio reflecting the greater numbers of females in the University. Their susceptibility to motion sickness was assessed using the MSSQ (Golding, 2006), and their percentile scores ($M = 48.5 \pm 36.0\%$) indicated that the sample was similar in overall susceptibility to the population norm, which is 50% by definition.

Questionnaires and Other Measurements

Questionnaires at Baseline

A variety of different questionnaires were administered at baseline prior to the visual stimuli in order to test their efficacy for predicting VIMS susceptibility.

(1) The short form of the VIMSSQ—a 6-item short version of the VIMSSQ (Golding and Keshavarz, 2017; Keshavarz et al., 2019)—was developed to capture one's susceptibility to VIMS and was designed with the expectancy that it would be used in conjunction with the MSSQ as a supplement for circumstances when VIMS is anticipated. The VIMSSQ-short inquires about the frequency of five different symptoms (nausea, headache, fatigue, dizziness, and eye-strain) and also possible consequent avoidance, when using a variety of visual devices and displays (e.g., smartphone, movie theatre, video games, tablets, and Virtual Reality glasses). Items are scored 0 (*Never*) to 3 (*Often*). A total scale score is formed by the addition of all items giving a maximum possible range for the VIMSSQ total scale score of minimum of 0 to maximum of 18. Higher scores indicate a stronger susceptibility to VIMS. The VIMSSQ is shown in **Table 1**.

(2) The short form of the MSSQ (Golding, 2006) was used to assess the participants' susceptibility to motion sickness. The MSSQ inquires about the participants' previous experiences of motion sickness when using nine different modes of transportation (e.g., boat, car, bus, and plane) or amusement rides (e.g., funfair rides). Participants have to rate each item on a scale from 0 (*never got motion sick*) to 3 (*often got motion sick*). They can also indicate if they never used or experienced the respective item. The MSSQ has two sections, one asking about childhood experiences before the age of 12 (MSSQ Child) and one asking about experiences during adulthood over the last 10 years (MSSQ Adult). A raw score of the whole MSSQ scale can be calculated and translated into percentile scores based on the population norms reported in Golding (2006). Higher scores indicate a stronger susceptibility to motion sickness.

(3) The Migraine Screen Questionnaire (Lainez et al., 2010) consists of five items that are rated on a binary scale (*yes, no*) in order to measure the participants' tendency to experience migraines. Items include, for instance, the person's experience of frequent or intense headaches and duration of those. A total score can be calculated by summing together the value of each item (max. score = 5). Higher scores indicate a greater likelihood of migraines.

(4) The Social Life and Work Impact of Dizziness questionnaire (SWID) measures the negative impact of dizziness on everyday activities (Bronstein et al., 2010). The SWID consists of a set of four social, travel, family, and work-related questions and has been previously validated in patient and control samples. Again, higher scores indicate greater probability of being affected by dizziness.

(5) A single-item syncope question was added to measure the participants' tendency to experience vasovagal syncope (Golding and Patel, 2017). Participants had to indicate how often they experience the feeling of faintness (e.g., if stressed, in pain, or sighting blood), with higher scores indicating more frequent syncope. This single-item question was adapted from Bosser et al. (2006).

(6) A Sleep Quality questionnaire (Yu et al., 2012) was added to measure the participants' general sleep quality. This questionnaire measures sleeping patterns in the past 7 days and consists of 16 items each rated on five-point scale *not at all* to *very much*, such as *My sleep was restless*, *I had problems during the day because of poor sleep*, etc. Higher scores indicate a worse sleep quality.

(7) The Ten Item Personality Inventory (TIPI; Gosling et al., 2003) is a brief measure of the Big Five Personality Factors and was used to investigate the relationship between the personality factors extraversion, agreeableness, conscientiousness, emotional stability, and openness to experience. Participants rate their level of agreement with 10 statements (e.g., *I see myself as extraverted/enthusiastic)* on a scale from 1 (*strongly disagree*) to 7 (*strongly agree*).

Rating Scales and Questionnaires During and Immediately After Exposure to the Visual Stimulus

The severity of VIMS was measured in two ways. First, immediately after cessation of the visual stimulus, the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993) was employed as the primary metric of VIMS. The SSQ contains 16 symptoms (e.g., general discomfort, fatigue, nausea, and stomach awareness) and the intensity of each item is scored on a 4-point Likert scale (0 = not at all, 1 = mild, 2 = moderate, and 3 = severe). Although three subscores (disorientation, oculomotor, and nausea) and a total score can be produced using specific weighting procedures suggested by the authors of the SSQ, this involves some items being counted twice whereas others are counted only once. Other researchers have failed to find any three-subscale-factor solution but find a clear 2-factor solution. Importantly no double scoring items are evident, i.e., no cross-loadings (e.g., Bouchard et al., 2007). Consequently, we decided to generate a simple, single overall score by summing the scores for each item for the purposes of simplicity. This has proved a useful approach in our previous experiments (Golding et al., 2012) and also in ship motion surveys in the Southern Ocean (Besnard et al., 2019). This has the advantage of capturing the greatest amount of data concerning level of motion sickness in a single variable, for subsequent analyses.

Second, the Sickness Rating scale (SR), a quick self-rating of motion sickness, was used to track the development of motion sickness on a minute-by-minute basis during stimulus exposures. The SR has been validated across a wide range of real and virtual provocative motion sickness environments (Golding et al., 2012). Participants indicate their level of sickness by choosing a score from 6-point scale (1 = *no symptoms*; 2 = *initial symptoms of motion sickness but no nausea*; 3 = *mild nausea*; 4 = *moderate nausea*; 5 = *severe nausea and/or retching*; 6 = *vomiting*). Initial symptoms commonly associated with motion sickness that do not include nausea (SR = 2) can include those commonly associated with motion sickness, including stomach awareness, feelings of bodily warmth, sweating, changes in salivation, and unusual tastes in the mouth. The SR scale was used to track development of motion sickness on a minute-by-minute basis during stimulus exposures. This was to ensure for ethical and safety reasons that the stimulus was stopped immediately if any participant reported moderate nausea and did not experience further adverse consequences. Although not the aim of this experiment, the SR scale also enables an immediate comparison of VIMS with "traditional motion sickness," since this may well be of interest to workers coming from other areas of research on seasickness, airsickness, Zero-G, etc.

In addition, participants' experiences of self-motion (vection) were measured after stimulus exposure. That is, participants had to report their level of vection by indicating the percentage of time that they experienced vection during stimulus exposure and its qualitative characteristics (e.g., constant, increasing, decreasing, or varying vection) (Golding et al., 2012).

The Stepping-Vection Test

The Stepping-Vection test was developed using pilot experiments to produce a shortened and reliable modification of an experimental procedure reported by Moss and Muth (2015). The study by Moss and Muth originated in the observation that perceptions of body orientation influence the planning of simple movements, enabling any necessary recalibration factors to be incorporated to ensure the accuracy of movements (Cohn et al., 2000). Based on this, the rationale of the Stepping-Vection test used in the present study was that, after exposure to wide field visual stimulus rotating in yaw, a participant stepping on the spot but now blindfolded will tend to rotate in the opposite direction to the previous visual stimulus, e.g., if the visual stimulus rotates to the left, vection is typically experienced in the opposite direction (to the right). After cessation of the visual stimulus and in the absence of any visual orientation cues (blindfolded), the subsequent direction of whole-body rotation when stepping on the spot will then also be in the same direction as the sensation of vection if experienced (turning rightwards). The visual stimulus used here for the Stepping-Vection test was the same as for the visual stimulus to provoke motion sickness (see next section), but importantly without the superimposed tilt wobble and with a very brief stimulus exposure of only 60 s. Immediately following cessation of this visual stimulus, any sickness was rated on the SR scale as a check, followed by the stepping part of the task. This required the participant to stand on a grid with their feet close together and start walking on the spot for 30 s with their eyes blindfolded and arms crossed over their chest. The instruction to the participants was simply to step on the spot while they were blindfolded. They were not instructed to follow the direction of the previous visual stimulus. Participants were then instructed to stop and remain in final standing position at the end of the task. Participants wore sound blocking headphones to remove any possible auditory spatial orientation cues during this task. The amount of degrees turned and the distance travelled or drifted (if any) from the starting grid were recorded.

Stimuli and Apparatus

The Visual (Optokinetic) Stimulus

A 360^o digital photographic panorama of a scene on Westminster bridge over the River Thames in London (see **Figure 1**) was used as a visual scene. The scene had been chosen to be universally familiar for participants and to contain numerous cues including Big Ben, Houses of Parliament, the London Eye, river, pedestrians, cars, pavement road signs, buildings, and a highly contrasted sky. The scene was rotated through 360^o (as if the camera were turning in yaw in a complete circle) for 10 min. The visual scene was projected to be viewed as though the participant was rotating at 72^o/s about the long axis of his/her body, tilted from the Earth Vertical by 18° of tilt. This produced a repetition frequency of the visual features of the 360^o scene at 0.2 Hz and at the same time an apparent cyclical movement of the horizon reference with an apparent upward and then downward movement of the horizon reference, again at 0.2 Hz. This latter effect we refer to as an apparent "wobble" of the scene, and this has been developed and proven to enhance nauseogenicity (Golding et al., 2009; 2012). The repetition cycle frequency is the same as is known to be maximal for inducing motion sickness by real motion in land, sea, and air environments as well as by visually induced apparent motion (Golding et al., 2009; Diels et al., 2013). This visual stimulus has

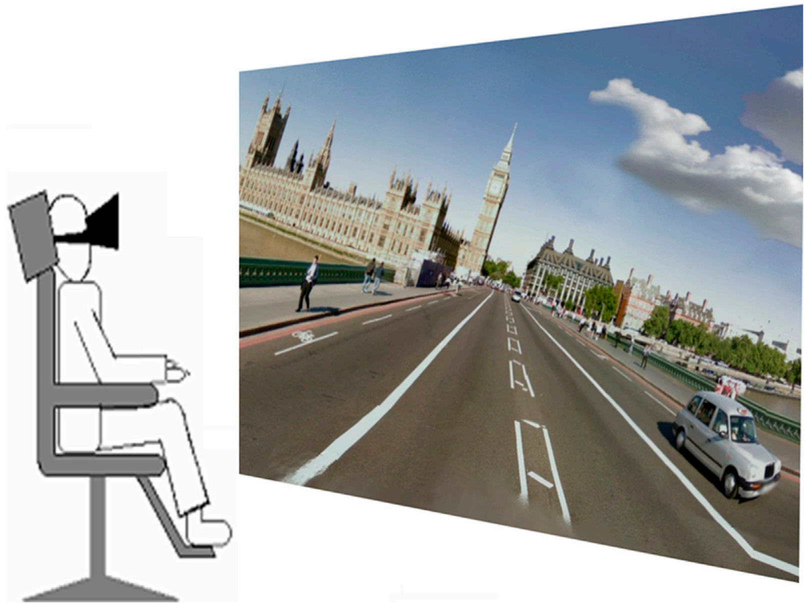

FIGURE 1 | Schematic of the visual stimulus: Rotating scene of complete 360° panorama; frequency 0.2 Hz (72 deg/s); "wobble" 18° axial tilt; field of view with mask to 83.5° with circular restriction (Golding et al., 2012).

been compared to equivalent real whole-body Off Vertical Axis Rotation (OVAR) at same 0.2 Hz frequency, 18° tilt, 10 min exposure. This visual stimulus is approximately half as strong in terms of induced motion sickness as exposure to real whole-body motion OVAR equivalent in frequency, tilt, and time duration in the same participants (Bijveld et al., 2008).

Apparatus and Laboratory Setting

The panoramic scene was projected to fill a 2 m × 2 m screen which displayed a 90° segment at any given moment in time. The display had a pixel resolution of 1024 × 768 at a refresh rate of 60 Hz. A comfortable supportive chair was positioned centrally in front of the screen such that, when seated, the distance between the participant's eyes and the screen would be 1.12 m. The armchair in which the participant sat back provided a comfortable head support for the participant but the head was not physically restrained. The participant wore a lightweight face mask mounted with a cone through which the subject viewed the screen to restrict the field of view to 83.5° to exclude peripheral vision of stationary cues of the laboratory. The cone gave a circular perimeter to the field of view.

Procedure

Participants attended the laboratory for a single session in the afternoon. They were given a familiarization briefing and then completed the baseline questionnaires. They then completed the Stepping-Vection test. This was followed by the exposure to visual (optokinetic) stimulus, recovery, and debriefing. The direction of rotation of the visual scenes was counter-balanced between participants, the same direction being used for the Stepping-Vection test and visual (optokinetic) stimulus within each participant.

The level of sickness was rated every minute during optokinetic stimulation using the SR scale. Stimulus exposures were for 10 min or until moderate nausea (SR = 4) was reported. The participants continued to rate their level of sickness during recovery at 1, 2, 3, 4, 5, 10, 15, and 30 min after optokinetic stimulation stopped. Recovery monitoring was necessary for ethical as well as research reasons.

Immediately after the visual stimulation, participants filled out the primary metric of VIMS and the SSQ, and vection was rated. The visual stimulation at 72° per second raised the possibility that participants could experience some optokinetic after-nystagmus (OKAN) which typically may last 10–60 s after stimulation. However, no participants commented on this occurring subjectively nor as a problem and it did not interfere with their completion of the questionnaire after stimulus.

Statistical Analysis

Results were analyzed using SPSS V25.0. Descriptive analysis, reliability analysis, correlations (Pearson and nonparametric), exploratory factor analysis, and multiple linear regressions were employed. Where statistical tests could be directional, the significances were 2-tailed.

RESULTS

General

Descriptive results for baseline variables are shown in **Table 2**. Comparative benchmark data for these variables are shown in an additional column to the right. The VIMSSQ is a recent scale and consequently there are no published population norms. The MSSQ (Golding, 2006) percentile scores indicated that the

TABLE 2 | Baseline questionnaires: descriptive data.

Variable	Mean (SD), median, or %	
	This study	Comparative data[a]
VIMSSQ total score	4.9 (4.1)	Not available[b]
MSSQ total score	14.4 (13.9)	12.9 (9.9)
MSSQ percentile	48.5 (36.0)	50
Migraine total score	0.77 (1.22)	1.6 (1.8)[c]
Syncope experience	13 %	16.0%
SWID total score	0.13 (0.35)	0.1 (0.5)
Sleep quality total score	37.1 (13.7)	36.0 (15.5)
TIPI extraversion score	4.2 (1.4)	4.44 (1.45)
TIPI agreeableness score	5.2 (0.9)	5.23 (1.11)
TIPI conscientiousness score	5.1 (1.4)	5.40 (1.32)
TIPI emotional stability score	4.7 (1.5)	4.83 (1.42)
TIPI openness score	5.5 (1.0)	5.38 (1.07)

[a]*See text for sources.*
[b]*VIMSSQ is new scale so has no normative comparison data yet.*
[c]*validation sample had more migraineurs than usual in the population.*

TABLE 3 | Stepping-vection and visual stimulus experiments: descriptive data.

Variable	Mean (SD) or %
Step-vection degrees of angle turned	25.5 (38.6)
Step-vection distance moved (cm)	36.2 (22.1)
Simulator sickness score (SSQ) total	6.4 (5.4)
Vection percentage of time experienced	38.3 (34.6)
Vection quality const: increase: decrease: vary	53: 17: 7: 23%
Maximum SR achieved	2.5 (0.9)
Stopping < 10 min due to SR = 4 mod. Nausea	17%
Recovery time to SR = 1 OK (min)	2.4 (2.0)

Degrees angle turned scored in opposite direction to visual stimulus; SSQ, simulator sickness questionnaire (Kennedy et al. (1993)); SR, sickness rating every minute where SR, 1 OK; SR, 2 initial symptoms; SR, 3 mild nausea; SR, 4 moderate nausea stop visual stimulus.

sample was similar in overall susceptibility to the population norms. The scores for the other variables, migraine (Lainez et al., 2010), syncope (Golding and Patel, 2017), SWID (Bronstein et al., 2010), sleep quality (Yu et al., 2012), and all "Big Five" personality scales (Gosling et al., 2003) were similar to published norms.

VIMS ratings during the visual stimulus experiment as well as descriptive data for the Stepping-Vection test are shown in **Table 3**. The reported sickness levels achieved were equivalent to those found in previous experiments using the same visual stimulus (Golding et al., 2012). Poststimulus sickness ratings followed an approximate exponential decline to full subjective recovery in most participants by 5 min and in all by 10 min. For the Stepping-Vection test, the angle turned was in the expected direction, with reversing direction between subjects according to the counter-balanced direction of stimulus rotation. No significant differences in the degrees of rotation or in the amount of drift from the starting grid showed with respect to motion direction of the stimulus (left *vs.* right). The Stepping-Vection test did not provoke any motion sickness.

Correlations

The VIMSSQ had good scale reliability (Cronbach's alpha = 0.84). Bivariate correlations between the SSQ and the other baseline variables are shown in **Table 4**. Stronger VIMS (measured by SSQ) was significantly associated with higher scores in the VIMSSQ, MSSQ, migraine, syncope, and SWID measures. However, the SWID just failed significance when reexamined using nonparametric correlation. There was a tendency for worse sleep quality to be associated with VIMS (measured by SSQ). The association with stepping distance moved was not significant when retested using nonparametric correlation and inspection of the scatterplot revealed that a few outliers were causing any association. All other correlations were low and not significant.

In addition to examining the correlations of variables with the SSQ, the full correlation matrix was scrutinized (for brevity not shown). Many of the variables which correlated with the SSQ also correlated with each other. An exploratory factor analysis was performed entering SSQ scores together with those variables which were significantly associated with the SSQ (i.e., VIMSSQ, MSSQ, migraine, syncope, and SWID; see **Table 4**). This revealed only a single factor on which each variable loaded highly and accounted for 52% of the total variance. This implies the existence of a single underlying latent variable encompassing VIMS (measured by SSQ) together with sickness susceptibility, migraine, dizziness, and autonomic reactivity exemplified by syncope.

Multiple Linear Regression Predictor Models

A series of regression models were examined to predict visually induced motion sickness as measured by the SSQ score. Three

TABLE 4 | Correlations of VIMSSQ and other variables with the Simulator Sickness Questionnaire (SSQ) as the metric of visually induced motion sickness after exposure to the visual stimulus video.

Variable	*r*	*p*	(Spearman *r*)
VIMSSQ total	0.58	**	(0.51**)
MSSQ percentile	0.46	*	(0.50**)
Migraine	0.52	**	(0.66**)
Syncope	0.62	**	(0.43*)
SWID	0.43	*	(0.30 ns)
Sleep quality	0.32	ns	(0.39*)
TIPI extraversion	−0.14	ns	(−0.07 ns)
TIPI agreeableness	0.25	ns	(0.24 ns)
TIPI conscientiousness	−0.13	ns	(−0.20 ns)
TIPI emotional stability	−0.24	ns	(−0.26 ns)
TIPI openness score	0.00	ns	(−0.08 ns)
Age	0.02	ns	(−0.06 ns)
Gender	0.01	ns	(−0.01 ns)
Vection	0.12	ns	(0.11 ns)
Step-vection degrees	0.02	ns	(0.00 ns)
Step-vection distance	0.39	*	(0.10 ns)

$^{**}p < 0.01$ and $^{*}p < 0.05$.

examples are shown in **Figure 2**. Since the primary aim of this experiment was to investigate the predictive power of the 6-item VIMSSQ, the first scatterplot simply illustrates the prediction of SSQ by VIMSSQ ($R^2 = 0.34$, $p = 0.001$). The next adds the MSSQ as an additional predictor in multiple linear regression and it can be observed how some outliers are immediately pulled in (adjusted $R^2 = 0.36$, $p = 0.001$). The final illustrative model entered all variables which were significant correlates of SSQ (see **Table 4**) used as predictors: VIMSSQ, MSSQ-pcn, migraine, syncope, and SWID (adjusted $R^2 = 0.56$, $p < 0.001$). This demonstrated how prediction efficiency increased as more predictor variables were added to the multiple linear regression models (see **Figure 2**). It should be noted that, depending on which combination of predictor variables was entered, the loadings of predictors would vary. This is due to collinearity between the predictor variables themselves (see comment at the end of the previous section 'Correlations'). As a consistency check concerning the possible effects of multicollinearity in the preceding multiple regression analysis, we performed an exploratory factor analysis on all predictor variables which were used in the multiple regression model to predict the SSQ scores (i.e., predictors VIMSSQ, MSSQ-pcn, migraine, syncope, and SWID). A one-factorial solution was found, which accounted for 49.3% of the variance. Factor scores were then computed and outputted. We then used these factor scores in a regression model to predict the SSQ scores. The correlation between the factor scores and SSQ was $r = 0.73$ ($R^2 = 0.54$, $p < 0.001$). This solution was very similar to the final multiple linear regression scatterplot shown above, both in terms of the amount of variance of SSQ predicted (54% vs. 56%) and also in the pattern of scatter of the individual datapoints.

DISCUSSION

The Prediction of VIMS

The main aim of the present study was to investigate the effectiveness of a short questionnaire, the 6-item Visually Induced Sickness Susceptibility Questionnaire (VIMSSQ), to predict individual susceptibility to VIMS when administered prior to exposure to a moving panoramic visual scene known to elicit VIMS. Higher scores on the VIMSSQ significantly predicted VIMS as measured by the SSQ (Kennedy et al., 1993). The VIMSSQ predicted approximately one-third of the individual variation in VIMS.

The secondary aim was to examine other possible predictors for VIMS. Significant baseline predictors for VIMS included higher scores on the MSSQ, greater scores on the migraine screening scale, greater susceptibility to syncope, and higher scores on the SWID. These additional variables, when combined with the VIMSSQ in a multivariate model, significantly improved the overall predictive power. However, this increase in predictive power was not as large as what might be expected, since all these variables significantly correlated with each other and with the VIMSSQ itself. The consequent collinearity produced redundancy. Indeed, exploratory factor analysis of all these variables, together with the SSQ as the measure of sickness, revealed only a single factor. This implies the existence of a single underlying latent variable encompassing VIMS together with motion sickness susceptibility, migraine, dizziness, and autonomic reactivity exemplified by syncope. Such a finding is reminiscent of what has been found in large surveys of the general population and patients experiencing vestibular disorders which produce vertigo (Golding and Patel, 2017). To explain this, it has been proposed that there is an underlying set of risk factors which distribute with increasing strength throughout the general population up into what is then termed the 'clinical population' for vestibular related disorders such as Visual Vertigo (Peverall and Golding, 2017) and Persistent Perceptual Postural Dizziness (PPPD) (Bronstein et al., 2020; Powell et al., 2020).

A number of variables measured at baseline failed as predictors. The Stepping-Vection test was a much shortened modification of an experiment reported by Moss and Muth (2015). This modification was successful in that it reliably

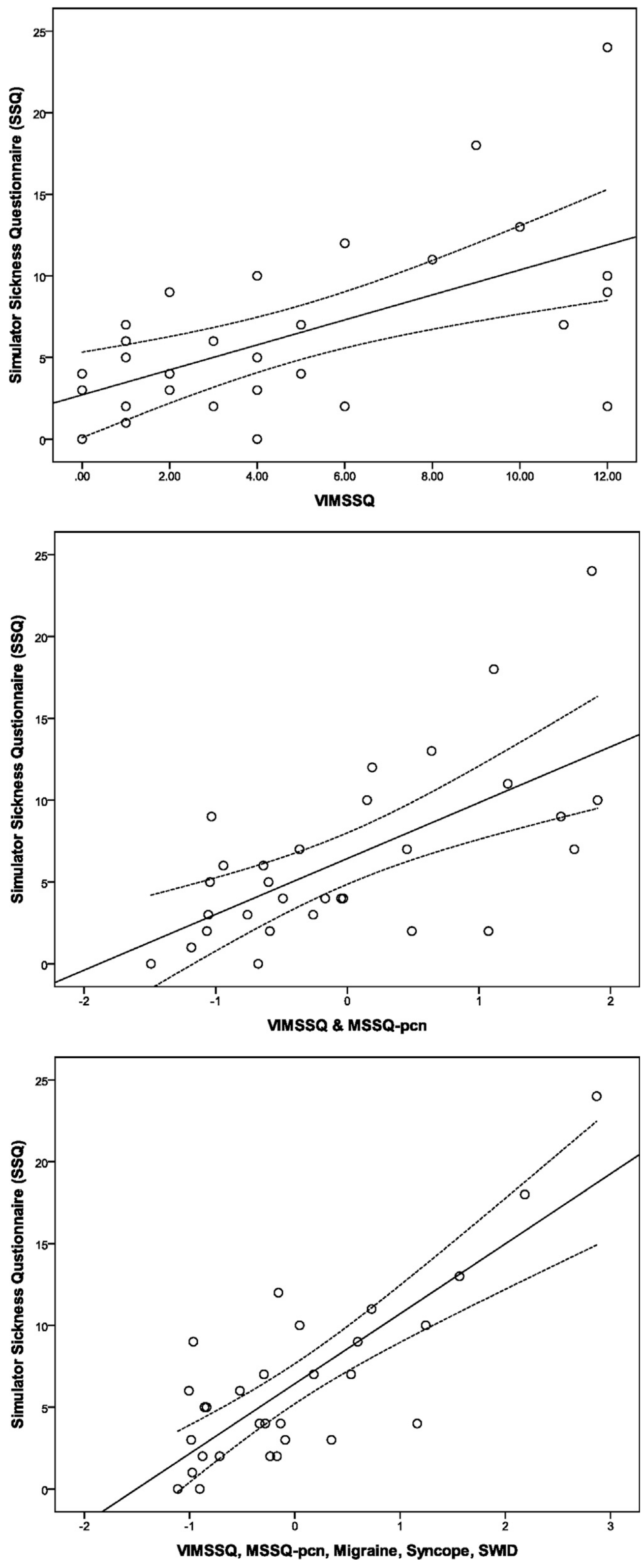

FIGURE 2 | Prediction of visually induced motion sickness (VIMS) as measured by the SSQ, showing how prediction efficiency increases as more predictor variables are added to the multiple linear regression models. Top using as predictor: VIMSSQ only (R^2 = 0.34); middle using: VIMSSQ and MSSQ percentile (pcn) (adjusted R^2 = 0.36); bottom using: VIMSSQ, MSSQ percentile (pcn), migraine, syncope, and SWID (adjusted R^2 = 0.56). The fitted regression line is shown in each scatterplot together with the 95%CI dashed lines on either side.

reproduced the expected movement bias in recalibration of multisensory integration observed by Moss and Muth (2015). However, the modified test failed to be useful in predicting susceptibility to VIMS. It might be argued that the shortening of the test to less than 2 min in total from the original 20 min of optokinetic exposure and 10 replications of a 45 s stepping task (total around half an hour or more) may have been the reason for failure to be a predictor. However, if the test were to be reinstated to the original duration, then it would be of no practical utility, since it would then be quicker to perform the actual visual exposure to elicit VIMS. Consequently, although of great theoretical interest, it seems at this point that this test has limited development potential as a predictor of VIMS susceptibility.

Age and, to a lesser extent, sex (gender) are known to influence motion sickness susceptibility. The failure of age to significantly correlate is unsurprising in the context of the present experiment. This is because the age range of the young adult participants was very narrow, with the consequent restriction of range statistical effect. The failure to find a sex effect might be due to various reasons: the sample size of $N = 30$ was relatively small to detect an effect of sex and the sample was unbalanced in sex ratio, which further reduced the test power. Additionally, it has been suggested that sex effects are more contradictory for VIMS than for classical motion sickness susceptibility, at least as understood so far given the number of studies at present (Saredakis et al., 2020). There was a trend for worse sleep quality to be associated with higher levels of VIMS, but this failed significance. It may be that effects of sleep deprivation can only be reliably observed when the amount of sleep deprivation is much stronger, similar to the study of Kaplan et al. (2017), which used sleep deprivation as an actual intervention against low frequency real motion. There were no significant relationships observed between any of the 'Big Five' personality factors and VIMS. The most likely relationship with greater motion sickness susceptibility is with trait anxiety or neuroticism, but these are weak (Reason and Brand, 1975) and are usually observed only in large studies (e.g., Paillard et al., 2013), perhaps because under those conditions enough highly anxious individuals can be tested.

The symptom scores and amount of time vection was experienced were similar in this experiment to a previous study using the same visual stimulus (Golding et al., 2012). Notably, no correlation was observed between vection and VIMS, and there was not any evidence that the quality of vection, for example increasing, decreasing, or changing, had any relationship to VIMS. Indeed, one notable feature of vection is that this illusion can onset and then vanish within seconds, whereas motion sickness usually builds up more slowly over time. This lack of relationship was also noted in our previous studies using this type of visual stimulus (Bijveld et al., 2008; Golding et al., 2009; Golding et al., 2012). Although some studies have found relationships between vection and VIMS (e.g., Nooij et al., 2017), the literature is contradictory with many failures to show such relationships (Lawson, 2014; Kuiper et al., 2019). A thorough discussion on the topic can be found in Keshavarz et al. (2015). Vection may play a role in VIMS but the relationship between them is not one-to-one and appears not to be directly causal in any obvious fashion. The explanation may be that vection is a conscious illusory perception, presumably happening at a cortical level in the brain. By contrast the visual-vestibular mismatches or conflicts provoking motion sickness are doubtless occurring at the brainstem–cerebellar level (Oman and Cullen, 2014) and may not be directly accessible to conscious perception. This may explain the lack of reliable association between vection and VIMS.

Limitations and Future Outlook

This study had some limitations. Although the stimulus used to provoke VIMS was well validated and reliable, it is important to note that it was only one type of stimulus. The effectiveness of the short 6-item VIMSSQ has to be shown for other settings such as driving simulators or VR. With Head Mounted Displays (HMDs) and virtual environments there are also other factors including eye-head coordination such as update lags, accommodation-vergence conflicts, flicker, etc. The prototype 67-item VIMSSQ did demonstrate predictive power for VIMS elicited by a driving simulator task (Keshavarz et al., 2019). Nevertheless, the 6-item VIMSSQ needs to be evaluated on a variety of stimuli capable of eliciting VIMS to demonstrate its general utility. One limitation of the present study was the small sample size of $n = 30$, which will require follow-up studies with larger sample size to strengthen our initial findings. Another limitation was that the participants in this study were healthy, fit young adults. The generalizability of predictive power of the VIMSSQ to the older population is necessary. This is because people become more visually dependent with increasing age as they reweight the three main sensory inputs used for balance and orientation. The reweighting is usually away from vestibular and proprioceptive inputs (which often become less reliably accurate with ageing) to greater dependence of visual inputs (Pavlou and Newham, 2013). Again, older adults may have had less experience with new visual technologies. Both these factors may increase susceptibility to VIMS. At the same time, an opposing factor comes into play, that overall motion sickness susceptibility to physical motion is known to decline with age (with individual variation) (Paillard et al., 2013). Consequently, the predictive efficiency of the VIMSSQ needs to be tested for the older population. Some room for optimism is provided by Keshavarz et al. (2019) study, which included both younger and older adults. This showed that the 67-item prototype VIMSSQ could predict VIMS with relatively small differences in predictive power across the age span.

CONCLUSION

The results of this study indicate that the short version of the VIMSSQ can successfully predict around a third of the individual variation in VIMS. At six items it is short and very quick to complete. To increase predictive power, it is probably best used in conjunction with the MSSQ. Researchers may also wish to consider adding other possible predictors such as migraine and a measure of autonomic reactivity such as syncope.

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 the Psychology Ethics Committee, University of Westminster, London. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JG and BK conceived the idea for the study. JG, BK, and AR wrote the manuscript. JG, BK, and AR analyzed and interpreted the data. AR and JG carried out the experiments. AR recruited participants.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2021.576871/full#supplementary-material.

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Visually Induced Roll Circular Vection: Do Effects of Stimulation Velocity Differ for Supine and Upright Participants?

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Visually induced circular vection (CV) has been the subject of a wide range of functional brain and behavioral research. Participants in MRI or PET studies on CV were mostly in a supine viewing position, while participants in behavioral studies on CV were mostly in an upright viewing position. This study examines the effects of viewing positions (upright and supine) on roll CV reported by 16 participants while watching random dots (92 × 60 degrees field-of-view) rotating at different angular velocities (2, 4, 8, 16, 32, 64 deg/s) for 30 s. Viewing positions affected roll CV durations differently depending on the stimulation velocities. At slower velocities (2, 4, and 8 deg/s), participants exhibited significantly longer roll CV sensations when they were sitting in an upright position as opposed to lying in a supine position. The onset of roll CV was also significantly earlier with participants in an upright position despite similar roll CV intensities in both viewing positions. Significant two-way interactions between effects of viewing positions and dot rotating velocities for some conditions were noted. Consistency between current findings and the hypothesis predicting a weaker roll CV in upright positions based upon perceived gravity by the otolith organs is discussed.

Keywords: circular vection, stimulation velocity, upright position, supine position, otolith cues

INTRODUCTION

Watching a wide, coherently moving scene can stimulate an illusion of self-motion in the opposite direction known as vection (Dichgans and Brandt, 1978; Hettinger et al., 2014; Palmisano et al., 2015). A common example of vection is the "train illusion." When passengers sitting in a stationary train watch a neighboring train moving, they often have the compelling sensation that their train is moving in the opposite direction while the neighboring train appears to be stationary. Vection is also a common perception experienced by virtual reality users. For those users who are susceptible to visually induced motion sickness (VIMS), the same moving scenes that can provoke vection have been reported to provoke VIMS and/or cybersickness (Hettinger et al., 1990; So et al., 2001; Smart Jr et al., 2002).

According to its moving direction, vection can be further classified as linear vection (Giannopulu and Lepecq, 1998; Trutoiu et al., 2009; Chen et al., 2016) or circular vection (CV) (Young et al., 1975; Allison et al., 1999; Ji et al., 2009). The occurrence of vection involves inputs from visual, vestibular, proprioceptive, and other somatosensory organs (Dichgans and Brandt, 1978; Warren and Wertheim, 1990). In particular, the vestibular system and visual system play a leading role in the perception of vection (Benson et al., 1986; Brandt et al., 1998; Deutschländer et al., 2004). As the human vestibular system responds to acceleration, changing the head orientation relative to the direction of the gravitational force may affect the levels of perceived vection.

CV has been the focus of many behavioral studies. Earlier research utilized CV as a tool to study the effect of gravity on visual vestibular interaction (Young et al., 1986a,b; Cheung and Howard, 1990; Young and Shelhamer, 1990). Viewing positions were found to affect both CV and the sensations of tilt (Young et al., 1975). An explanation related to otoliths was given. Specifically, if otolith responses to gravitational acceleration conflict with any perceived CV, sensations of CV will be suppressed. This suggests weaker roll CV to be perceived when participants adopt an upright viewing position as compared to a supine position. A review of literature indicates that most behavioral studies on vection instructed their participants to observe visual stimulation only in upright positions (Kim and Khuu, 2014; Chen et al., 2016; Palmisano and Riecke, 2018; Keshavarz et al., 2019; Fujimoto and Ashida, 2020; Weech et al., 2020). Specifically, most past research on effects of velocity on CV only asked participants to adopt an upright viewing position (Brandt et al., 1973; Held et al., 1975; Ujike et al., 2004). This is understandable as vection-provoking stimuli typically appear from VR applications that are usually viewed in upright positions. However, many PET and MRI studies on vection were conducted with participants in supine viewing positions due to constraints of the scanners (Brandt et al., 1998; Kleinschmidt et al., 2002; Cardin et al., 2012; Uesaki and Ashida, 2015). The use of different viewing positions aggravates the challenge of integrating their findings given the existing differences in research methodology (Berti and Keshavarz, 2020). In particular, if the viewing position does affect CV sensations, its effects and the interactions with other factors influencing CV should be investigated.

Unfortunately, there is a gap in the research on exactly how viewing position affects roll CV. Young et al. (1975) studied the tilt sensation of participants when they watched random rectangles rotating at different velocities (5–60 deg/s) in different viewing positions: upright; head-inverted ("upside-down"); head forward 25 degrees and head tilted to the right. They noted that when a participant was asked to tilt the head forwards at an angle of 25 degrees, the perceived tilting sensation was reduced (Young et al., 1975). The phenomenon was explained by the alignment between the dominant plane of utricular otolith and the earth-horizontal plane. It was suggested that by aligning the two planes, otolith responses to the gravity might have been maximized and they suppressed the visually induced roll CV. Their results supported a conclusion that visually induced tilt depended on head orientation; however, their study did not investigate actual effects of a supine viewing position. In later investigations concerning weightlessness in space flights, effects of viewing visual roll stimulation in both supine and upright positions were examined (Young et al., 1986b; Young and Shelhamer, 1990). As the space flight research focused on gravity conditions, there was limited comparison between data collected in supine and upright positions. Nonetheless, the presence of gravity was shown to suppress roll CV sensation in both viewing positions and the suppression effect was stronger in upright positions. This led to the hypothesis that if gravitation vestibular cues were in conflict with roll CV sensations, the latter would be suppressed. As such, roll CV experienced in a supine position should be more robust than that experienced in an upright position because there was less suppression from the otolith cues in the supine position. It can be hypothesized that, given all conditions equal, roll CV in an upright position will be weaker than that in a supine position. Cheung and Howard (1990) compared the CV magnitude provoked by random dots rotating at 45 deg/s among participants in a supine and an upright position experiencing microgravity, hypergravity and normal gravity. From the reported results from all gravity conditions, the average roll CV intensity measured in the supine position was slightly higher than that in the upright position; however, statistical comparison was not reported (Cheung and Howard, 1990). Tanahashi et al. (2012) examined the effects of body positions (supine, left lateral recumbent and sitting upright) on CV induced by viewing scenes rotating in roll, yaw, and pitch axes at a constant angular velocity of 60 deg/s. Their results indicated that the reported intensity of roll CV was higher when participants were in an upright position than that in a supine position, which conflicts with the prediction from our hypothesis.

In this paper, we report our studies and comparisons of roll CV perception when participants were viewing dots rotating in different velocities and in an upright and a supine viewing position. Possible two-way interactions between the effects of viewing positions and stimuli velocities are examined.

METHODS

The experiment was approved by the Human Research Ethics Committee of the Hong Kong University of Science and Technology and written consents were obtained from all participants.

Participants

Sixteen healthy university students (five females, 11 males) aged between 22 and 26 years old (mean = 24, SD = 1.1) participated in the experiment. All participants had normal or corrected-to-normal. The sample size was supported by a power analysis based on data reported by Tanahashi et al. (2012) and is compatible with past studies on vection (Chen et al., 2016: $n = 13$; Palmisano and Riecke, 2018: $n = 16$; Tanahashi et al., 2012: $n = 7$, 4, and 4).

Apparatus and Stimulus

Figures 1, **2** illustrate the experimental setup and the stimulus. The random-dot pattern was adapted from Brandt et al. (1998). This stimulus has been commonly used in functional brain studies of CV (Deutschländer et al., 2004; Antal et al., 2008; Reinhart et al., 2016) and has been shown to induce visually induced motion sickness among participants who viewed the stimulus for 20 min (Zhao, 2017). The random-dot pattern had a total of 839 black dots of sizes ranging from 0.6 to 1.6 degrees

FIGURE 1 | (**Top left**) A photo of the apparatus when participants were in the upright positions; (**top right**) a photograph of a participant in the upright position. The light would be off during the experiment); (**bottom left**) a photograph of the apparatus when participants were in supine positions; and (**bottom right**) a photograph of a participant in a supine position. The light would be turned off during the experiment.

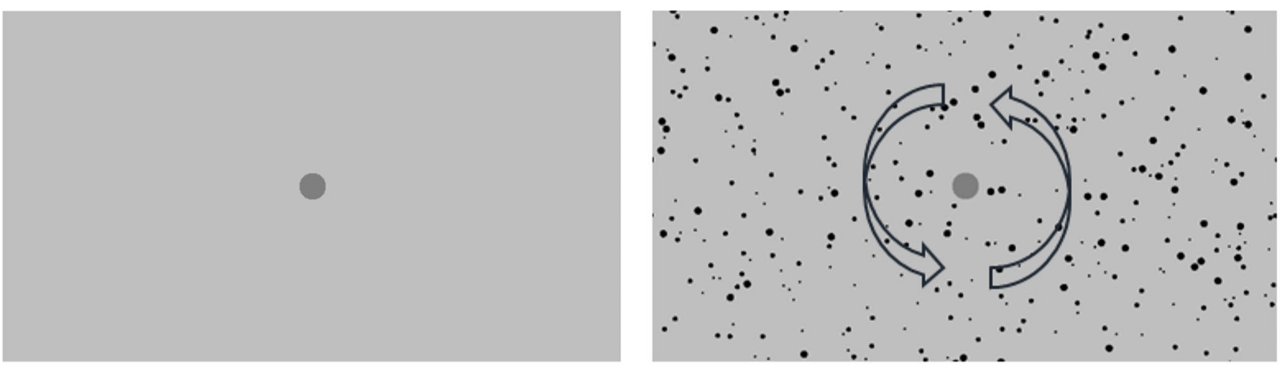

FIGURE 2 | Snap shots of the stimulus in the resting period **(left)** and in the stimulus condition **(right)**, in which the arrows do not show during the experiment and just indicate the rotation direction of the dots pattern.

on a light-gray background and with a dark-gray central disk for eye fixation. All participants followed the eye fixation instruction as their eye gazes, measured by an EyeTech TM3 eye monitoring system, fell within the area of the dark-gray fixation disk for all trials. The random-dots rotated in the counter-clockwise direction according to the assigned velocity. During the resting condition, only the light-gray background and the dark-gray central disk were shown and the pattern remained stationary. Each condition consisted of a 30 s stimulus period followed by a 20 s resting period. The movement of the stimulus pattern, displayed on the 46-inch LCD monitor, was controlled by a C++ program using OpenGL libraries running on a PC with GPU. The field-of-view of the stimuli was 92 degrees horizontally and 60 degrees vertically and the viewing distance was maintained at 50 cm from the center of LCD monitor. A key pad was used to collect responses from the participants. All experiments were conducted in the absence of any light sources.

Experimental Design

A within-subject design was adopted. Exhaustive combinations of six velocity levels (2, 4, 8, 16, 32, 64 degree/s), two viewing positions (upright, supine); and six repeated trials were tested in the experiment. A total of 72 conditions (six velocities × two positions × six repeats) were presented over two separate days, with 36 conditions (six velocities × six repeats) for the same viewing positions on a single day. To minimize possible fatigue, the six trials were separated into six sessions with a 5-min break between each session. Within one session, the order of presenting the six velocity conditions was randomized. The order of presenting the position was counterbalanced so that half of the participants were in a supine viewing position first while the remaining were in an upright viewing position first. The separation of the two exposure days ranged from 3 to 6 days.

Procedures and Measurements

Two training sessions, one for each viewing position, were conducted to acquaint participants with the instructions and the experimental tasks. Participants were given 5 min to adapt to the darkness. Studies have shown that auditory motion cues can affect CV sensation (Campos et al., 2018). In order to control the auditory environment, each participant worn a pair of sponge earplugs (NRR value: 29 dB) to block out background noise.

During the experiment, participants were required to stare at the dark-gray central disk from the outset to the end. During the period of watching rotating dots, participants needed to keep pressing the key "a" or "b" to give an assessment of roll CV intensity as soon as they experienced any sensations of self-motion ("a": participants feel both object and self-motion; "b": participants feel only self-motion). Either pressing "a" or "b" was taken as a vection status, and pressing "b" was additionally recorded as full CV status (full-CV). No keypress indicated no sensation of CV. In subsequent analysis, we focused on CV (both "a" and "b" pressing) including both full CV and non-full CV. During the period of resting, no keypress was required but they needed to verbally report the CV intensity to the experimenter using a scale from 1 to 5 (**Table 1**). Between sessions, participants were allowed to have a 5-min rest. All six sessions were conducted consecutively on 1 day.

TABLE 1 | Scaling of 5-level vection rating (Webb and Griffin, 2003).

Perception of CV	Scores report
You feel like you are stationary and it is the dots which appear to be moving only.	1
You feel like you are moving a bit, but the dots are moving more.	2
You feel like you are moving at the same speed as the dots.	3
You feel like you are moving a lot and the dots are moving a bit.	4
You feel like you are moving and the dots appear stationary.	5

The keypress data were analyzed to extract CV onset time, accumulated CV duration, average CV duration, and CV frequency. Each continuing roll CV sensation reported however short was counted as one occurrence of CV sensation. Average CV duration was the average of the duration of each CV occurrence per participant per condition. Accumulated CV duration was calculated by the sum of intermittent duration in each stimulus condition (30 s). Similarly, the CV frequency referred to the number of times the participant experienced roll CV during each condition. For example, during a 30 s stimulation, if a participant reported roll CV from the 10th second to the 13th second and from the 20th second to the 22nd second, the CV frequency would be two, while the average and accumulated CV durations for this trial would be 2.5 and 5 s, respectively.

Data Analysis

Nonparametric statistical analyses were conducted since the data violated the normality assumption (Shapiro-Wilk test, $p < 0.05$). More specifically, analysis of variance of Aligned Rank Transformed (ART) data was used (ARTool: Wobbrock et al., 2011) to study the effects of viewing position, stimulation velocity and their two-way interactions. Friedman test and pairwise Wilcoxon Signed Ranks test were also used to analyze the effects of velocity and position. *Post hoc* analysis with Bonferroni correction was applied to address the multiple comparison problem. The data analysis software R 3.2.3 with package ARTool and IBM SPSS Statistics v26 were used.

RESULTS

Effects of repeated trials were significant on accumulated CV duration [$F_{(5,75)} = 2.316$, $p = 0.042$], CV frequency [$F_{(5,75)} = 2.352$, $p = 0.039$] and CV onset time [$F_{(5,75)} = 2.917$, $p = 0.013$]. When the first three trials were removed, the effects of repeated trials were not significant. For subsequent analyses, data collected in the last three trials were averaged to give better mean estimations. The median CV measurements collected in two viewing positions and six velocity conditions are shown in **Figure 3** with inter-quartile ranges. In the following sections, main effects of position and velocity and their interaction

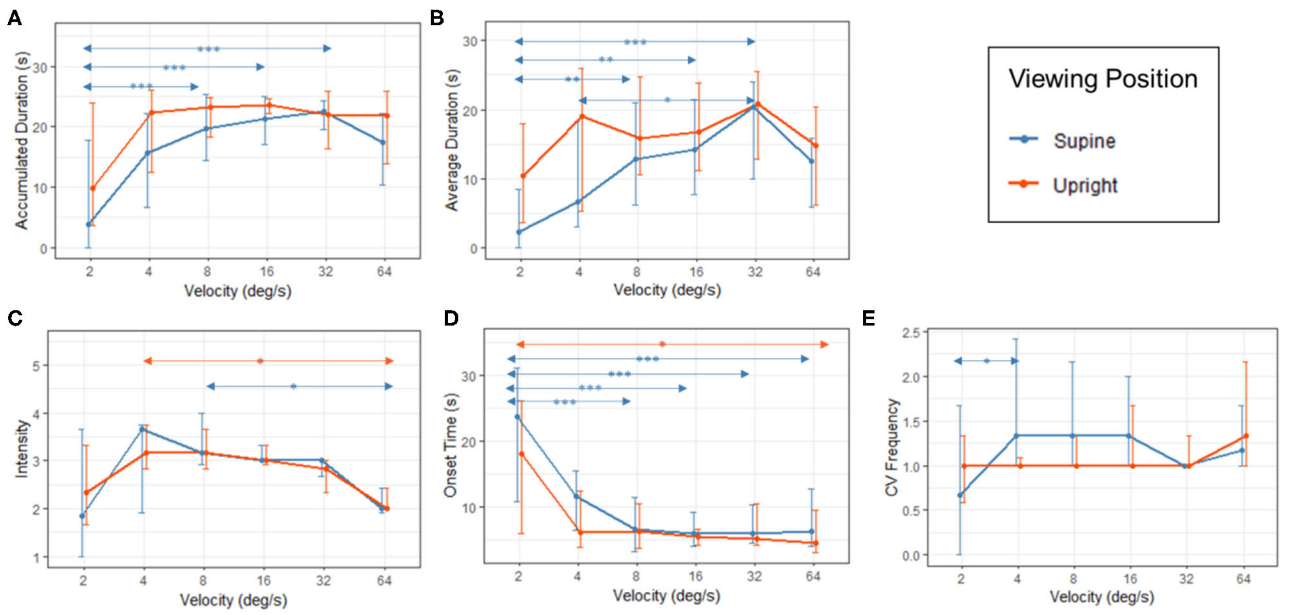

FIGURE 3 | Results of **(A)** accumulated CV duration; **(B)** average duration of CV; **(C)** CV Intensity; **(D)** onset time of CV and **(E)** CV frequency in the supine (red) and upright (blue) viewing positions. The values for median, 1st quartile and 3rd quartile were calculated based on the means collected from the last three trials of 16 participants. Statistically significant pairwise comparison results (with Bonferroni correction) were labeled with arrows and asterisks (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$).

effects will be examined by ART ANOVA first followed by additional analysis.

Analysis of Variance With Aligned Rank Transform

Results of repeated measures two-way ART ANOVA indicated that the overall interaction effects between viewing position and stimulation velocity were not significant among all five roll CV measurements (**Table 2**).

With repeated measures two-way ART ANOVA on roll CV measurements, significant main effects of position were revealed on accumulated CV duration, average CV duration and onset time of CV (**Table 2**). The roll CV durations in an upright viewing position were generally longer than those in a supine viewing position. In a supine viewing position, the participants perceived roll CV later than when they were in an upright viewing position.

The main effects of stimulation velocity over the two viewing positions were found to be significant for all five roll CV measurements: accumulated CV duration, averaged CV duration, CV frequency, onset time, CV intensity (**Table 2**). *Post hoc* analyses with Bonferroni adjustment on stimulation velocity levels were conducted to investigate the differences between each pair of stimulation velocities. Both accumulated and average CV duration reported in the 2 deg/s stimulation condition were shorter than those reported in conditions using higher stimulation velocities (accumulated CV duration: 2 and 8 deg/s, $p < 0.001$; 2 and 16 deg/s, $p < 0.001$; 2 and 32 deg/s, $p < 0.001$; 2 and 64 deg/s, $p = 0.016$; average CV duration: 2 and 8 deg/s, $p = 0.001$; 2 and 16 deg/s, $p < 0.001$; 2 and 32 deg/s, $p < 0.001$). Significantly shorter average duration was reported when participants were exposed to a stimulation velocity of 4 deg/s as compared to a stimulation velocity of 32 deg/s (4 and 32 deg/s, $p = 0.018$). Furthermore, more frequent CV occurrence and longer CV onset time were reported in conditions with a stimulation velocity of 2 deg/s than those reported in other velocity conditions (CV frequency: 2 and 4 deg/s, $p = 0.017$; 2 and 8 deg/s, $p = 0.025$; 2 and 16 deg/s, $p = 0.016$; 2 and 64 deg/s, $p = 0.005$; onset time: 2 and 4 deg/s, $p = 0.026$; 2 and 8

TABLE 2 | Results of ART ANOVA on roll CV measurements.

Responses	Effects	Statistics
Accumulated CV duration	Position	$F_{(1,15)} = 11.947$, $p < 0.001$***
	Velocity	$F_{(5,75)} = 7.101$, $p < 0.001$****
	Position × velocity	$F_{(5,75)} = 1.247$, $p = 0.289$
Average CV duration	Position	$F_{(1,15)} = 12.660$, $p < 0.001$***
	Velocity	$F_{(5,75)} = 8.223$, $p < 0.001$***
	Position × velocity	$F_{(5,75)} = 0.882$, $p = 0.495$
CV frequency	Position	$F_{(1,15)} = 1.658$, $p = 0.200$
	Velocity	$F_{(5,75)} = 4.228$, $p = 0.001$***
	Position × velocity	$F_{(5,75)} = 1.951$, $p = 0.089$
Onset time	Position	$F_{(1,15)} = 8.474$, $p = 0.004$**
	Velocity	$F_{(5,75)} = 10.853$, $p < 0.001$***
	Position × velocity	$F_{(5,75)} = 1.373$, $p = 0.237$
Intensity	Position	$F_{(1,15)} = 0.091$, $p = 0.764$
	Velocity	$F_{(5,75)} = 10.797$, $p < 0.001$***
	Position × velocity	$F_{(5,75)} = 0.131$, $p = 0.985$

Asterisks have been labeled according to the p-values ($p < 0.05$; **$p < 0.01$; ***$p < 0.001$).*

deg/s, $p < 0.001$; 2 and 16 deg/s, $p < 0.001$; 2 and 32 deg/s, $p < 0.001$; 2 and 64 deg/s, $p < 0.001$). As to CV intensity, stimulation conditions with a velocity of 2 or 64 deg/s resulted in significantly weaker roll CV than those with a velocity of 4, 8 and 16 deg/s (2 and 4 deg/s, $p = 0.016$; 2 and 8 deg/s, $p = 0.003$; 2 and 16 deg/s, $p = 0.040$; 64 and 4 deg/s, $p < 0.001$; 64 and 8 deg/s, $p < 0.001$; 64 and 16 deg/s, $p < 0.001$). In addition, CV intensity reported in conditions with a stimulation velocity of 32 deg/s was stronger than that reported in conditions with a stimulation velocity of 64 deg/s (32 and 64 deg/s, $p = 0.028$). In summary, significantly shorter CV durations, longer onset time and smaller CV frequency were reported in conditions with a stimulation velocity of 2 deg/s. Participants reported the highest CV intensity when watching the stimuli rotating at 8 deg/s.

Further Analysis

In the analysis results reported in section Analysis of Variance With Aligned Rank Transform, the overall interactions between effects of viewing positions and stimulation velocities were not significant. However, the absence of significant interaction is not consistent with **Figure 3**. Data curves collected from two viewing positions are not parallel to each other (**Figure 3**). To substantiate the observation, we analyze the main effects of stimulation velocity on data collected in different viewing positions separately. If there is a trend of interaction, the two main effects would be different. In addition, we grouped the data into low velocity (2, 4, and 8 deg/s) subgroup and high velocity (16, 32, and 64 deg/s) subgroup for further analyses of interactions (**Figure 4**).

Effects of Stimulation Velocity on Roll CV Reported in the Upright and Supine Positions

Results of Friedman tests on five roll CV measurements in upright conditions indicated significant main effects of velocity on CV intensity [χ^2 (5) $= 14.495$, $p = 0.013$] and CV onset time [χ^2 (5) $= 19.698$, $p = 0.001$]. *Post hoc* pairwise comparisons with Bonferroni correction found that the CV intensities at 4 and 64 deg/s were significantly different ($p = 0.032$). The onset time of roll CV induced by stimulation with a velocity of 2 deg/s was significantly longer than that of 64 deg/s ($p = 0.001$). For CV frequency, the velocity was only marginally significant [χ^2 (5) $= 10.982$, $p = 0.052$] and it was not significant on CV durations (Accumulated CV duration: [χ^2 (5) $= 8.113$, $p = 0.150$]; average CV duration: [χ^2 (5) $= 9.064$, $p = 0.107$]). It should be noted that accumulated durations of roll CV remained long for most stimulation velocities (**Figure 3**: 20–24 s within the 30 s exposure for 4, 8, 16, 32, and 64 deg/s). Such a CV duration can be considered long and might have reached their ceiling levels because after adding the median onset times of 6 s (**Figure 3**), the total ranged from 26 to 30 s. This suggests little room for accumulated CV duration to increase further. For the condition at 2 deg/s, although the accumulated CV duration for the upright position was shorter (median: 10 s), the corresponding median onset time was significantly longer at 18 s and the sum of both reached 28 s. In other words, the lack of velocity effects should not be misinterpreted as lack of roll CV sensation. Rather, the insensitive to stimulation velocity could have been due to ceiling effect.

When participants adopted the supine position, roll CV measurements were much affected by stimulation velocity. Results of Friedman tests showed significant main effects of velocity on all five roll CV measurements: accumulated CV duration [χ^2 (5) $=$ 28.080, $p < 0.001$], average CV duration [χ^2 (5) $= 30.348$, $p < 0.001$], CV frequency [χ^2 (5) $= 15.426$, $p = 0.009$], CV intensity [χ^2 (5) $= 14.435$, $p = 0.013$] and CV onset time [χ^2 (5) $= 37.138$, $p < 0.001$]. From **Figure 3**, when participants viewed the roll CV provoking stimuli in the supine position, all roll CV measurements except onset time exhibited significant inverted-U shaped profiles as the velocity of the stimuli increased. Pairwise comparisons with Bonferroni correction showed that, as the velocity of the rotating dots increased from 2 to 32 deg/s, CV durations (both average and accumulated) increased significantly (**Figures 3A,B**). For CV intensity, the peak occurred at 8 deg/s (**Figure 3C**). As stimulation velocity increased, CV onset time reduced (**Figure 3D**). and CV frequency significantly increased when stimulation velocity switching from 2 to 4 deg/s (**Figure 3E**).

In summary, as stimulation velocity increased from 2 to 64 deg/s, reported roll CV became stronger, longer and with quicker onset times before they peaked and then reduced in intensity and duration at 64 deg/s. These effects of stimulation velocity were more significant among participants adopting the supine position. With the upright position, the effects of velocity were less significant because roll CV measurements reached their ceiling levels as the stimulation velocities increased to 4 deg/s and beyond.

Effects of Viewing Position Under Low and High Velocity Stimulation Conditions

To further examine the observed differences in effects of position as velocities changed, as depicted in **Figure 3**, roll CV measurements induced by high velocity stimuli (2, 4, and 8 deg/s) and low velocity stimuli (16, 32, and 64 deg/s) were analyzed separately (**Table 3**, columns entitled "Low velocities" and "High velocities" and **Figure 4**). Although the interaction effects remained not significant (**Table 3**), significant position effects were found only in data collected from low-velocity stimulation conditions. As shown in **Figure 4**, when stimulation velocities were low (2–8 deg/s), significantly shorter accumulated CV duration, shorter average CV duration and longer onset time were reported when participants adopted the supine position compared to the upright position (**Table 3**). When stimulation velocity was high (16–64 deg/s), the viewing position did not affect roll CV measurements (**Table 3** and **Figure 4**).

To further verify the observed dependency between the effects of position and stimulation velocity, ART ANOVA were conducted on CV durations and onset time collected from two stimulation velocity conditions. Results of repeated measures ART ANOVA showed significant two-way interactions on accumulated CV duration between 4 and 32 deg/s [$F_{(1,45)} = 4.904$, $p = 0.032$]. Specifically, the reported increases in CV duration when the stimulation velocity switched from 4 to 32 deg/s were significantly larger in the supine position than that

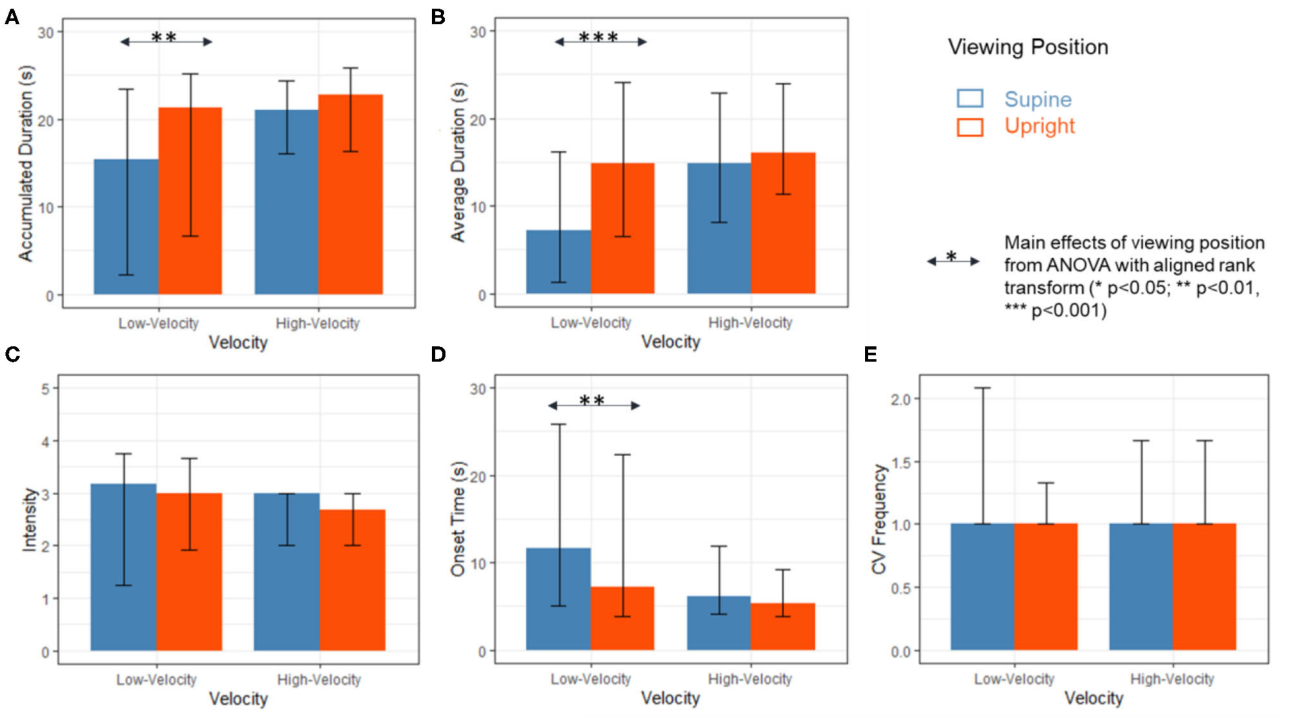

FIGURE 4 | Results of **(A)** accumulated CV duration; **(B)** average duration of CV; **(C)** CV Intensity; **(D)** onset time of CV and **(E)** CV frequency provoked by low-velocity stimuli (2, 4, and 8 deg/s) and high-velocity stimuli (16, 32, and 64 deg/s) in the supine (red) and upright (blue) viewing positions. The values for median, 1st quartile and 3rd quartile were calculated based on the means collected from the last three trials of 16 participants. Significant main effects of viewing position from ART ANOVA were labeled with arrows and asterisks (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$).

in the upright position ($t = -2.214$, $p = 0.032$). On the CV onset time, significant interaction was found between 4 and 8 deg/s [$F_{(1,15)} = 6.152$, $p = 0.017$]. In the supine position, the onset time of roll CV induced by stimuli rotating at 4 deg/s was significantly longer than that induced by stimuli rotating at 8 deg/s ($p = 0.048$). Similar significant result was not found in the corresponding onset time data collected in the upright viewing condition. This suggests the relationship between stimulation velocity and roll CV measurements can depend on the viewing position.

DISCUSSION AND CONCLUSION

In this paper, we investigated the extrinsic effects of angular velocity (2, 4, 8, 16, 32, 64 deg/s) of provoking stimuli and viewing positions on the perception of roll CV. Two major findings are reported.

Major Finding 1: Stimulation Velocity Affects Roll CV Measurements in Different Ways Dependent on Viewing Positions

As the stimulation velocity increased from 2 to 64 deg/s, roll CV measurements were affected differently depending on the viewing positions. For the upright position, both average and accumulated CV durations reached substantial levels in all stimulation velocity conditions (10–23 s out of 30 s exposure time). This was not so for the supine position, when participants were supine and velocities were low (2–4 deg/s), significantly shorter CV durations (both average and accumulated) were reported. For both CV onset time and CV intensity, viewing positions did not change the ways that stimulation velocity affected them. Participants in both viewing conditions reported that they were moving in equal speeds, and in opposite direction of, the stimuli at all velocity conditions except for the 64 deg/s condition during which they reported significantly less roll CV (**Figure 3**). The CV intensity results collected in the upright position are consistent with Ujike et al. (2004) and Held et al. (1975) although both of their studies did not report statistical results. Brandt et al. (1973) used a cylindrical drum to induce yaw vection and reported that CV latency was independent of stimulation velocity (10–180 deg/s). In Brandt et al. (1973) experiments, CV latency ranged within 5 s for all different velocities. Our results agree with Brandt's finding except for 2 deg/s condition in which the reported CV latency (onset time) was 25 s. Brandt did not examine the 2 deg/s condition.

The results of this study uniquely fill the gap of reporting statistically verified results for multiple roll CV measurements (CV durations, CV onset times and CV intensities) provoked by viewing stimuli rotating at different velocities in an upright or supine viewing position.

TABLE 3 | Results of ART ANOVA on roll CV induced by low-velocity and high-velocity stimuli (low velocities: 2, 4, and 8 deg/s; high velocities: 16, 32, and 64 deg/s).

Responses	Effects	Low velocities	High velocities
Accumulated CV duration	Position	$F_{(1,15)} = 8.634$, $p = 0.004$**	$F_{(1,15)} = 3.153$, $p = 0.080$
	Velocity	$F_{(2,30)} = 15.979$, $p < 0.001$***	$F_{(2,30)} = 2.056$, $p = 0.135$
	P × V	$F_{(2,30)} = 1.554$, $p = 0.218$	$F_{(2,30)} = 1.121$, $p = 0.331$
Average CV duration	Position	$F_{(1,15)} = 18.638$, $p < 0.001$***	$F_{(1,15)} = 1.557$, $p = 0.216$
	Velocity	$F_{(2,30)} = 12.123$, $p < 0.001$***	$F_{(2,30)} = 4.202$, $p = 0.019$*
	P×V	$F_{(2,30)} = 0.354$, $p = 0.703$	$F_{(2,30)} = 0.114$, $p = 0.893$
CV frequency	Position	$F_{(1,15)} = 2.352$, $p = 0.129$	$F_{(1,15)} = 0.405$, $p = 0.526$
	Velocity	$F_{(2,30)} = 7.162$, $p = 0.001$***	$F_{(2,30)} = 3.362$, $p = 0.040$*
	P×V	$F_{(2,30)} = 2.374$, $p = 0.100$	$F_{(2,30)} = 1.172$, $p = 0.315$
Onset time	Position	$F_{(1,15)} = 8.229$, $p = 0.005$**	$F_{(1,15)} = 1.018$, $p = 0.316$
	Velocity	$F_{(2,30)} = 24.945$, $p < 0.001$***	$F_{(2,30)} = 0.130$, $p = 0.879$
	P×V	$F_{(2,30)} = 2.001$, $p = 0.142$	$F_{(2,30)} = 0.502$, $p = 0.608$
Intensity	Position	$F_{(1,15)} = 0.381$, = 0.539	$F_{(1,15)} = 0.224$, $p = 0.637$
	Velocity	$F_{(2,30)} = 7.753$, $p < 0.001$***	$F_{(2,30)} = 30.676$, $p < 0.001$***
	P×V	$F_{(2,30)} = 0.597$, $p = 0.553$	$F_{(2,30)} = 0.128$, $p = 0.880$

*Asterisks have been labeled according to the p-values (*p < 0.05; **p < 0.01; ***p < 0.001).*

As highlighted by our results, CV durations and onset times are significantly sensitive to changes in stimulation velocities around 2 deg/s, while CV intensity is significantly sensitive to changes in stimulation velocities around 64 deg/s. These findings suggest that future roll CV studies should consider these different dependencies on stimulation velocity when they determine roll CV measurements and stimulation velocity.

Major Finding 2: Longer Durations, Shorter Onset Time and Higher Frequency of Roll CV Were Achieved When Participants Were Upright Compared to Supine at Lower Stimulation Velocities (2, 4, and 8 Deg/s)

In this study, significant longer CV durations were reported among participants in the upright position compared to those in the supine position with low stimulation velocities (2, 4, 8 deg/s, **Figures 4A,B**). When watching random dots rotating at 4 deg/s, the same participants in the upright positions reported 4 times longer CV duration (median: 20 s) than when they were in the supine positions (median: 5 s, **Figure 3B**). Further, when watching dots rotating at 2 deg/s for 30 s, participants in supine only exhibited 2 s (median) duration of roll CV verses 10 s when they were upright (**Figure 3B**). The CV onset times reported in upright conditions were shorter than those in supine conditions when the stimulation velocities were low (2, 4, and 8 deg/s). Especially with a stimulation velocity at 2 or 4 deg/s, those participants in the supine positions required significantly more time to develop the roll CV sensations. The short duration and long latency of roll CV could affect the validity of functional brain studies. In this study, we found evidence to suggest that we should avoid using dots rotating at 2 and 4 deg/s in a supine functional brain study on roll CV even though CV intensity were higher with dots rotating at 4 and 8 deg/s. In summary, viewing position can significantly affect CV duration and onset time when the stimulation velocity is low.

When participants were exposed to roll stimulation in an upright viewing position, both visual-otolith conflict and visual-semicircular canal conflict arise. When participants watching roll stimulation in a supine viewing position, the otolith cues were not expected to inhibit or confirm the self-motion illusion. Since a vection sensation is associated with visual-vestibular conflicts, it has been hypothesized that viewing position can significantly affect roll CV sensations and that CV duration at a supine position should be longer than that at an upright position. However, the exact opposite was found in our study. Tanahashi et al. (2012) reported that the strength of roll vection perceived in an upright viewing position was slightly but not significantly greater than that perceived in a supine viewing position. Cheung and Howard (1990) also did not report significant difference in roll vection intensity between two viewing positions. To a certain extent, their findings are consistent with the results from our experiments; we have extended their findings to lower velocities (2, 4, and 8 deg/s) with larger effects of viewing position found in CV duration and onset time. One possible explanation of why our findings do not agree with the otolith hypothesis that reported CV duration should be shorter in upright positions is that somatosensory and tactile cues are also involved. Young and Shelhamer (1990) suggested that tactile cue was found to inhibit vection in space flight. In addition, a few studies on linear also reported stronger or longer lasting self-motion illusion in upright positions (Guterman et al., 2012; Oyamada et al., 2020), where there was tactile difference but no difference in otolith conflicts between two positions. In our experiment, the tactile cues in the supine position indicated implicit stationary sensation and might have inhibited the self-motion illusion. At slow velocities (2–8 deg/s), the inhibition on roll CV by proprioceptive tactile cues in the supine position providing sensations of stationary might be more prominent than that by otolith in the upright position. Thus, the CV onset times were longer and CV durations were shorter when participants, assuming in a supine position, watched stimulation with low velocities. Another possible reason for the disagreement with the otolith hypothesis may be due to the use of different reporting methods as compared to previous studies (Young et al., 1986b). With that said, in this study, the same reporting procedure was used in both supine and upright viewing positions. Further research is required to substantiate this explanation.

In conclusion, this paper investigated roll CV perception of stimuli of different velocities among participants in two viewing positions, upright and supine. Findings provide the basis for accurately interpreting and comparing results of roll CV studies in which participants were in different positions. In particular, the results indicate that, when the same group of participants is exposed to roll random dots rotating at lower velocities (2, 4, and 8 deg/s), they would report significantly different roll CV durations and onset times according to whether they were in upright or supine viewing positions. In some cases, the difference can be as large as 4 or 5 times. Since most functional brain imaging studies on CV require participants to assume supine positions while most behavioral studies on CV adopt upright positions, results of the current study suggest caution should be exercised when comparing findings of functional brain studies and behavioral studies on roll CV with different viewing positions. The current study only examined roll CV in counter-clockwise direction. Future work on pitch and yaw as well as roll in clockwise direction is desirable.

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 HKUST Human Subject and Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

YW, BD, and YW conducted the experiments and analyzed the data. RS is their thesis supervisor. All authors contributed to the article and approved the submitted version.

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Effects of Linear Visual-Vestibular Conflict on Presence, Perceived Scene Stability and Cybersickness in the Oculus Go and Oculus Quest

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Humans rely on multiple senses to perceive their self-motion in the real world. For example, a sideways linear head translation can be sensed either by lamellar optic flow of the visual scene projected on the retina of the eye or by stimulation of vestibular hair cell receptors found in the otolith macula of the inner ear. Mismatches in visual and vestibular information can induce cybersickness during head-mounted display (HMD) based virtual reality (VR). In this pilot study, participants were immersed in a virtual environment using two recent consumer-grade HMDs: the Oculus Go (3DOF angular only head tracking) and the Oculus Quest (6DOF angular and linear head tracking). On each trial they generated horizontal linear head oscillations along the interaural axis at a rate of 0.5 Hz. This head movement should generate greater sensory conflict when viewing the virtual environment on the Oculus Go (compared to the Quest) due to the absence of linear tracking. We found that perceived scene instability always increased with the degree of linear visual-vestibular conflict. However, cybersickness was not experienced by 7/14 participants, but was experienced by the remaining participants in at least one of the stereoscopic viewing conditions (six of whom also reported cybersickness in monoscopic viewing conditions). No statistical difference in spatial presence was found across conditions, suggesting that participants could tolerate considerable scene instability while retaining the feeling of being there in the virtual environment. Levels of perceived scene instability, spatial presence and cybersickness were found to be similar between the Oculus Go and the Oculus Quest with linear tracking disabled. The limited effect of linear coupling on cybersickness, compared with its strong effect on perceived scene instability, suggests that perceived scene instability may not always be associated with cybersickness. However, perceived scene instability does appear to provide explanatory power over the cybersickness observed in stereoscopic viewing conditions.

Keywords: virtual-reality, presence, cybersickness, motion sickness, vestibular, head mounted displays

INTRODUCTION

Over the past decade, we have seen a rapidly expanding consumer uptake of head-mounted displays (HMDs) for virtual reality (VR) in numerous applications. These applications have included education (Polcar and Horejsi, 2015), entertainment (Roettl and Terlutter, 2018), telehealth (Riva and Gamberini, 2000), anatomy and diagnostic medicine (Jang et al., 2017; Chen et al., 2020). The recent success of consumer-grade HMDs for VR is not only attributed to their increasing affordability, but also to their operational enhancements (e.g., larger field of view, relatively low system latency). These enhancements contribute to generating compelling experiences of *spatial presence*—the feeling of being "*there*" in the virtual environment, as opposed to *here* in the physical world (Skarbez et al., 2017). However, symptoms of cybersickness (nausea, oculomotor, discomfort, and disorientation) can still occur during HMD VR, particularly when *angular* head rotation generates display lag (e.g., Feng et al., 2019; Palmisano et al., 2019, 2020; Kim et al., 2020). Here, we examine whether the cybersickness in these HMDs can also be attributed to the visual-vestibular conflicts generated during *linear* head translation.

Previous research on HMD VR has primarily been concerned with studying the effects of visual-vestibular conflicts on *vection*—the illusory perception of self-motion that occurs when stationary observers view visual simulations of self-motion (Palmisano et al., 2015). In one vection study, Kim et al. (2015) used the Oculus Rift DK1 HMD to systematically vary the synchronization between visual simulations of angular head rotation and actual yaw angular rotations of the head performed at 1.0 Hz in response to a metronome. They found that vection was optimized when synchronizing the visually simulated viewing direction with the actual head rotation (i.e., when the display correctly compensated for the user's physical head motion). Vection strength was found to be reduced when no compensation was generated (i.e., when head tracking was disabled), and lower still when inverse compensation was generated (i.e., where the compensatory visual motion in display moved was in the opposite direction to normal for the user's head-movement). These findings suggest that synchronizing visual and vestibular signals concerning angular head rotation improve vection.

In a follow-up study to assess whether angular visual-vestibular interactions are also critical for cybersickness, Palmisano et al. (2017) systematically varied visual-vestibular conflict using the Oculus Rift DK1 HMD during sinusoidal yaw angular head rotations. They used the Simulator Sickness Questionnaire (SSQ) to measure cybersickness (Kennedy et al., 1993) and found that full-field inverse display compensation generated greatest cybersickness. The mean display lag was determined to be $\sim$ 72 ms for the HMD VR system they used to generate their virtual environment. This latency is quite high compared to modern systems like the Oculus Rift CV1 and S, which use Asynchronous Time Warp (ATW) to effectively eliminate angular latency. Indeed, Feng et al. (2019) and Palmisano et al. (2019) both reported that cybersickness was considerably reduced (during yaw head movements, respectively) when using these more recent HMDs with very low display lags. They measured cybersickness using the FMS—the Fast Motion Sickness questionnaire (Keshavarz and Hecht, 2011). They found that increasing display lag above baseline latency monotonically increased reported cybersickness severity from low to moderate levels. Even at baseline levels of lag (<5 ms), participants tended to report a very small level of discomfort consistent with cybersickness.

One potential explanation for this effect of display lag on cybersickness is the level of sensory conflict it generates (e.g., Reason and Brand, 1975; Reason, 1978). It is often assumed that cybersickness arises when one or more senses provide information that is incongruent with information provided by other senses (i.e., intersensory conflict). Recently, we have proposed that DVP—the magnitude of Difference between the orientation of the Virtual head relative to the Physical head—can be used to quantify the overall amount of sensory conflict generated by a stimulus. In the first study to examine this proposal, Kim et al. (2020) examined the effects of experimentally manipulating the level of display lag during active HMD VR. They instructed their participants to make oscillatory 1.0 or 0.5 Hz head rotations in pitch while viewing a simulated wireframe ground plane. They found that increasing display lag increased the magnitude of DVP. Critically, as the magnitude of this DVP increased, the participants' perceptions of scene instability and cybersickness both increased, and their feelings of presence decreased. These findings suggest that sensory conflict (as operationalised by DVP) can offer diagnostic leverage in accounting for cybersickness severity. However, conscious perceptions of scene instability and feelings of presence may also contribute to the severity of these symptoms (see Weech et al., 2019).

In early research, Allison et al. (2001) found that human observers could tolerate very significant system latencies before the virtual environment became perceptually unstable. In that study, significant scene instability was only perceived when observers executed high-velocity head movements that revealed the inconsistency between head and display motion. However, other researchers have proposed that moderate head-display lags (40−60 ms) can impair perception of simulator fidelity (Adelstein et al., 2003), and that even shorter temporal lags (< 20 ms) can be perceptible to well-trained human observers (Mania et al., 2004). Most previous studies have only considered the effect of *angular* sensory conflicts on perception. However, studies are yet to examine the effects of *linear* sensory conflict caused by head translation on cybersickness, as well as spatial presence and perceived scene instability. Ash et al. (2011) found that linear visual-vestibular conflicts can influence perceptual experiences of self-motion generated by external visual motion displays (c.f., Kim and Palmisano, 2008, 2010). Hence, it is possible that such linear visual-vestibular conflicts in HMD VR could affect perceived scene instability, presence and cybersickness.

New HMDs offer portable VR solutions (e.g., Oculus Go and Oculus Quest), but have significant functional differences in their response to changes in angular and linear head position. Whereas the Oculus Quest provides six-degrees of freedom

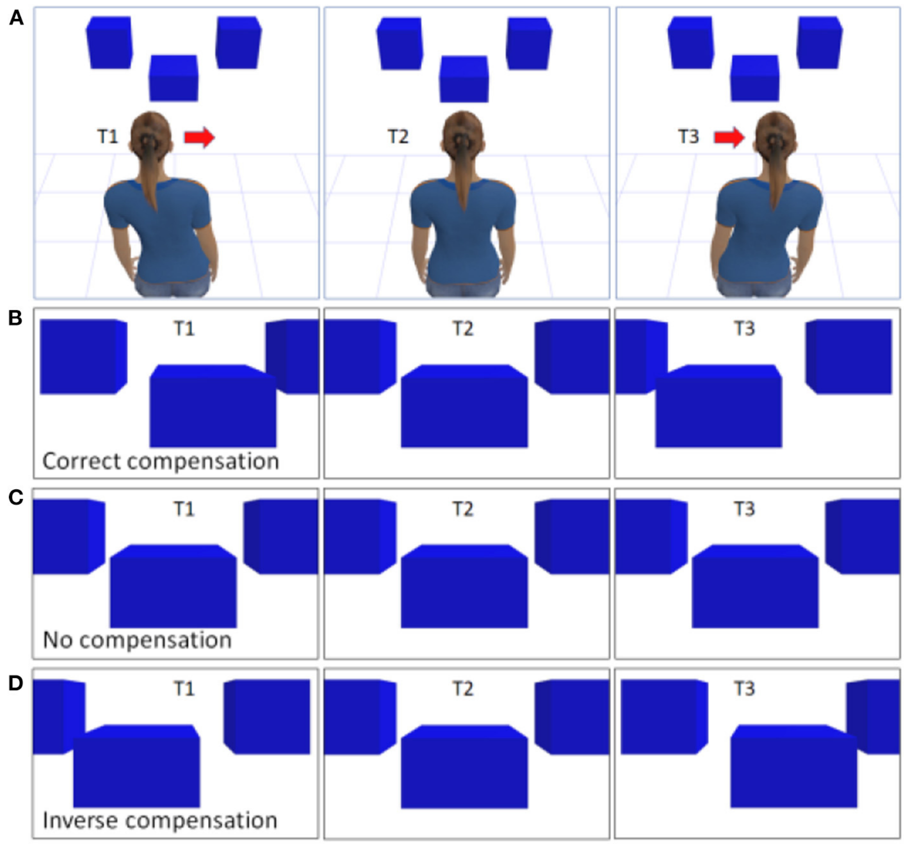

FIGURE 1 | Environmental appearances during linear head translation. **(A)** Physical relationship between stationary 3D objects and the point of regard during a linear translation of the head from left to right over time (T1–T3). **(B)** Correct compensation results in a retinal image that presents the correct perspective on the scene at each point in time. **(C)** No compensation generates no change in the visual image during changes in linear head position. **(D)** Inverse compensation presents visually simulated head motion in the opposite direction to that expected for physical head movement.

(6DOF) head tracking and compensates for both angular and linear head displacement, the Oculus Go only provides 3DOF tracking to compensate for angular rotations of the head (with no linear head tracking). Hence, the Oculus Quest generates "Correct Compensation" during linear head translation, but the Oculus Go generates a condition of "No Compensation" during the same head translation (see **Figure 1**). We can use the linear gains of 1.0 and 0.0 to describe the amount of potential sensory conflict provided by linear compensation in the Oculus Quest and Go, respectively. Using this convention, a gain of −1.0 would represent "Inverse Compensation" and should generate the greatest level of visual-vestibular sensory conflict. We predict that cybersickness should be less likely and less severe when using the Oculus Quest compared to the Oculus Go. We further predict that attenuating the gain of linear tracking in the Quest to zero should generate similar user experiences to the Oculus Go, but that inverse compensation (i.e., negative gain) should generate greatest cybersickness, perceived scene instability and reduced presence. Given that stereoscopic viewing might exacerbate cybersickness (Palmisano et al., 2019), we compared these attributes across displays viewed stereoscopically or monoscopically.

MATERIALS AND METHODS

Participants

A total of 14 normal healthy adults (age range 19–36 years) participated in this study. All had no neurological impairment and had good visual acuity without the need for the correction of refractive errors. All procedures were approved by the Human Research Ethics Advisory panel (HREA) at the University of New South Wales (UNSW Sydney).

Head Mounted Displays (HMDs)

We used two different devices, the Oculus Go and the Oculus Quest. These mobile HMDs are both completely portable but have quite different manufacturer specifications (developer.oculus.com/design/oculus-device-specs/). Both systems use ATW to minimize the effective/perceived angular display lag during head rotation.

The Oculus Go uses a single fast-switching LCD with a total resolution of 2,560 × 1,440 pixels. It supports two refresh rates (60 or 72 Hz) with natural color reproduction (sRGB, 2.2 gamma, and CIE standard D65 white illuminant). The binocular field of view is ∼100°. The Oculus Go's head movement tracking system offers only 3DOF positional tracking of only angular head rotation (not linear head displacement).

The Oculus Quest uses dual OLEDs with individual resolutions of 1,440 × 1,600 pixels, somewhat superior to the Oculus Go. The Oculus Quest operates at the 72 Hz refresh rate for each eye with default SDK color reproduction (native RGB, 2.2 gamma, but still with CIE standard D65 white illuminant). Like the Oculus Go, the binocular field of view is ∼100°, but the Oculus Quest uses an inside-out optical head movement tracking system to offer 6DOF positional tracking (tracking both angular and linear head position).

We configured both these devices after pairing the hand remote(s) to the respective HMDs using an Apple i-Phone running the Oculus App. This application showed the view being presented in the HMD in real time on the phone's display. The devices were set to enable developer mode to allow the addition of new Android applications to be uploaded to the HMDs for running our experiment.

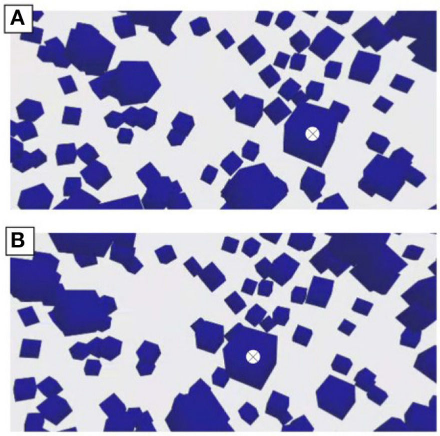

FIGURE 2 | Sample screenshots of the virtual environment. These two screenshots show the same environment viewed from two different vantage points. These views were produced by a roughly linear head displacement of ∼30 cm from the left horizontal position **(A)** to the right horizontal position **(B)**. Individual cube orientations maintained between views to show the motion parallax capabilities of this system. Corresponding foreground cubes in the two images have been marked with an '×' for reference. Note that the black background has been set to white for print reproduction.

The Virtual Environment

We adapted the Native Mobile SDK application "NativeCubeWorldDemo" accompanying the Oculus developer code examples on the Oculus website (https://developer.oculus.com/). We configured the compiler using Android Studio based on the recommended settings provided by the Oculus developer website. The experimental application code was compiled to build an Android application package (APK), which was then pushed to the Oculus Quest and Go using the Android Debug Bridge (ADB). These devices were connected to the development PC via direct USB connection.

The default behavior of the example application was modified by setting the color of 3D generated cubes to a darker bluish hue sRGB (0.0, 0.0, 0.2∼0.4). Two opposing faces were configured to have slightly different blue intensities (0.2 and 0.4). This ensured that the chromaticity of the simulated visual elements was comparable to similar traditional research studies on perception of self-motion in virtual environments (e.g., Kim and Palmisano, 2008, 2010—both of which examined display lag manipulations during physical head movements using large external displays).

A static screenshot of the virtual environment from one vantage point is shown in **Figure 2**. Because the cubes surround the user within a ± 4 m perimeter, many of the cubes will never been seen. To increase the depth of the display beyond the default behavior of the sample code, we shifted all the cubes in front of the participant to generate an 8 m deep display. A sample code snippet shows the method we used to preserve stereopsis or determine the cyclopean view (for monoscopic viewing), while still supporting motion parallax as a function of linear gain (see **Appendix A**). Essentially, the gain served as a multiplier that affected simulated head displacement along the three cardinal axes. All rotational mappings of head movements were preserved (i.e., correct angular compensation was applied in all situations of linear gain manipulation).

Procedure

Prior to participation, all participants consented to the recruitment requirements of the study by providing written informed consent. Participants were instructed to stand upright wearing one of the HMDs and perform interaural head translations at a rate of 0.5 Hz. The rate was maintained using an audible metronome running continuously on a separate host PC with speakers. Participants were each given a small amount of time to practice the head movements with feedback provided by the experimenter trained on the assessment of head movements. This was done to ensure the participants understood the instructions and that they had good range of mobility for generating the required inter-aural head movements with minimal head rotation. During the experiment no further feedback was provided on performance. Participants were instructed to maintain their gaze off in the distance to one of the farthest targets while viewing each simulation. No fixation was used to create conditions that were comparable to typical viewing in natural viewing conditions.

In each test session, participants viewed 14 conditions on the Oculus Quest: stereoscopic vs. monoscopic viewing (two levels) × different amounts of translational gain: −1.0, −0.5, −0.25, 0.0, +0.25, +0.5, +1.0 (seven levels). Participants also performed two separate conditions on the Oculus Go: stereoscopic vs. monoscopic viewing at 0.0 translational gain. Participants viewed simulations on the Oculus Quest and Oculus Go in counterbalanced order (e.g., 14 trials on the Quest followed by 2 trials on the Go for one participant, and then, 2 trials on the Go and 14 trials on the Quest for the next participant). After participants viewed each display condition for 30 s, the simulation ceased and the display faded to complete darkness. At this time, participants were instructed to verbally report perceived scene instability, spatial presence and cybersickness. Time was provided before participants commenced their subsequent trial. This was done to mitigate the build-up of cybersickness and contamination between trials. The minimum delay between trials was 30 s (to reduce the possibility of any experience of cybersickness transferring between trials). However, the experimenter could pause the display between trials if participants requested a break. Participants were told that they should not proceed onto the next trial until their cybersickness symptoms had dissipated (i.e., their FMS score had returned to 0). On the few occasions, a break of up to ∼90 s was necessary for the participant to report that their symptoms had resolved.

Perceived scene instability was reported as a subjective 0–20 rating on how much the simulated cubes in the virtual environment appeared to move with the participant as they translated their head inter-aurally (0 = remained stationary independent of head movement like objects in the real world; 10 = moved as much as the participants own head; 20 = moved twice as much the participants head moved). Spatial presence was reported on a 0–20 rating scale, where 0 indicated the participant "feels completely here in the physical environment" and 20 indicated the participant "feels completely there in the virtual environment". This rating system is based on those used in previous studies (IJsselsteijn et al., 2001; Clifton and Palmisano, 2019). Cybersickness was measured using the Fast Motion Sickness (FMS) scale (Keshavarz and Hecht, 2011). This FMS scale provides discrete values per trial, and therefore, is a convenient method for making inter-trial comparisons. The FMS was originally validated against the Kennedy Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). Although it does not provide information about cybersickness symptoms (only its severity), it requires far less time than the SSQ for participants to complete (Keshavarz and Hecht, 2011). To gain insights into the overall level of cybersickness generated by participation in this study, and the symptoms experienced, we did however have participants complete the SSQ prior to, and at the conclusion of, their HMD VR testing.

Statistical Analysis

For data obtained using the Oculus Quest, participant reports of perceived scene instability and spatial presence were analyzed using repeated-measures ANOVAs. A Poisson mixed model was used to test the effect of linear gain and viewing type on cybersickness. We also correlated these perceptual outcome measures against one another to identify any perceptual interrelationships. For data obtained using the Oculus Go, we used repeated-measures *t*-tests to assess whether our outcome measures differed to the mean Correct Compensation and No Compensation conditions obtained using the Oculus Quest. For the Oculus Quest, we also assessed the overall amplitudes of the 6DOF head movements generated by participants to determine how consistent they were across viewing conditions. We also verified that the comparable levels of angular head rotation were minimal and consistent between tasks performed on the Oculus Quest and Go HMDs.

RESULTS

Oculus Quest

Each of our three outcome metrics are plotted as a function of linear gain imposed on the Oculus Quest in **Figure 3** below. Whereas results from monoscopic viewing are represented by open points and dashed lines, results from stereoscopic viewing are represented by dark points and solid lines.

Perceived scene stability improved when the linear gain increased from negative to positive (inverse to correct) compensation (i.e., perceived scene instability was reduced). A repeated-measures ANOVA found a significant main effect of linear gain on perceived scene instability ($F_{6,78} = 19.71$, $p < 0.001$). There was no main effect of viewing type (stereoscopic or monoscopic) on perceived scene instability ($F_{1,13} = 0.04$, $p = 0.84$). However, there was a significant interaction effect between linear gain and viewing type on perceived scene instability ($F_{6,78} = 7.29$, $p < 0.001$). This interaction can be attributed to the greater perceived scene instability found for monoscopic viewing in the correct-compensation condition, but lower perceived scene instability under the no-compensation condition (compared with stereoscopic viewing).

Spatial presence was unaffected by changes in linear gain. A repeated-measures ANOVA found no main effect of linear gain on spatial presence ($F_{6,78} = 1.41$, $p = 0.22$). There was also no main effect of viewing type on spatial presence ($F_{1,13} = 1.68$, $p = 0.22$). There was no interaction between linear gain and viewing type on spatial presence ($F_{6,78} = 1.66$, $p = 0.14$). These results show that spatial presence is robust to changes in linear gain.

Cybersickness was consistently reported to be zero for many of our participants across all levels of gain. A total of seven participants reported cybersickness in at least one stereoscopic viewing condition, six of whom also reported cybersickness in monoscopic viewing conditions. Hence, seven participants did not report any cybersickness during their participation in this study. Due to the large number of zero ratings reported, we used a Poisson mixed model with viewing type and gain as fixed effect factors and trial order as a separate time-varying covariate. For this analysis, monoscopic viewing was coded as 0 and stereoscopic viewing was coded as 1. We treated linear gain as a numeric variable based on the assumption the overall trend is linear as evident in **Figure 3** (Right). There were no detected significant fixed effects on cybersickness for both linear gain ($\beta = -0.78$, SE $=1.24$, $p = 0.53$) and viewing type ($\beta = +2.73$, SE $= 1.62$, $p = 0.09$). However, there was a significant interaction effect between viewing type and gain on cybersickness ($\beta = -0.88$, SE $= 0.29$, $p = 0.002$). The effect of trial order on reported cybersickness was also found to be significant ($\beta = +0.06$, SE $= 0.02$, $p = 0.004$). These results show we could not detect any significant effect of linear gain on cybersickness under monoscopic viewing conditions. However, the significant interaction suggests that the effect of linear gain on cybersickness is significantly different under stereoscopic viewing conditions.

To assess other possible order effects, we performed correlations between the two remaining outcome metrics and the temporal order of all conditions performed by participants

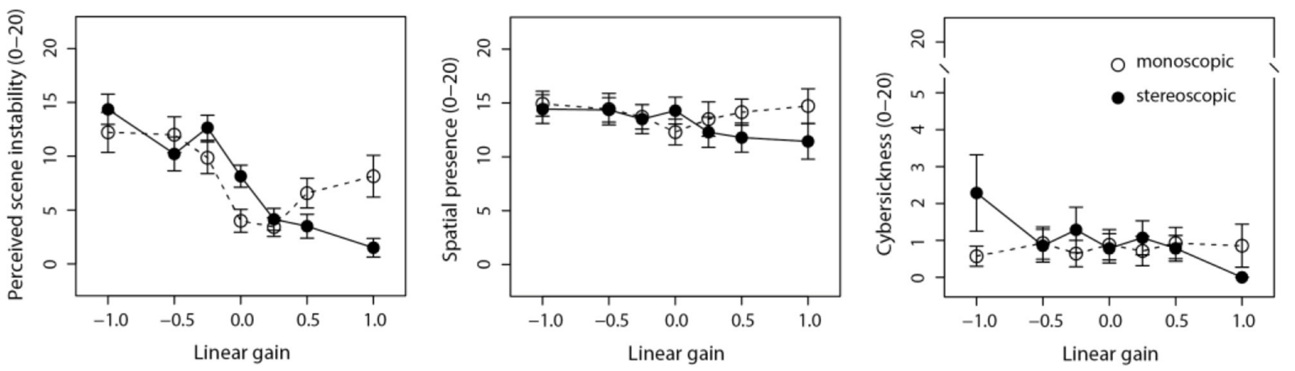

FIGURE 3 | Outcome measures plotted as a function of linear gain on the Oculus Quest HMD. Mean perceived scene instability plotted as a function of linear gain **(Left)**. Mean spatial presence plotted as a function of linear gain **(Middle)**. Mean cybersickness ratings plotted as a function of linear gain **(Right)**. Dark points and solid lines show data for stereoscopic viewing, open points and dashed lines show data for monoscopic viewing. Error bars show standard errors of the mean.

irrespective of viewing condition or linear gain. There were no detected significant correlations between perceived scene instability and trial order ($r = -0.01$, $p = 0.99$) or between spatial presence and trial order ($r = -0.06$, $p = 0.43$).

We assessed whether the small amounts of reported cybersickness on average could be accounted for by perceived scene instability. A Pearson's product-moment correlation found a significant linear relationship between perceived scene instability and cybersickness severity during stereoscopic viewing conditions ($r = +0.81$, $p = 0.028$). No significant correlation was detected between perceived scene instability and cybersickness when viewing displays monoscopically ($r = -0.27$, $p = 0.55$). These findings suggest that variations in perceived scene instability account for 66% of the variations in cybersickness associated with stereo viewing only.

Oculus Go

Bar graphs in **Figure 4** show the mean outcome metrics for the Oculus Go compared with the equivalent zero-gain (i.e., no compensation) for linear tracking on the Oculus Quest. Repeated-measures ANOVAs were used to examine the effects of device type and viewing type on perception and well-being in these zero-gain conditions. For perceived scene instability, there was no main effect of device type ($F_{1,13} = 2.61$, $p = 0.13$). However, there was a significant main effect of viewing type on perceived scene instability ($F_{1,13} = 19.02$, $p < 0.001$)—with stereoscopic viewing resulting in greater scene instability than monoscopic viewing. There was also a significant interaction between device type and viewing type for perceived scene instability ($F_{1,13} = 19.02$, $p < 0.001$). For spatial presence, there was no significant main effect of device type detected ($F_{1,13} = 0.097$, $p = 0.76$). There was no significant main effect of viewing type on spatial presence detected ($F_{1,13} = 2.69$, $p = 0.13$). The interaction between device type and viewing type was also not statistically significant for spatial presence ($F_{1,13} = 2.69$, $p = 0.13$). No device type or viewing type effects were found to be significant for cybersickness (none of the conditions examined generated mean FMS scores that were statistically greater than zero). Of the 14 participants, the number of participants who reported any cybersickness was 6 in zero-gain conditions on the Oculus Quest and 4 on the Oculus Go.

Head Movements

Typical head movements generated by a representative participant are shown in **Figure 5**, which plots the time-series data for changes in linear and angular head position generated in the no-compensation condition under stereoscopic (top) and monoscopic (bottom) viewing conditions. Further analysis on the overall peak-to-peak change in head displacement confirmed that there were no consistent differences in linear head movement across gain conditions. A three-way ANOVA did not find significant main effects of viewing condition ($F_{1,5} = 1.01$, $p = 0.36$) or linear gain ($F_{6,30} = 0.64$, $p = 0.70$) on the amplitude of cardinal *linear* head displacement. However, there was a significant main effect of peak-to-peak amplitude of linear head displacement along the three cardinal axes of head displacement ($F_{2,10} = 14.70$, $p = 0.001$). Linear displacement of the head along the inter-aural axis (M = 20.9 cm, SD = 5.8 cm) was greater than naso-occipital head movements (M = 4.0 cm, SD = 4.1 cm) and dorso-ventral head movements (M = 8.0 cm, SD = 9.6 cm).

Another three-way ANOVA detected no significant main effect of viewing condition ($F_{1,5} = 0.087$, $p = 0.78$) or linear gain ($F_{6,30} = 0.75$, $p = 0.62$) on the amplitude of cardinal *angular* head rotation. There was a significant main effect of peak-to-peak amplitude of angular head rotation around the three cardinal axes ($F_{2,10} = 9.87$, $p = 0.004$). Mean angular displacement of the head around the vertical dorso-ventral axis (M = 11.5°, SD = 6.19°) was significantly greater than head rotation around the naso-occipital axis (M = 5.95°, SD = 2.42°) and inter-aural axis (M = 5.73°, SD = 2.44°).

DISCUSSION

When using the Oculus Quest (with linear head tracking), perceived scene instability was found to increase as linear

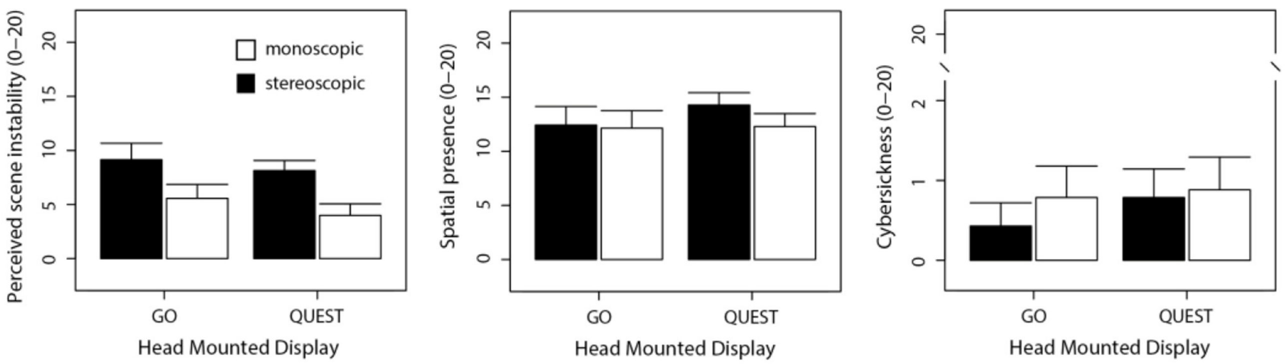

FIGURE 4 | Bar graphs of the outcome measures for the zero-gain conditions on the Oculus Go and Oculus Quest HMDs. Mean perceived scene instability **(Left)**. Mean spatial presence **(Middle)**. Mean cybersickness ratings **(Right)**. Dark bars show data for stereoscopic viewing, white bars show data for monoscopic viewing. Error bars show standard errors of the mean.

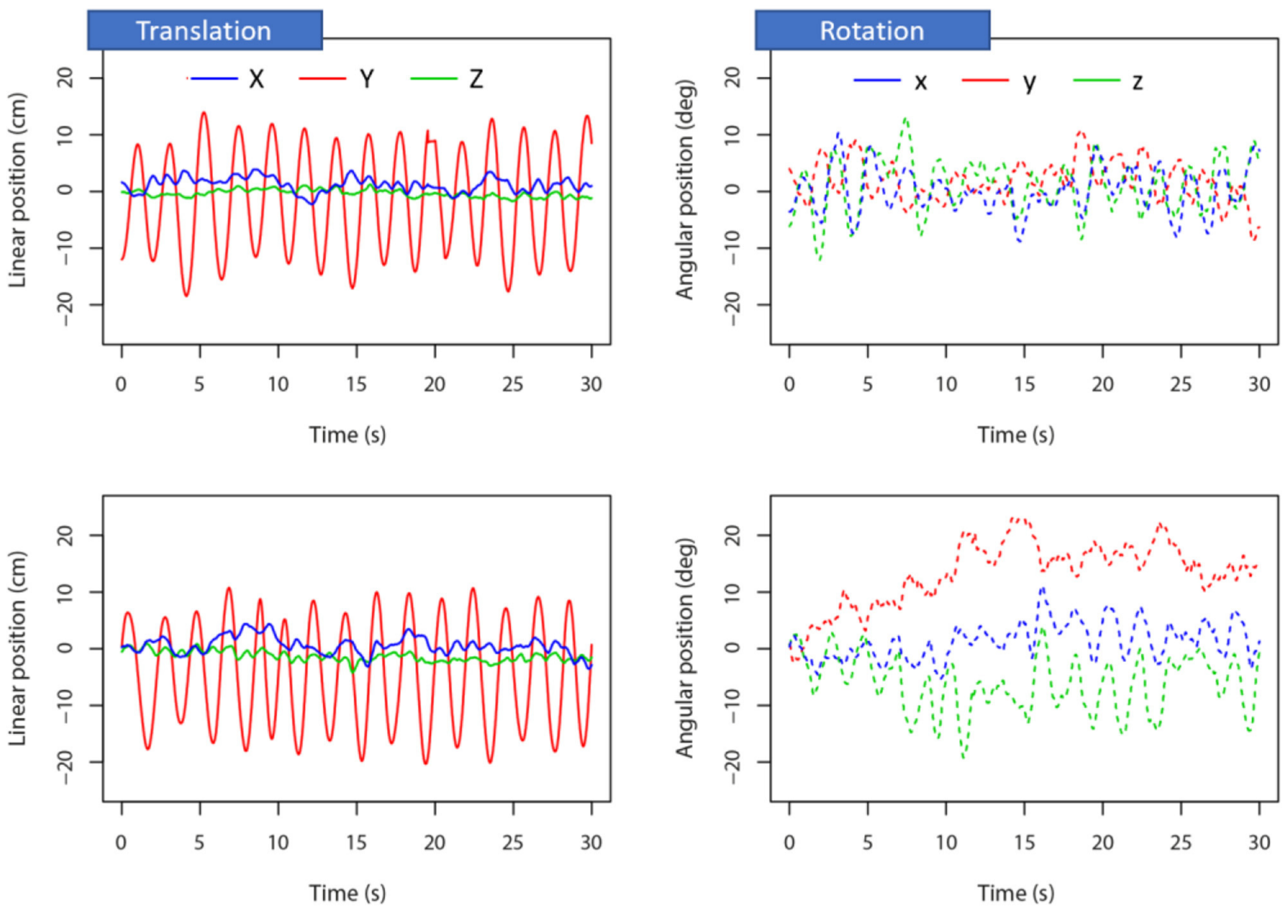

FIGURE 5 | Head movements from a representative participant in the zero-gain condition on the Oculus Quest. Left panel shows linear head position and right panels show angular head position. Upper panel shows results from stereoscopic viewing and lower panels show results from monoscopic viewing. X corresponds to translation along the naso-occipital axis, Y corresponds to translation along the inter-aural axis, and Z corresponds to translation along the dorso-ventral axis (x, y, and z show rotations around the same axes).

display gain was reduced from correct compensation toward inverse compensation. However, this manipulation only altered cybersickness in stereoscopic viewing conditions. Estimates of spatial presence were also found to be invariant across changes in linear display gain. When using the Oculus Go (without linear head tracking), we found that levels of perceived scene instability, presence and cybersickness were similar to those obtained with the Quest under comparable (i.e., zero-gain linear compensation) conditions. While monoscopic viewing in these zero-gain conditions was found to improve perceived scene stability on both devices, it also had the effect of reducing spatial presence (compared to stereoscopic viewing). However, under correct compensation conditions, perceived scene stability was higher under stereoscopic viewing conditions.

Our past research has shown that cybersickness is increased by brief exposures to angular visual-vestibular conflicts (produced by artificially inflating display lag—Feng et al., 2019; Palmisano et al., 2019, 2020; Kim et al., 2020). These increases in cybersickness were found even with brief exposures of around 12 s. In these studies, participants were instructed to engage in active angular head displacements at a comfortable functional range (similar in terms of amplitude to those they would normally use when exploring virtual environments in most use cases). Although we found in the current study that instructing participants to engage in purely linear changes in head orientation at a comfortable biomechanical range generated cybersickness, the severity of cybersickness was lower and only reported during stereoscopic viewing conditions.

One potential explanation for the difference in findings between our active linear conflict study and angular conflicts studied previously is the salience of the vestibular stimulation involved. The angular range of 0.5 Hz head rotations in previous studies was typically about $\pm$ 20°, which can potentially achieve angular accelerations of up to $\sim$200°/s^2. These levels of angular head acceleration were sufficient to generate compelling cybersickness during head rotations in yaw (Feng et al., 2019; Palmisano et al., 2019, 2020) and pitch (Kim et al., 2020). In the current study, participants generated head movements over a 20 cm range on average. Hence, a $\pm$ 10 cm head translation of 0.5 Hz should have generated short peak acceleration of $\sim$1.0 m/s^2. This vestibular stimulation is shorter and less intense than many of the linear head accelerations encountered in the real-world (e.g., in situations like driving a car; Bokare and Maurya, 2016). So, it is possible that longer lasting and more intense linear visual-vestibular conflicts may be more provocative for cybersickness. However, an alternative interpretation of the current findings is that humans may be biomechanically resistant to linear conflicts generating cybersickness (at least compared to the effects of angular conflicts).

Otolithic Contributions to Linear Sensory Conflict

As noted above, even with significant stimulation of the vestibular system, it is possible that conditions of linear conflict might be less provocative than angular conflicts. The general lack of cybersickness found with linear visual-vestibular conflict could be attributed to functional differences of the otolith system, compared with the semicircular canal (SCC) system. Eye-movement responses to angular head acceleration have a latency of around 10 ms (Collewijn and Smeets, 2000). However, these latencies can typically be longer in response to linear head accelerations; the latency of the otolith-ocular reflex is about 10 ms for high-acceleration linear head translations (Iwasaki et al., 2007), but can range up to 34 ms in response to low-acceleration linear head translations (Bronstein and Gresty, 1988). The relatively low translatory head accelerations generated by our participants would have invoked activity of this longer latency low-frequency otolith-ocular system, which may be more tolerant to sensory conflict.

Neurological evidence further suggests that endogenous otolith-mediated conflicts might be less provocative than conflicts associated with SCC dysfunctions. Neurologists routinely carry out assessments of vestibular evoked myogenic potentials (VEMPs), which measure short-latency click-evoked responses of the cervical muscles (cVEMP) (Colebatch et al., 1994) or short-latency ocular responses to high-frequency head vibrations administered to the hairline at Fz (e.g., Iwasaki et al., 2007). These clicks and vibrations are known to selectively stimulate primary otolith receptors, as verified in neurophysiological studies on guinea pigs (Murofushi et al., 1995; Curthoys et al., 2006). Surveys of hospital records on vestibular patients have identified patients with normal vestibular ocular responses to angular head impulses indicative of normal SCC function, but abnormal VEMPs indicative of otolith dysfunction (Iwasaki et al., 2015; Fujimoto et al., 2018). Fujimoto et al. (2018) found these patients with otolithic-specific vestibular dysfunction (OSVD) often reported symptoms attributed to rotary vertigo caused by dislodged otoconia in one of the SCCs ($\sim$14%)—a condition known as benign paroxysmal positional vertigo (BBPV). Non-rotary disturbances were not generally reported by those diagnosed with BPPV nor by the 47% of OSCD patients not formally diagnosis with a specific vestibular disorder. These findings suggest that (real/simulated) otolith dysfunctions per se are less likely to generate noteworthy subjective disturbances than SCC dysfunctions.

Based on this neurophysiological evidence, it is possible that participants may be more perceptually tolerant of visual-vestibular sensory conflict generated by linear head motion during HMD VR. This may account for the limited cybersickness in the current study, compared to previous studies that found angular sensory conflicts generate compelling cybersickness (Palmisano et al., 2017, 2019; Feng et al., 2019; Kim et al., 2020). Coupled with the low intensity brief translational accelerations imposed in the present study, no significant cybersickness was reported. It is possible that more salient linear conflicts would ultimately be required to generate provocative experiences of cybersickness in HMD VR. However, healthy users can find low frequency, large amplitude vertical or horizontal linear body translations to be highly sickening, so our predictions do not extend to these types of otolith-medicated cases, which can occur in the transportation and laboratory settings (e.g., Vogel et al., 1982).

Functional Comparison of the Oculus Quest and Oculus Go HMDs

Significant cybersickness was not consistently reported on either the Quest or the Go in any of the linear head movement and viewing conditions examined in this study. When we considered the responses in the zero-gain condition of the Oculus Quest and the Oculus Go, stereoscopic viewing generated significantly greater presence than monoscopic viewing. Perceived scene instability was found to also be significantly greater in the stereoscopic condition, compared with the monoscopic viewing condition. However, perceived scene instability was lower for stereoscopic viewing under correct-compensation on the Oculus Quest compared with monoscopic viewing (evident in the significant interaction effect between viewing condition and linear gain). We did not observe any main effects of linear gain or stereoscopic viewing on spatial presence when using the Oculus Quest. Overall, the rates of perceived scene instability, presence and cybersickness were quite similar across the two types of displays when matched on functional limitations, but functional advantages were achievable when using the Oculus Quest with correct-compensation linear gain.

Dependence on Properties of the Visual Environment

In the current study, perceived scene stability/instability was found to depend on the level of linear gain on the Oculus Quest. The steep decline from −0.25 through zero to +0.25 would suggest that participants are more sensitive to scene instability inferred from a head-centric rather than world-centric coordinate frame. Hence, participants appear to rely on the velocity of retinotopic motion to assess visual-vestibular compatibility when judging perceived scene instability. The findings also suggested that perceived scene instability accounted for cybersickness observed in stereo viewing conditions, which could depend on retinotopic assessment of motion conflict between visual and vestibular signals about variations in lateral linear head velocity. These findings have some similarity to the perceived "angular" scene instability and cybersickness reported in Kim et al. (2020). However, spatial presence was generally found to be robust to changes in linear gain, unlike the strong dependence on angular conflicts observed in the previous Kim et al. (2020) study. The differences in the findings of these two studies is likely to be due to differences in the salience of the visual-vestibular conflicts involved, and properties of the displays may also account for these differences.

One major difference between these studies was the previous emphasis on display lag. Our past research on perceived scene instability has focussed on the effects of adding display lag (on both DVP and cybersickness) during angular head rotations (Palmisano et al., 2019; Kim et al., 2020). In the current study, no additional display lag was imposed, only changes in the direction and velocity of visual motion relative to active linear head movements. It appears that display lag was important for generating cybersickness in previous work. However, display lag per se may not be critical for the compelling experience of cybersickness, but rather, the simulation of significant visual motion presented during angular (and possibly linear) head displacements.

Other previous research has shown that cybersickness tends to be higher when viewing displays with angular inverse compensation (Arcioni et al., 2019), a difference found to be significant when viewing full-field visual motion (Palmisano et al., 2017). During head rotation, all the display elements move at the same velocity during angular rotation of the head. In contradistinction, linear head translations (like those used in the current study) generate motion parallax; nearer simulated visual features are displaced more than visual features simulated in the distance. The relatively stable visual elements simulated in the background could serve as a rest frame (Prothero, 1998), constraining the generation of cybersickness. Although our participants were instructed to rate perceived scene instability, these perceptual estimates may have been based on any set of visual elements distributed in depth. Following their participation, some observers noted that monoscopic conditions appeared to generate the appearance of a larger, but less stable virtual environment (because it appeared less rigid). Nearer/larger objects appeared more unstable than smaller/farther objects. It would be advantageous in future to consider whether reducing the simulated depth of the scene increases perceived scene instability and generates cybersickness during conditions of inverse linear display compensation.

In the present study, we rendered 3D cubes that were distributed in depth to create a volumetric cloud with geometric perspective cues and size cues to depth of the scene. Stereoscopic viewing also facilitated the appearance of depth in the display. Though we did not assess apparent size of the environment, informal reports (from some participants after the experiment) were that the scene appeared to be larger in scale when viewed monoscopically. It is possible the "no linear compensation" displays appeared more stable with monoscopic viewing because the elements appeared to be farther away and provided less information about their organization in depth. It is possible then that using an environmental simulation with intrinsic perspective (e.g., a textured ground plane), may help to increase visual sensitivity to processing information about scene instability under these conditions.

Ultimately, it is expected that industry developments in optimizing render times should further improve user experiences in a variety of VR applications by enhancing image quality and minimizing cybersickness. In this study, we found that linear conflicts appear to be tolerated better than the angular conflicts found previously with sensory conflicts generated by display lag. It is possible that modulation of render quality over render time could be dynamically altered during the simulation based on the amount of linear or angular head movements engaged in by users. This may have critical benefits for GPU rendering architectures where near-photorealistic rendering is preferred for AR or VR applications and planet scale XR (Xie et al., 2019, 2020).

Suggested Design Guidelines

It is important to consider the implications of the findings of the current study for the future design of HMD VR hardware and software. Our collective findings across studies suggest that the self-generated angular conflicts we generated during VR use in Kim et al. (2020) may be less provocative than the linear visual-vestibular sensory conflicts we observed in the present study. This remains to be confirmed in a direct within-study comparison with a larger sample and additional controls for carryover effects, further control of linear and angular head movements, and the contribution of angular versus linear movement in the absence of artificially-introduced VR conflict. One possible interpretation of these findings is that users are more tolerant of linear conflicts, compared with angular conflicts. It would therefore be strategic to prioritize the implementation of innovations to reduce angular conflicts over linear conflicts. For example, software methods used to reduce render time (e.g., foveated rendering or reduced rendering quality) could be dynamically applied depending on the instantaneous angularity or linearity of head movements. This dynamic rendering may need to be implemented in a way that is also dependent on scene content. It is possible that the user's tolerance of linear sensory conflict may decline when a structured ground-plane is used, which could be exacerbated by the rendering of diffuse or specular reflectance properties informative of surface shape and gloss (Honson et al., 2020; Ohara et al., 2020). In these situations, it may be necessary to rely on rest frames to provide users with a stable physical frame of reference (Prothero, 1998). This may help by providing a stable world-centric frame of reference to reduce any perceived scene instability, which was found to be positively correlated with cybersickness in a recent study (Kim et al., 2020).

Potential Limitations

It is possible that the large number of zero scores for cybersickness reflects statistical censoring in the reporting of the magnitude of cybersickness experienced by our participants. However, we believe that these results indicate that linear visual-vestibular conflicts are less likely to generate cybersickness. In previous work, we found that angular conflicts for head rotation generated significant levels of cybersickness that were ∼20% of the reportable FMS maximum of 20 (Feng et al., 2019; Palmisano et al., 2019; Kim et al., 2020). The minimal cybersickness reported in the present study was obtained using considerably longer HMD VR exposure durations (30 s) compared to these previous angular conflict studies (12 s). Even if we were to consider only reportable values that were greater than 0 (e.g., a value of 1), the magnitude of the effect would be no greater than 5% of the reportable FMS range. Hence, after considering the potential limitation of statistical censoring, linear sensory conflicts still do not appear to be as provocative of cybersickness as angular conflicts (at least for the virtual environment we used in this study). However, future research using an articulated ground plane will help ascertain whether this finding generalizes beyond 3D point-cloud virtual environments.

Researchers should take care to mitigate any carryover effect between trials, caused either by cybersickness building from trial-to-trial, or conversely, by adaptation to the stimuli causing less cybersickness overall (compared to what would have been present in the absence of adaptation-based carryover effects). The current study did not allow for pauses long enough to confidently rule out potential carryover effects, and our verification that symptoms elapsed between trials is not a guarantee against confounding sickness sensitization caused by a one trial to carryover to another. Nevertheless, the reported symptoms in this study were infrequent and low in severity when felt, which implies there was less overt sickness to carryover from trial to trial. However, we observed a significant effect of trial order, which provided evidence consistent with a build-up of cybersickness over successive trials. To address these potential limitations, it would be ideal to allow more time to mitigate the likelihood of cybersickness sustaining or even accumulating across conditions. It would be valuable to also consider to what extent variations in cybersickness across successive trials could be subject to learning and sensorimotor recalibration (Wilke et al., 2013). The oscillatory head movements used in our study were also very unusual. Hence, there may be limited ability to generalize the findings from our study to these kinds of linear (and angular) head movements likely to occur more typically in regular VR situations.

It should be noted that angular self-movement can elicit symptoms even when an artificial sensory conflict such as ours has *not* been introduced. Previous research by Bouyer and Watt (1996a,b,c) shows that torso-rotation can generate motion sickness over a period of 30 min. This motion sickness was found to habituate over a period of 3–4 days (Bouyer and Watt, 1996a). The habitual decline in motion sickness was *not* associated with changes in gain of the angular vestibulo-ocular reflex (aVOR) during active oscillatory head rotation at 1–2 Hz (Bouyer and Watt, 1996a). However, the amplitude of these active head movements was found to increase with measured declines in aVOR (Bouyer and Watt, 1996b,c). This suggests that participants may unintentionally generate different active head movements under conditions that alter vestibular function. In the current study, we found that the amplitude of head movements was consistent across conditions, despite the imposed changes visual-vestibular coupling. The 30 s duration of our head-displacement task was also much shorter than the torso rotations used in the Bouyer et al. studies, reducing the likelihood of any significant adaptation occurring. This evidence appears to support the view that linear visual-vestibular conflicts are less provocative than angular conflicts. Although the literature offers evidence that a comparable angular motion in a normal room can be sickening, no such evidence has been found concerning a comparable linear motion. It will therefore be important for future studies to compare our experimental angular and linear self-motion conditions to identical movements inside a normal room when no virtual conflict is introduced.

Another potential limitation is the lack of provision of feedback on head movements made during the linear head displacement tasks. Overall, linear head translation along the inter-aural axis was a dominant feature in head movements generated by our active participants. However, the head movements also contained small amplitudes of linear translation in other directions and small amounts of 3D angular rotation. It is possible that some of these extraneous head movements could be responsible for the cybersickness reported here. Future studies could mitigate these undesired head movements using feedback provided about tracked head movements in real-time, which should help users control head movements more precisely. However, this feedback might introduce attentional effects, which we opted to avoid introducing in the design of the current study. Although it is possible that small inadvertent angular rotations of the head might be more visually salient in zero gain conditions, angular head movements were correctly compensated for at all times. This experimental arrangement should have mitigated the potential effects of these angular head rotation on generation of cybersickness.

Given the potential role of the linear VOR and gaze holding, it may also be valuable to consider the role of gaze in future. Although we requested participants to look deep into the virtual environment, it is difficult to ensure that gaze was constrained in depth without eye tracking. It is possible that eye movements may influence experiences of the virtual environment by modifying the pattern of retinal motion generated by optic flow (Kim and Khuu, 2014; Fujimoto and Ashida, 2020). Therefore, it would be advantageous to assess whether vestibular-mediated gaze holding in depth might also influence the effect of linear gain on perceived scene instability, presence and cybersickness.

The sex composition of our sample was primarily male (11 vs. 3), but the effect we report with subjects between HMDs devices would seem to have been appropriately controlled. Previous studies have reported sex differences when using HMDs, whereby females tend to either experience more cybersickness severity, or experience it sooner, compared with males (Munafo et al., 2017; Curry et al., 2020). However, such sex differences were not supported by recent systematic reviews of the literature on cybersickness (Grassini and Laumann, 2020) and motion sickness more generally (Lawson, 2014). A recent study by Stanney et al. (2020) showed this effect is principally attributed to the design of HMDs to have fixed disparities that accommodate the average inter-pupillary distances of males more than females. It is possible that the fixed disparities of mobile VR devices like the Oculus Go could contribute to enduring systemic causes of cybersickness onset and severity. However, given that we compared cybersickness reported between devices in a counterbalanced order, we propose that the limited effect we observe is not due to the participant pool being primarily male. In our recent study on angular sensory conflict, we found that all participants (male and female) experienced compelling cybersickness when short-duration angular visual-vestibular conflicts were imposed for 12 s. The lack of cybersickness we report here with longer viewing times (20 s) suggests that linear conflicts do not generate compelling cybersickness, at least for the stimulus conditions we imposed. It would be advantageous to consider whether other displays (e.g., a simulated ground plane) might amplify any effects of linear conflict on cybersickness.

CONCLUSION

While linear visual-vestibular conflicts (produced by desynchronising visual and vestibular cues to linear head displacement) can generate perceived scene instability, they do not appear to significantly reduce presence or increase the likelihood/severity of cybersickness. Linear conflicts on the Oculus Go were found to produce very similar experiences to those encountered on the Oculus Quest with linear head tracking disabled. These findings suggest that the visual system is neurophysiologically tolerant to visual-otolith conflicts generated by brief, low-acceleration head movements. This could explain why positional time warping algorithms have not been prioritized to date, as active linear head movements are less likely to induce sensory conflicts that significantly generate cybersickness (compared to angular conflicts, which are known to be provocative). Future studies will hopefully identify the visual-otolithic constraints under which linear sensory conflicts might contribute to cybersickness generated during active and passive visual exploration of virtual environments experienced using HMD VR.

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 Human Research Ethics Advisory Panel, University of New South Wales, Australia. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JK created the stimuli and WL and JK collected the data. JK analyzed the data. All authors interpreted the findings and wrote the article. All authors contributed to the design of the study.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2021.582156/full#supplementary-material

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Granulated Rest Frames Outperform Field of View Restrictors on Visual Search Performance

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Dynamic field of view (FOV) restrictors have been successfully used to reduce visually induced motion sickness (VIMS) during continuous viewpoint motion control (virtual travel) in virtual reality (VR). This benefit, however, comes at the cost of losing peripheral awareness during provocative motion. Likewise, the use of visual references that are stable in relation to the physical environment, called rest frames (RFs), has also been shown to reduce discomfort during virtual travel tasks in VR. We propose a new RF-based design called Granulated Rest Frames (GRFs) with a soft-edged circular cutout in the center that leverages the rest frames' benefits without completely blocking the user's peripheral view. The GRF design is application-agnostic and does not rely on context-specific RFs, such as commonly used cockpits. We report on a within-subjects experiment with 20 participants. The results suggest that, by strategically applying GRFs during a visual search session in VR, we can achieve better item searching efficiency as compared to restricted FOV. The effect of GRFs on reducing VIMS remains to be determined by future work.

Keywords: human performance, visual search, rest frames, virtual reality, HCI

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1 INTRODUCTION

As part of the immersive experience in virtual reality (VR), navigation in the virtual environment (VE) is an essential action along with selection and manipulation. Several application areas, such as the military (Zyda, 2005; [Dataset] Baumann, J., 1993), medicine (Seymour et al., 2002; Seymour, 2008), athletics (Sorrentino et al., 2005), and manufacturing (Kozak et al., 1993) require long-distance or frequent virtual travel[1]. However, virtual travel has the common side effect of visually induced motion sickness (VIMS) (Keshavarz et al., 2014; Jerald, 2015), also known as cybersickness (LaViola, 2000), experienced when visual motion conflicts with motion provided by the vestibular system (Irwin, 1881; Reason, 1970; Reason and Brand, 1975; Johnson, 2005). VIMS generally provokes an unpleasant VR experience and is expressed by headaches, stomach awareness, nausea, and disorientation (Johnson, 2005).

As a way to mitigate VIMS, field of view (FOV) reduction techniques, such as dynamic FOV Restrictors (Fernandes and Feiner, 2016), manipulate the FOV to decrease the peripheral visual flow information presented to users during provocative (travel) motion (**Figure 1C**). However, FOV

[1]In this paper, we consider virtual travel as continuous motion control of the viewpoint, and distinguish it from other forms of virtual travel, such as teleportation.

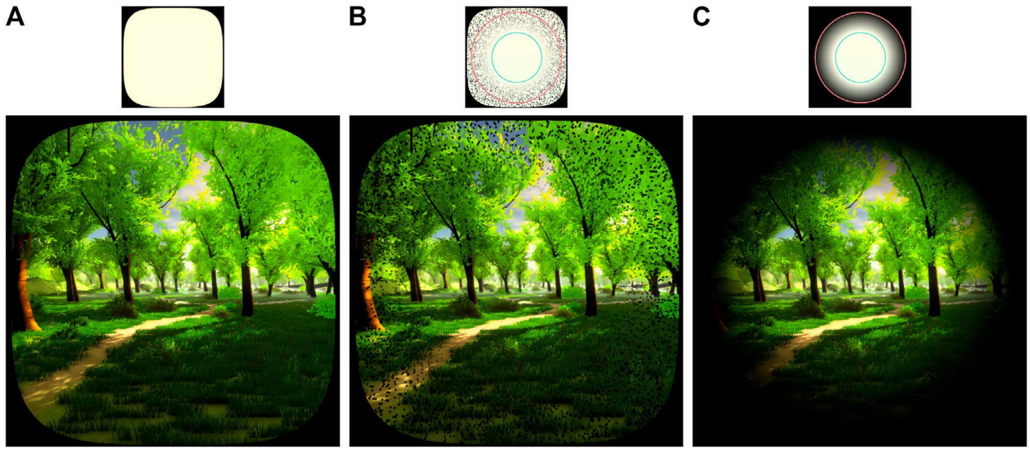

FIGURE 1 | The Granulated Rest Frames design allows the visual recreation of most details from the original image by exploiting human's ability to discern objects even in the presence of visual noise. **(A)** Reference Image: a virtual scene with no modifications; **(B)** Granulated Rest Frames: the scene with Granulated Rest Frames using a 36° IFOV (green circle at the top diagram) and 80° OFOV (red circle at the top diagram) soft-edged circular cutout; **(C)** FOV Restrictor: the scene using a FOV restrictor with same IFOV and OFOV parameters.

Restrictors carry the drawback of potentially leading to lower peripheral awareness, which may demand more effort and time to discern the surrounding scene (Jang et al., 2016). There is an open challenge in identifying a way to maintain the benefits from FOV reduction while maximizing the usage of peripheral FOV.

Rest frames (RFs) have been proposed as an alternative to FOV Restrictors, where they were shown to mitigate VIMS by adding virtual elements that remain stable in relation to the physical environment, such as the use of cockpits in many commercial VR games (e.g., [Dataset] Astrofish Games Ltd, 2018; CCP Games, 2017). However, RFs are application-dependent and, similar to FOV reduction techniques, usually block large parts of the peripheral view (Cao et al., 2018).

Blocking the user's peripheral view can have critical influences on performance. Previous studies have shown that the performance in search tasks depends mostly on FOV size, where users tend to adjust their search behavior (such as the visual scanning pattern) based on the size of the FOV (Ragan et al., 2015), and small FOVs cause performance deterioration (Hogervorst et al., 2013). Conversely, the human visual system can tolerate occluding noise to a great extent, even when processing time is very brief (Meng and Potter, 2008). The challenge, then, is to explore designs of RFs to leverage amodal completion–the ability humans have to detect objects as a whole even if they are partially occluded (Michotte et al., 1991)–and VIMS mitigation so that RFs' adverse effects on the peripheral view are minimized.

In this work, we propose Granulated Rest Frames (GRFs), a new RF-based design that adds random noise-like grains to the periphery of the FOV (**Figure 1B**), in a similar way that happens with restricted FOV. However, rather than blocking much of the peripheral view as traditional RFs, it provides an optimized way to generate occluding noise-like RFs that allows amodal completion.

Given that RFs reduce VIMS to a similar extent as FOV restrictors, we compared GRFs to restricted FOV on visual search, a common task in many VR applications. We evaluated different designs of GRFs, combining Density and Size to establish how they affect visual search performance. Thus, by comparing visual scanning performance (search time and amount of head rotation) under different conditions, we assessed the hypothesis that GRFs could increase peripheral awareness compared to restricted FOV. Our overarching research questions are, "can users have better visual scanning performance under GRFs, as compared to FOV restrictors?," and "what is the optimal design of GRFs that can degrade user performance the least?" Specifically, we focus on the effects of FOV restrictors and GRFs on search time and the amount of head rotation during an item searching task in virtual reality.

The results provide a deep understanding of the distinction between GRFs and FOV restrictors on visual scanning task performance. Importantly, our results add to the growing body of literature on the generic generation of RFs (Frey et al., 2007; Lin et al., 2002a; Lin et al., 2004).

2 BACKGROUND

In this section, we review related literature on human tolerance to visual noise, and the impact of FOV restrictors and RFs.

2.1 Visually-Induced Motion Sickness

As early as the 1890s, visually induced disturbances have been reported in some devices like Haunted Swing (Wood, 1895) and eyeglasses with inverting prisms (Stratton, 1897). It results in sensations similar to motion sickness: nausea, dizziness, vertigo, and sweating, among other symptoms. In such situations, those symptoms caused by visual artifacts are referred to as Visually-induced Motion Sickness (VIMS) (McCauley and Sharkey, 1992; Kennedy et al., 2010). Aside from VIMS, it has also been found that visual stimuli can lead to perceived illusory self-motion (referred to as "vection") (Henn et al., 1974; Dichgans and Brandt, 1978). Later work found that vection can also be triggered by auditory cues (Larsson et al., 2004; Valjamae et al., 2005).

The analysis of the associated occurrence of vection and VIMS provides a way to investigate the mechanism of VIMS. Hettinger et al. (1990) suggested that vection was a necessary precondition for VIMS. Nooij et al. (2017) also discovered that VIMS increases with vection strength. They also found that this relation was detected when pooling correlations across all conditions, but not for all conditions considered individually. In a later study, Nooij et al. (2018) hypothesized that strong vection enhanced the velocity storage, a central integrative network involved in motion sickness. However, some work contradicted the positive relation between vection and VIMS (Webb and Griffin, 2003; Weech and Troje, 2017; Weech et al., 2018; Keshavarz et al., 2019). Kuiper et al. (2019) also argued that vection is not a direct cause of VIMS, but a state that relies on other factors to cause VIMS. One striking part of studying the relation between vection and VIMS is the variability of the results in the literature. For example, Palmisano et al. (2018) failed to find a relation between vection and VIMS in a spontaneous postural activity measurement study. However, they affirmed the contribution of vection to VIMS in other work (Palmisano et al., 2017; Risi and Palmisano, 2019). What the existing research suggests is that the real mechanism of VIMS causation is still not entirely understood.

Despite the divergent conclusions regarding the contributors to VIMS, it is clear that vection relates to the visual stimuli, specifically the optical flow patterns induced by visual stimuli (Telford and Frost, 1993; Palmisano et al., 2000; Bubka et al., 2008; Fujii and Seno, 2020). Seya et al. (2014) described the participants felt stronger vection even if facing much smaller and slower-moving optical flow in the background space than in the foreground space. Other studies also have reported that the more distant stimulus causes vection when visual stimuli differ in depth (Ito and Shibata, 2005; Seno et al., 2009). Although there are studies that disagree with the direct correlation between vection and VIMS, considering the incoherent findings in the literature and the potential positive relationship between vection, VIMS, and optical flow, we hypothesize that certain optical flow types elicit vection and may contribute to VIMS. Our approach is to explore static references at the foreground, while maintaining peripheral awareness through the use of a particular implementation of rest frames, which have been demonstrated to alleviate symptoms of VIMS (Cao et al., 2018).

2.2 Peripheral Vision and Visual Search

Previous work has investigated the link between visual search and peripheral awareness. When performing visual searches, people rely on saccades interleaved with periods of fixation more often than smooth eye movements (Collewijn et al., 1988). The angular speed of eye movement can reach up to 600 deg/s during a saccade (Collewijn et al., 1988). Such high retinal speed requires peripheral vision to select potential targets and guide eyes in search tasks efficiently (Erkelens and Hooge, 1996; Rajashekar et al., 2002). Peripheral vision operates coarsely on patches containing multiple items rather than accurately on individual items (Rosenholtz et al., 2012). Geringswald and Pollmann (2015) confirmed that peripheral vision loss could prevent integrating local configurations with the global display layout. The integration failure led to reduced spatial configuration learning and impaired contextual cueing in visual search.

2.3 Effects of Visual Noise on Visual Perception

Amodal completion is a remarkable characteristic of the human visual system that helps people tolerate visual noise, reconstruct, and recognize partially occluded objects (Gerbino and Salmaso, 1987; Sekuler and Palmer, 1992). In three-dimensional (3D) scenes–those occurring in VEs–, Tse (1999) argued that "mergeable" 3D enclosures are crucial elements in amodal completion. Objects with "mergeable" 3D enclosures are partially occluded can be merged by the human visual system when their surfaces have content-related or similar patterns, even if they are geometrically separated. This concept has been validated by other researchers (Anderson et al., 2002; Nanay, 2010; Soska et al., 2010).

2.4 Effects of Field of View on User Experience in Virtual Environments

Several studies in the literature have pointed out the benefits and detriments to large FOVs in VR. Although large FOVs can increase the sense of presence (Howlett, 1990; Prothero et al., 1995), they have also been demonstrated to worsen VIMS (Jex, 1991; Fernandes and Feiner, 2016). A cue conflict generally explains VIMS: the contradictory information received by visual information and vestibular system triggers the nervous system's reaction to motion sickness (Reason and Brand, 1975). Hence, the larger the FOV, the more apparent a possible conflict might be, which can result in more sickness. It has been observed that people experience more instability, sickness, and presence with larger FOV (Duh et al., 2001; Lin et al., 2002b).

Studies have also found critical influences of FOV over other aspects of the user experience. Low FOV appears to decrease the user's sense of presence (Arthur and Brooks, 2000), widen the user's search paths in a visual search task (Cunningham et al., 1995), increase reaction time in shape identification (Robinett and Holloway, 1992), and significantly impair virtual travel performance (Geruschat et al., 1998; Hassan et al., 2002).

2.5 Effects of Rest Frames on VIMS

Several theories have been proposed to explain VIMS. Among them, the Sensory Conflict Theory and the Postural Instability Theory (Irwin, 1881; Reason, 1970; Reason and Brand, 1975; Riccio and Stoffregen, 1991; Johnson, 2005) focus on the role of vestibular systems or postural balance. The Rest Frames Hypothesis (RFH), on the other hand, emphasizes the role of spatial-perceptual references on the effects of VIMS (Prothero, 1998; Prothero and Parker, 2003).

According to the Rest Frames Hypothesis (Prothero, 1998; Prothero and Parker, 2003), whose essential concepts were first introduced in the work by Steele (1961), when the brain selects rest frames for the body next-step motion, the preferable option to select rest frames is heavily influenced by what is perceived to be the visual background. The reason is that most visual cues in the environment with coherent motion status are in the visual background.

Studies on projection-based systems, such as CAVEs (Cruz-Neira et al., 1993), show that the seams between screens and elements of the real world visible beyond the screens acting as RFs on the foreground may induce lower VIMS (Cruz-Neira et al., 1993; Lin et al., 2004, Lin et al., 2002a). Lin et al. (2004) employed a Virtual Guiding Avatar to alleviate VIMS, where the avatar, a visual cue, provided a relatively stable cue. The results from a revised simulator sickness questionnaire (SSQ) (Kennedy et al., 1993) indicated that a Virtual Guiding Avatar with rotational cues alone or with translation could reduce VIMS (Lin et al., 2004). Cao et al. (2018) demonstrated that software-based RFs in HMD systems could also effectively achieve similar impacts.

As a whole, prior research points to a benefit in user comfort of restricting the FOV, under the cost of adverse effects to presence and other user experience factors. Rest frames can mitigate these side effects of FOVs while also reducing discomfort. Based on the human ability to amodal completion, we propose to use Granular RFs that look like visual noise. Our contribution takes advantage of the human visual system's tolerance to noise in the RF design.

3 GRANULATED REST FRAMES

The design of our proposed GRF technique was inspired by human tolerance to visual noise and the ability to mentally recreate the entire object despite parts of it being occluded by other objects (known as amodal completion, Gerbino and Salmaso, 1987; Sekuler and Palmer, 1992). Our solution uses granulation and random distribution of tiny black circles (grains) as RFs.

With GRFs, we combine the benefits of RFs and FOV restrictors into one visualization technique. RFs are always visible to the user, leveraging the benefits of reducing VIMS, as demonstrated by Cao et al. (2018). Furthermore, the central part of the view is always unrestricted, as is the case with FOV restrictors, (Fernandes and Feiner, 2016). Effectively, our GRF design emulates FOV restrictors without completely obstructing the user's peripheral view, but, instead, offering stable references in that region of the FOV.

Previously, Cao et al., 2018 demonstrated that RFs effectively alleviate VIMS. However, their design used an application-specific prop–a metal net–as the RF, which, to some extent, restricted the FOV due to the metal net blocking parts of the environment. Notably, some parts of the FOV were continually blocked, making it impossible for a person to reconstruct objects beyond the net with amodal completion. Therefore, we proposed an improved design of RFs, which is application-agnostic. The design ensures that each RF grain can be made small enough to allow human amodal completion, and the random distribution minimizes the possibility of patterns that can continuously block the view. **Figure 1B** shows an example of the GRFs distribution and how it affects the surrounding environment.

Figure 2 summarizes the design of GRFs. Two parameters control their generation: Size and Density. Size represents the amount of FOV (in degrees) that every single grain (black circle) should cover (**Figure 2A**), which is measured by

$$S_g \text{ (meter)} = \tan\frac{Size\ (^\circ)}{2} \times d \text{ (meter)} \sim 0.5 \times \frac{Size \times \pi}{180} \text{ (radians)} \times d \text{ (meter)}, \quad (1)$$

where d is the distance between the user's viewpoint and the GRFs, and S_g is the linear radius of a single grain. For example, *Size* = 1 covers 1 degree of the FOV independently of its distance from the user's head. Smaller *Size* means more RF granulation and, consequently, lower view obstruction.

Density represents the number of GRFs per degree of FOV (**Figure 2C**). Its value can range from 0, representing no RF coverage (as in **Figure 1A**), to $4/(\pi \times S_g^2)$, where each degree of FOV is totally covered by RFs, acting as a FOV restrictor (Fernandes and Feiner, 2016, as in **Figure 1C**). *Density* is calculated by:

$$Density \text{ (GRFs/degree of FOV)} = \frac{N_g \text{ (particles/ degree of FOV)} \times \pi \times \left(S_g\right)^2}{d^2} \sim N_g \times Size^2, \quad (2)$$

where N_g represents the number of grains for each degree of FOV, d is the distance between the user's viewpoint and the GRFs, and $\pi \times S_g^2$ is the size of each GRFs. In other words, *Density* is the ratio between the area covered by GRFs and the FOV. The level of *Density* dominates the randomness and sparsity of RFs. High *Density* makes RFs less random.

In our implementation, the GRF is composed of separated same-size grains (2D circle). All grains are randomly distributed around the user's head as a sphere with a radius of 1 m. Based on *Size*, we first calculated the spherical coordinates of all grains with an even distribution. In other words, there is no overlap or gap between any two grains. Then, according to the *Density*, for each $1^\circ \times 1^\circ$ area, we randomly choose precalculated coordinates to render the grains. To avoid the computational load for the applications, all rendered grains are combined as one mesh. Additionally, the combined mesh was triggered and rendered by a free plugin from Unity Asset Store–"VR Tunnelling Pro" ([Dataset] SIGTRAP Ltd, 2019).

By controlling the *Size* and *Density* parameters, the GRF design can be more user-friendly and application-based. To allow the fovea to be fully available, we left a soft-edged circular cutout at the center of the user's FOV, as **Figure 1A** shows. Same as Fernandes and Feiner (2016), the cutout's opacity linearly increases from completely transparent within the 36° inner FOV, to completely opaque beyond the 80° outer FOV.

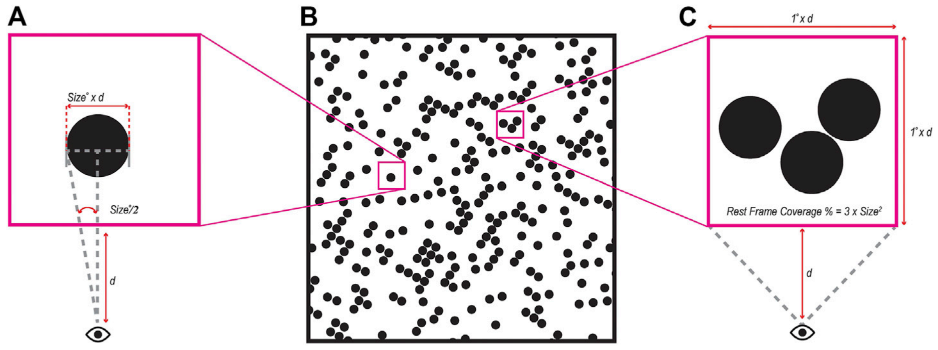

FIGURE 2 | Granulated Rest Frames design. Image **(B)** illustrates the layout distribution of the RFs at d meters away from the user's view. GRFs are created using two parameters: **(A)** *size*, which represents the amount of FOV one single particle covers and **(C)** *density*, which represents the coverage of RF per degree of FOV.

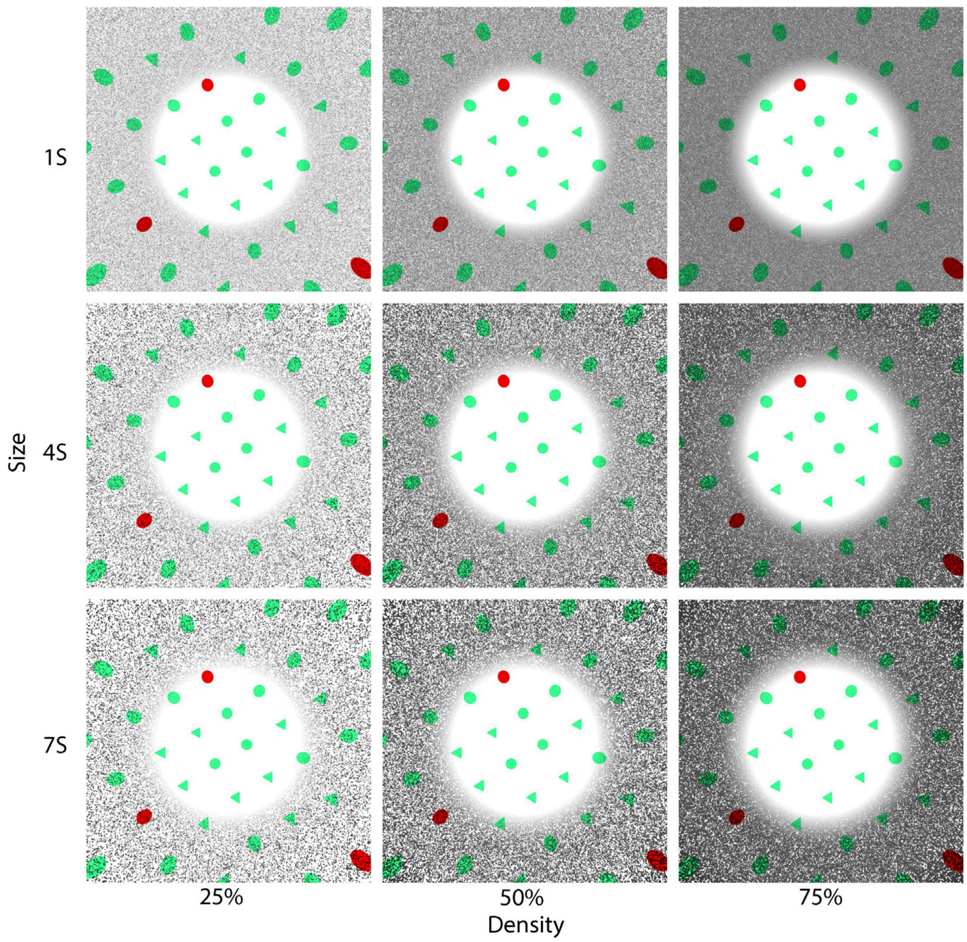

FIGURE 3 | Representation of the 9 combinations of GRFs distribution used in our user study. Note that the two red spheres outside the cutout would not be visible by the FOV Restrictors technique.

4 USER STUDY

We conducted a user study to assess different GRF variations on item searching efficiency, specifically, search time and amount of head rotation. Moreover, we compared the effect of GRFs to that of FOV Restrictors (Fernandes and Feiner, 2016). The study was approved by Duke Campus Institutional Review Board.

4.1 Experimental Design

The experiment followed a within-subject design with repeated measures, where *Size* and *Density* are the independent variables (IVs) and *Time*, *Accuracy*, and *Head Rotations* are the dependent variables (DVs). A control condition with FOV restrictors recreating the Fernandes and Feiner (2016) technique was added for comparison with our GRF design.

The levels for each IV were:

– Size: 1S(1°), 4S(4°), 7S(7°);
– Density: 25%, 50%, 75%, 100%.

Note that the condition with 100% density represents FOV restrictors. Both of these are considered control conditions in the experiment. **Figure 3** shows the FOV coverage of the 9 unique combinations of GRFs. We encoded the combinations as following: *size_density*. Thus, the code for each conditions was: 1S_25%, 4S_25%, 7S_25%, 1S_50%, 4S_50%, 7S_50%, 1S_75%, 4S_75%, 7S_75%.

The DVs are detailed as follows (all data were sampled at 50 Hz):

– Search Time: Time in seconds to identify a target, calculated by:

$$t = \frac{total\,time\ (\text{sec})/(per\ condition)}{\#identified\ targets/(per\ condition)} \tag{3}$$

– Accuracy: The ratio between the targets counted by the participant and the real number of targets.
– Head rotation: The average amount of head rotations, in degrees, to identify one target

$$\theta_{head} = \arccos\left(\frac{\overrightarrow{P_1}\cdot\overrightarrow{P_2}}{\left|\overrightarrow{P_1}\right|\left|\overrightarrow{P_1}\right|}\right) \tag{4}$$

where $\overrightarrow{P_1}$ and $\overrightarrow{P_2}$ are the unit direction vectors of the user's face at two different moments. Moreover, $\overrightarrow{P_1}$ and $\overrightarrow{P_1}$ are represented as a vector $\overrightarrow{P} = (P_x, P_y, P_z)$. The coordinates were calculated by $P_x = -\sin\psi\cos\theta\cos\psi\sin\phi\sin\theta$, $P_y = \sin\psi\sin\theta - \cos\psi\sin\phi\cos\theta$, $P_z = \cos\psi\cos\theta$, where ψ, ϕ, θ, are the angles of head roll, pitch, and yaw.

4.2 Participants

Twenty participants from the same institution participated in the experiment (6 females), with mean ages of 26.75 ± 1.83. They were recruited by posts and emails. All subjects attended the whole session. The subjects read and agreed to an Informed Consent Form before the experiment. Only three of them had little VR experience before the study. Participation was voluntary without compensation.

4.3 Hypotheses

According to the RFH (Prothero, 1998) and its influence on peripheral awareness, we formulated four hypotheses for our study.

- H1: GRFs lead to faster search and lower head rotations as compared to FOV Restrictors.
- H2: Small grains lead to better performance than large grains.
- H3: Low-density GRFs lead to better performance than high-density GRFs.
- H4: Small grains in low-density GRFs are the optimal combination for the lowest search time and head rotation amount.

In order to make our design comparable with dynamic FOV restrictors, we configured the parameters of the circular cutouts with the same inside FOV (IFOV) (36°) and outside FOV (OFOV) (80°) in the center of the FOVs as Fernandes and Feiner (2016). **Figure 1A** shows an example view of an unrestricted VE; **Figure 1B** shows a view from a VE with GRFs; **Figure 1C** shows a VE with the restricted FOV. Red and green circles at the top icon represent IFOV and OFOV, respectively.

4.4 Task and Stimuli

The visual search task is one of the most popular methods to investigate the attention spent in visual object recognition, in which an observer actively scans the visual environment for a particular target among an array of distractors (Treisman and Gelade, 1980; McElree and Carrasco, 1999). The visual search contains feature search and conjunction search. Searching for a target amongst distractors that differ from the target by a simple visual feature, such as color, shape, or orientation, is known as feature search (Treisman, 1998; McElree and Carrasco, 1999). The other one requires a process to distinguish targets from distractors possessing one or more common visual features, which involves bottom-up processes at an early stage to locate analogs to the target fast, and top-down process in later stages to eliminate distractors (McElree and Carrasco, 1999; Shen et al., 2003). It's believed that visual search in the real world is more similar to conjunction search with less complexity (Alexander and Zelinsky, 2011, 2012; Hout and Goldinger, 2015).

However, either Fernandes and Feiner (2016) or us apply the visual modification to the periphery, which yields more impacts on the bottom-up process of fast locating targets, like feature search, rather than the top-down process that requires one's previous knowledge (Zhaoping and Frith, 2011; Rosenholtz et al., 2012). Therefore, we designed a classic feature search experiment in VR. The task consisted of identifying and counting targets that were distributed in the distractors. We separated the field into 2 × 2 quadrants for each trial, and each quadrant had a similar number of sparsely and pseudo-randomly distributed targets. The targets were red circles, and the distractors were green triangles with the same size, as seen in **Figure 4**. We minimized any unintended distractions during the search task by using a blank background.

4.5 Formative Pilot Study

We ran a formative pilot study to determine the stimuli distribution layout around the user. We assessed three layouts: spherical target distribution (360° vertically and horizontally), semi-spherical target distribution (180° vertically and

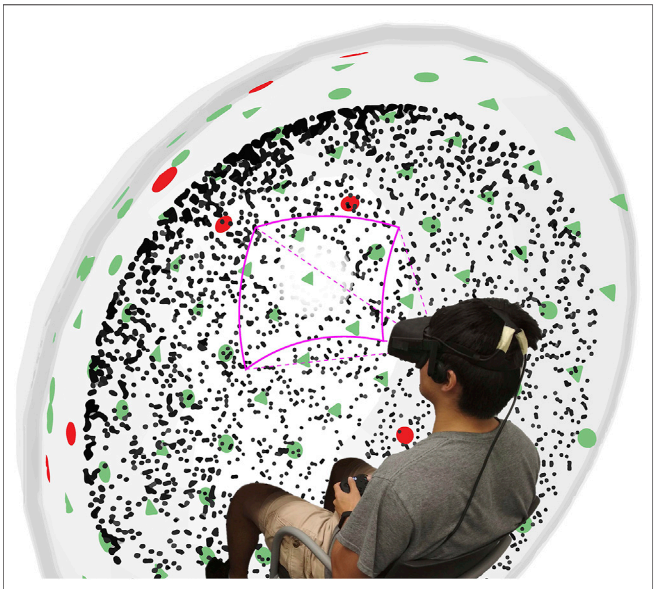

FIGURE 4 | Representation of the search experiment setup. The virtual targets (red circles) and distractors (green circles and triangles) were placed at a 2-meter radius in a semi-sphere in front of the participant. The GRFs are rendered at a 1-meter radius around the participant's head (for clarity, in this representation, we just show the front half-sphere of the GRFs). The pink area represents the FOV of the HMD. The point of view is changed by rotating the head and body. (Note. The figure was shot to explain the experimental design, and the person in the figure is the author.)

horizontally), and quarter spherical distribution (180° horizontally and 90° vertically). All layouts have 5–7 targets, and the amount of distractors is 193–195 for spherical target distribution, 93–95 for semi-spherical target distribution, and 43–45 for quarter spherical distribution. The stimuli were placed at a 2-meter radius from the user. Three participants experienced the 3 distribution layouts in 4 GRFs combinations and 1 restricted FOV condition. We used an unmodified condition as training to make the user familiar with the task and the restricted FOV condition as a control. Each condition had 5 trials. Participants were requested to finish the tasks as quickly as possible while maintaining accuracy high.

The formative study aims to find the layout to yield the largest different search time between the restricted FOV and our design.

Results (**Table 1**) from the formative study show that the conditions that caused a variation in search time were the semi-sphere distribution layout and the complete sphere distribution layout. Thus, we chose the semi-sphere distribution layout since navigation rarely requires the users to look back when they are moving. The final task layout consisted of 8–13 targets (red circles) embedded among 187–192 distractors (half is circles, and the other half is triangles. If the distractor amount is odd, the extra one is a circle.) that were equally distributed along the 3D regions around the user. The target distribution is illustrated in **Figure 4**.

4.6 Equipment

An Oculus Rift CV1 (about 80° horizontal and about 90° vertical FOV ([Dataset] Doc-Ok.org, 2016) with six degrees of freedom (6DOF) position and orientation tracking was used. It's driven by OculusClient 0.1.0.0 on an Intel(R) Core i7-8700K CPU (3.7 GHz) with 16 GB RAM and an Nvidia GeForce GTX 1080 Ti running Windows 10. 6DOF head tracking allowed the system to render the RF stable relative to the real world even as the user freely moved his head while seated or standing (**Figure 4**). An XBox One Gamepad wireless controller was used to capture the user's inputs.

4.7 Procedure

The participants answered a biographical questionnaire and were instructed on the task goals and guided through the XBox controller's input commands. They practiced in a scene without visual restrictions to get familiar with the task. Then, they experienced 10 conditions in a random sequence. One with fixed FOV restrictor, and 9 conditions with different GRF combinations of *Size* and *Density*. Each condition had five trials, followed by a 30-second rest, where the screen of the headset was blacked out, and participants could rest. For each trial, the number of targets randomly ranged from 8 to 13 to avoid a learning effect. When the participant finished the counting, they pressed the Xbox controller right trigger to finish the trial and stop the timer. The targets were deactivated, the time and head rotations data were automatically recorded, and the participant verbally informed the researcher about the number of identified targets and the answer was recorded by the researcher. We instructed the participants to be as accurate as possible, considering time. After the study, the participants were asked their preference on the GRFs and FOV restrictors via the post-experiment questionnaire. The question was "Among all 10 conditions, which one did you feel much easier and more comfortable to identify the target?"

In summary, the experiment consisted of: (3 *Size* × 3 *Density* + *FOV Restrictors*) × 20 participants × 5 Trials = 1,000 unique observations.

5 RESULTS

5.1 Data Analysis

We analyzed whether the Granulated Rest Frames (GRFs) IVs (*Size* and *Density*) and their interaction had a significant effect in the *Search Time*, *Accuracy* and *Amount of Head Rotation* with a 2-way repeated measure ANOVA test. We verified if the ANOVA assumption of normality of the residuals was violated with the Shapiro-Wilk test. Then, we used repeated-measures ANOVA to analyze the effect of the nine *GRF* combinations plus the *FOV Restrictors* (Fernandes and Feiner, 2016) conditions on *Search Time* and *Amount of Head Rotation*, and the non-parametric Friedman test to analyze the effect of the *GRF* variations plus and the *FOV Restrictors* condition on *Accuracy*. The alpha significance level was set to 0.05. We conducted a Post-hoc analysis if a variable was found statistically significant.

5.2 Search Time

We conducted a two-way ANOVA that examined the effect of *Size* and *Density* level. There was a statistically significant

TABLE 1 | Average search time in the formative study.

Layout	GRF condition				
	FOV restrictor	1S_25%	1S_75%	7S_25%	7S_75%
Spherical distribution	25.85 s	17.61 s	21.46 s	19.02 s	17.06 s
Semi-spherical distribution	13.28 s	10.79 s	9.06 s	7.99 s	8.84 s
Quarter spherical distribution	8.10 s	6.98 s	5.82 s	6.18 s	6.20 s

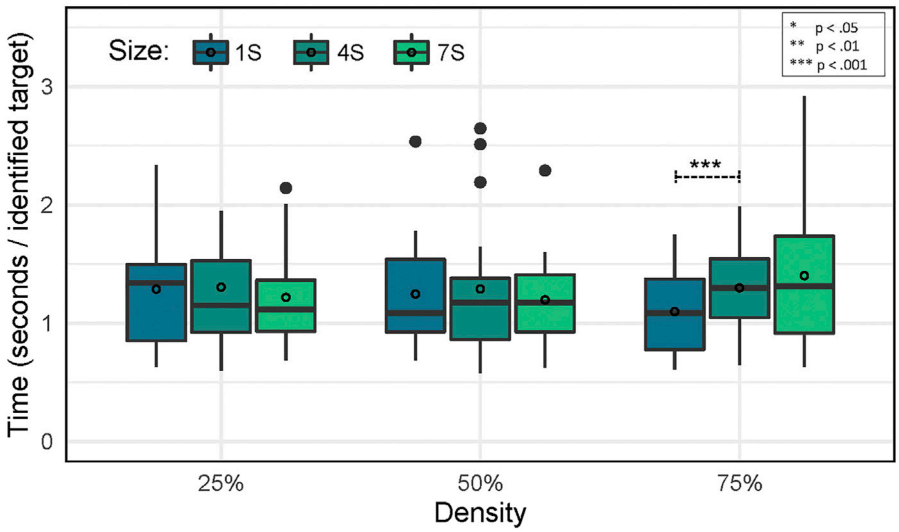

FIGURE 5 | Search time for each level of GRF *Size* and *Density*. When *Density* is 75%, GRFs with Size 1S (M = 1.236 ± 0.692) perform significantly faster than Size 2S (M = 1.426 ± 0.690). The circle outlines represent the mean values for each condition.

interaction between the effect of *Size* and *Density* on search time ($F_{4,76} = 2.70, p < 0.037, \eta^2 = 0.01$), while there was no significant difference among the levels *Size* ($F_{2,38} = 0.24, p = 0.79$) and *Density* ($F_{2,38} = 0.10, p = 0.90$) individually. Simple main effect analysis only showed that *Size* 1S was significantly faster than *Size 4S* when *Density* was *75%* ($p < 0.005$). **Figure 5** shows the interaction between the *Size* and *Density* factors.

A single factor analysis was conduced that examined the effect of *FOV Restrictors* and *Rest Frames (9 GRFs variations)* conditions. The statistical analysis indicates that there was a statistically significant effect of the conditions on search time ($F_{9,171} = 5.24, p < 0.001, \eta^2 = 0.061$). Post-hoc comparisons using dependent t-tests with Bonferroni correction indicate that the GRFs variations 1S_50% ($p = 0.029$), 1S_75% ($p < 0.001$), 4S_25% ($p < 0.001$), 4S_50% ($p = 0.013$), 7S_25% ($p < 0.013$) and 7S_50% ($p = 0.006$) performed significantly faster than the *FOV Restrictors* condition. **Figure 6** shows the search time results for each condition.

In conclusion, regarding the search time per identified target, the results confirm our first hypothesis that GRFs help users obtain better performance compared to FOV Restrictors. Nevertheless, it only partially demonstrated our second and fourth assumptions that low *Size* only prevails large *Size* with large *Density*.

5.3 Accuracy

The Shapiro-Wilk test ($p < 0.05$), the visual inspection of histograms, normal Q-Q plots, and box plots showed that accuracy was not normally distributed. We then conducted a non-parametric Friedman test to determine the effect of *FOV Restrictors* and *Granulated Rest Frames (9 GRF variations)* conditions on target identification accuracy. There was a statistically significant difference in *Accuracy* depending on *Condition*, $\chi^2(9) = 23.45, p = 0.005$. The Wilcoxon post-hoc analysis comparing the levels of *FOV Restrictor* and *GRFs* indicates that the *GRF 1S_50%* ($M = 0.986 \pm 0.024$, $p = 0.003$) and *4S_25%* ($M = 0.984 \pm 0.025$, $p = 0.021$) had significantly higher accuracy than the *FOV Restrictors* ($M = 0.951 \pm 0.076$).

5.4 Amount of Head Rotations

A two-way ANOVA indicates a statistically significant interaction between the effect of *Size* and *Density* on search movements ($F_{4,76} = 2.60, p = 0.042, \eta^2 = 0.01$). However, simple main effect analysis did not yield a significant difference among *Size* and *Density* combinations.

The single factor analysis examining the effect of *FOV Restrictors* and *Granulated Rest Frames(9 Rest Frames variations)* conditions on search movements revealed a statistically significant effect of the conditions on search

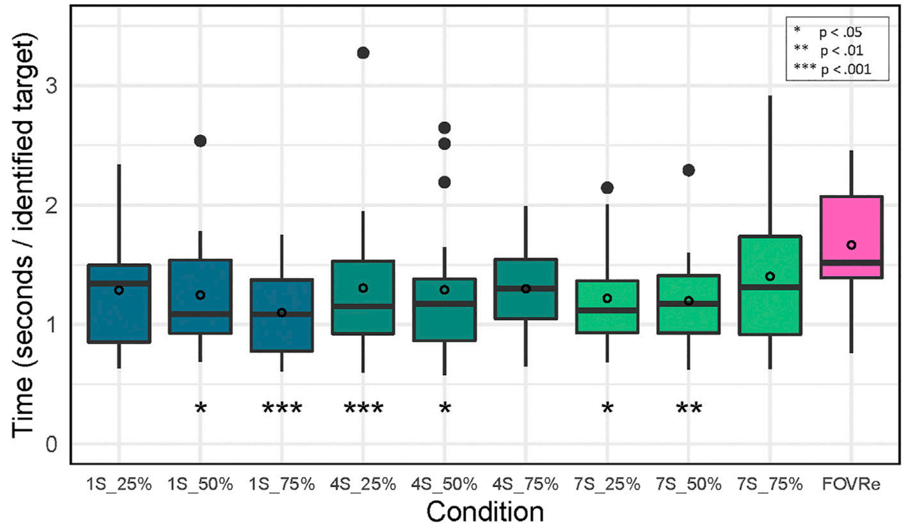

FIGURE 6 | Search time performance. Each variation of GRFs is compared with FOV Restrictors. GRFs combinations 1S_50% ($M = 1.440 \pm 0.974$), 1S_75% ($M = 1.236 \pm 0.692$), 4S_25% ($M = 1.305 \pm 0.621$), 4S_50% ($M = 1.290 \pm 0.573$), 7S_25% ($M = 1.382 \pm 0.837$) and 7S_50% ($M = 1.333 \pm 0.723$) performed significantly faster than FOV Restrictors ($M = 1.783 \pm 0.701$). The significance stars represent the difference between GRF conditions and FOVRe, the circle outlines represent the mean values for each condition.

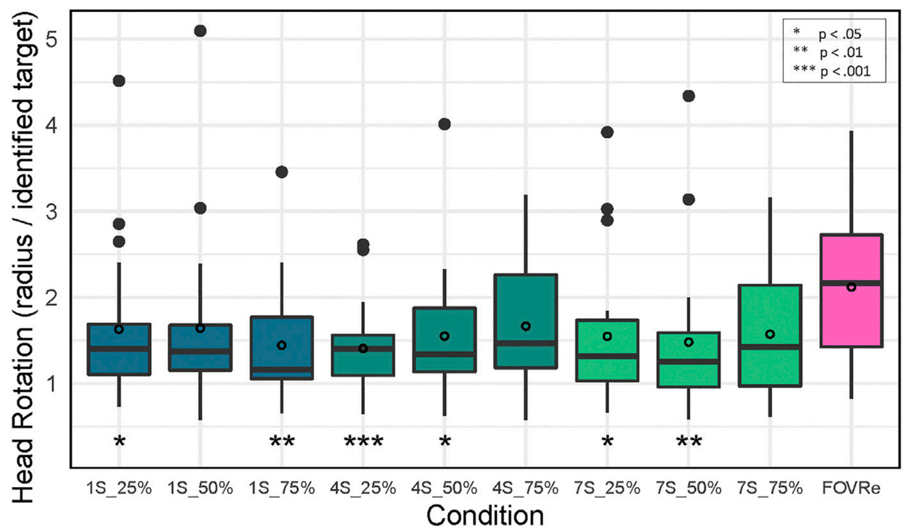

FIGURE 7 | Amount of head rotations to identify the targets. Each variation of GRFs is compared with FOV Restrictors. GRF combinations 1S_25% ($M = 1.630 \pm 0.902$), 1S_75% ($M = 1.442 \pm 0.699$), 4S_25% ($M = 1.406 \pm 0.524$), 4S_50% $M = 1.550 \pm 0.753$), 7S_25% ($M = 1.546 \pm 0.832$), 7S_50% ($M = 1.480 \pm 0.889$) had significantly less amount of head rotation than FOV Restrictors condition ($M = 2.120 \pm 0.801$). The significance stars represent the difference between GRF conditions and FOVRe, the circle outlines represent the mean values for each condition.

movements ($F_{9,171} = 5.76, p < 0.001, \eta^2 = 0.061$). **Figure 7** shows the results of search movements. Post-hoc pairwise t-tests with Bonferroni correction (which multiplies p-values by the number of comparisons) comparing the levels of *FOV Restrictors* and *GRFs* indicates that the *GRF* variations *1S_25%* ($p = 0.04$), 1S_75% ($p = 0.001$), 4S_25% ($p < 0.001$), 4S_50% ($p = 0.05$), 7S_25% ($p < 0.02$) and 7S_50% ($p = 0.007$) had significantly lower search movements than the *FOV Restrictors* condition.

As with direct association with search time, the number of head rotations presented highly similar results to search time, where 1S_75%, 4S_25%, 4S_50%, 7S_25% and 7S_50% produced significantly fewer search movements than the FOV Restrictors condition. The only exception is the conditions 1S_25% and 1S_50%, where the former presented fewer head rotations than the reference condition, while under the 1S_50% condition, the search time was faster, even without a difference in head rotations. Likewise, the results confirmed the first hypothesis, and partially accepted the second and fourth hypotheses, but rejected the third.

5.5 Post-experiment Users Preference

We also collected the participants' post-experiment preferences on the GRFs and FOV restrictors.

Among all 20 participants, 5 people preferred FOV restrictors, since GRFs distracted them. The other 15 participants preferred GRFs. They reported that it helped them concentrate on the target and use peripheral vision to search for items. "The viewport with GRFs helps in concentration while I can perceive the background as well." (Subject 1 and 4). Subject 17 mentioned that with the FOV restrictors, it was hard to track the targets due to the limited view. She had to scan the whole graph line by line.

Of the subjects that preferred GRFs, eleven voted against the highest *Density*. According to their opinions, high *Density* blocked too much view, and they felt it difficult to see information on the peripheral vision. *Size* had the same results and responses.

6 DISCUSSION

Based on our understanding of peripheral awareness, visual searching, and previous work (Xiao and Benko, 2016), we hypothesized the granulated rest frames could accelerate people's visual searching efficiency by contrast to FOV Restrictors (Fernandes and Feiner, 2016) due to it blocks the fewer peripheral view, and our visual systems can reconstruct the environment with amodal completion. As a result of this, we proposed four hypotheses regarding the influence of *Size* and *Density* of granulated rest frames over visual search performance.

We reported the results of a user study that compared combinations of *size* and *density* and the performance of each GRFs combination with FOV Restrictors. FOV Restrictors are considered the standard and have already been implemented in various applications that require virtual navigation. However, the reduction of FOV has a major limitation in peripheral awareness. As hypothesized, users have significantly better visual perception with GRFs compared to restricted FOV. Both the search time efficiency, accuracy and scene scanning (head rotations) are significantly lower when using the specific settings of size and density. Interestingly, the combinations 1S_75%, 4S_25%, 4S_50%, 7S_25% and 7S_50% achieved better time efficiency and lower head rotations. We analyzed the correlation of time and head rotations using the Pearson test and found a strong effect between the two factors ($r = 0.86, p < 0.0001$), where fewer head rotations led to lower search times. The setting 4S_25% achieves significantly better results for the three DVs tested (Search time, Accuracy and Scene scanning) when compared with FOV Restrictors. The reason for the better performance of GRFs could be due to the improved peripheral awareness and the better distinction between the central vision and peripheral vision. Participants may change the direction they gazed, which can explain the performance improvement. However, we assume the gaze is not a major contributor, due to the participants tending to rotate their head frequently to count the targets during the task. Furthermore, all targets were distributed sparsely, making it difficult to identify the targets just with the gaze.

The significantly faster search time with the combination of *Size* 1S and *Density* 75% compared to *Size* 4S and *Density* 75%, partially demonstrated our second and fourth hypotheses that only when the *Density* is very large, the small *Size* is better than large *Size*. Along with the fact that no significant main effect but significant interaction effect of *Density* or *Size* over the head rotation amount, we can conclude the GRFs' influence is due to the combination of *Density* and *Size*. It might be due to the *Density* rather than *Size* causes a more continuous block of FOV. When the *Density* is low, regardless of the *Size*, it serves more like a regular FOV containing a more continuously perceived visible peripheral view, which weakens the utilization of amodal completion. That is why only medium *Density* associated with all *Size*s achieved better performance than other conditions.

Therefore, if we want to take advantage of this technique with very high density, it would be best to use small grain sizes. Medium level density can work well with all sizes, but the low-level density performs worse with small grains concerning search time.

One concern we had was the user acceptance of the visual noise added by our technique. The post-experiment questionnaire results suggest that the participants quickly adapted to the GRFs in the peripheral vision, confirming that our implementation of RFs can be successfully tolerated without degrading the experience.

Overall, GRFs helped subjects achieve better peripheral awareness than restricted FOV. On the other hand, performance did not change significantly among conditions with different settings of GRFs. While we can't make a strong conclusion on the lack of significance, this may suggest that different layouts of GRFs do not influence peripheral awareness. Considering the majority of participants voted against high *Density*, as well as considering the computational performance, we suggest choosing low-level density combined with medium size to set up the Granulated Rest Frames. Not only because the fundamentals of GRFs are maintaining the advantages of FOV modification, but also using the ability to amodal completion to avoid the loss of peripheral information.

Inspired by the Rest Frames Hypothesis (Prothero, 1998; Prothero and Parker, 2003), previous work applied rest frames in a cockpit design to moderate VIMS (Cao et al., 2018). Similar to Cao et al. (2018), we employed GRFs, a type of foreground visual stimuli that occupies the peripheral FOV, which, according to the Rest Frames Hypothesis, is sufficient to be selected as stationary references, even if there are conflicting cues from the background.

Unlike other types of rest frames, such as a cockpit (Cao et al., 2018) or a virtual nose (Wittinghinll et al., 2015), GRFs can be created as visual noise that is generic and content-irrelevant. With *Size* and *Density*, the format of GRFs can be more flexible, user-friendly and context-free, which allows this technique to be implemented at the graphics driver-level and seamlessly applied to various HMDs or applications. However, we still need to validate our proposed GRF design as effective to alleviate VIMS symptoms, which we plan to investigate in future work.

7 CONCLUSION AND FUTURE WORK

We have discussed an improved design of rest frames–Granulated Rest Frames, summarized how we iterated on variations of its design, and performed a within-subject user study exploring seated users' visual perception performance under granulated rest frames with different parameters to a condition with FOV restrictors. The data from the 20 participants we analyzed indicated that densely granulated rest frames might degrade visual perception efficiency. The comparisons among different conditions suggested users tend to perform more efficiently with GRFs as compared to FOV restrictors.

Spatial recognition ability will be an essential aspect to further exploration, which might be achieved, in part, by employing another counterbalanced study comparing FOV Restrictors and medium-size sparse GRFs. Since we limited our work on the effects of RFs' peripheral awareness using a static scene, future work should validate the expected benefits of GRFs on VIMS reduction during virtual navigation tasks. Moreover, future improvements of the GRFs technique will require a real-time dynamic modification of the rest frames (size and density), considering the scene features and user locomotion speed and actions. Besides, the search performance highly depends on the specific task and stimulus parameters. For example, when the search task requires top-down processes involving previous knowledge, such as words or elaborate patterns, the performance will likely be different from the task involving bottom-up search processes. Also, the stimulus's size plays an important role, especially when the GRFs size is similar or larger. In this study, we investigated the influence of GRFs on bottom-up search processes rather than the top-down processes, which only involves fast locating according to color and shapes. Besides, the GRFs size or density was set at a low level to avoid the impacts. Nevertheless, the potential influence of stimulus size and tasks' specificity also should be studied in the future.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Duke Health Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

ZC performed the study design, examined patients, took samples, and wrote the manuscript draft. JG contributed to the data, crafted the illustrations, corrected the draft of the manuscript. RK contributed to study design, supervised and coordinated the project, and corrected the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2021.604889/full#supplementary-material

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