Effects of display lag on vection and presence in the Oculus Rift HMD

Juno Kim[1*], Andrew Charbel-Salloum[1], Stuart Perry[2], Stephen Palmisano[3]

[1]School of Optometry and Vision Science, University of New South Wales (UNSW Sydney)
[2]School of Electrical and Data Engineering, University of Technology Sydney
[3]School of Psychology, University of Wollongong, Australia

[*]**Corresponding author:**
Dr Juno Kim
Sensory Processes Research Laboratory, School of Optometry and Vision Science
University of New South Wales, Kensington NSW, Australia, 2052
Email: juno.kim@unsw.edu.au
Tel: +61-2-9385-7474

ABSTRACT

We used the Oculus Rift head-mounted display (consumer release – CV1) to simulate forward self-motion in depth. Observers made continuous yaw head movements at approximately 0.5 Hz or 1.0 Hz while viewing these self-motion simulations. We examined the perceptual effects of increasing the head-to-display lag, by adding lag to the baseline lag of the system (estimated to be approximately 5.3 ms). We found that increasing the head-to-display lag up to 212 ms reduced the presence and the strength of the illusory self-motion (vection). In addition, faster (1.0 Hz) head oscillations were found to generate weaker presence and vection than the slower (0.5 Hz) head oscillations. Both vection and presence in virtual environments can therefore be impaired by either increasing head-display lag or making more rapid angular head movements.

Keywords: virtual reality; head-mounted display; presence; vection.

Declarations

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1.0 INTRODUCTION

For the past few decades, there has been a growing demand for effective virtual reality (VR) solutions across a wide range of industries (Lombard and Ditton, 1997), including telemedicine (Crump and Pfiel, 1995; Hamit, 1995), distance education (Hackman and Walker, 1990), and video gaming (Cook, 1992). The principal perceived benefit of VR – particularly head-mounted display (HMD) based VR – is its ability to generate presence (i.e., feelings of "being there" in the virtual environment; see Slater and Wilbur, 1997 and Witmer and Singer, 1998; for a recent review of debate on this presence construct, please see Skarbez et al., 2017). According to Slater (2009), this presence depends on the degree to which the user perceives that: 1) he/she is actually there in the virtual environment; and 2) what is apparently happening to him/her is actually happening. The recent release of next-generation HMDs has accelerated the potential for presence and immersion in VR at an increasingly affordable cost to consumers. This financial accessibility offers increased opportunities for creative development not just in home-brew entertainment, but also for laboratory scientists interested in understanding the perceptual principles of self-motion (Steinicke et al., 2013), increasing engagement for education and training (e.g., Coyne et al., 2019), and remote rehabilitation (Pedram et al., 2020).

1.1. Possible relationship between vection and presence in HMD-VR

Another feature of HMD-VR is its ability to generate illusions of self-motion, known as *vection* (for a review please see Palmisano, Allison, Kim and Bonato, 2011). According to Palmisano et al. (2015), vection has previously been defined as: (i) a visual illusion of self-motion in stationary observers (Dichgans and Brandt, 1978), (ii) an illusion of self-motion induced by stimulating either the visual or the non-visual senses (e.g., auditory vection, see Sakamoto et al., 2004), (iii) a real or illusory visually-mediated perception of self-motion (Kim and Tran, 2016), or (iv) the conscious subjective experience of self-motion (as in Ash et al., 2013). Thanks to their wide fields of view and their ability to provide the user with stereoscopic first-person views of their virtual environment, HMDs commonly induce highly compelling visual illusions of self-motion. However, in HMD-VR, auditory and other non-visual sources of stimulation can also contribute to the user's overall experience of vection.

Several studies suggest that the user's experience of vection is positively related to their feelings of presence in VR (e.g., Riecke et al., 2006; Keshavarz et al., 2018). In the earliest of these studies, Riecke et al. (2006) used a large external display, simulating a natural light field of a streetscape, to generate circular vection. They reduced the coherence and realism of the virtual scene (by either progressively scrambling the image content or changing the orientation of the light field) and found that vection and spatial presence both declined as scene realism was degraded. The authors proposed the observed (positive) relationship between vection and presence was due to participants perceiving that they were moving more when they felt more spatially present in the virtual environment. In a second, more recent, study, Keshavarz and colleagues (2018) compared the relationship between vection and spatial presence during different types of simulated head rotation (yaw, pitch and roll) in VR. They also found evidence of positive relationships between presence and both vection intensity and duration (for simulated pitch and roll self-motions, but not for those in yaw). Despite these insights on the relationship between vection and presence provided by these studies, it should be noted that they both used large field-of-view stereoscopic external displays to present their self-motion displays. To our knowledge, only one study has examined the possible relationship between vection and presence in HMD-VR (Clifton and Palmisano, 2019). While this failed to find a significant relationship between vection and presence, it should be noted that only half of the VR exposure trials in this study used a virtual navigation method that produced continuous visual motion stimulation (i.e., teleportation was used for all of the remaining trials). Thus, the current study plans to re-examine this relationship in HMD-VR under more favorable conditions for vection induction.

1.2 Effects of head-to-display lag on vection and presence

Since users in HMD-VR are typically quite active when exploring and interacting with their virtual environment, it is important to consider the effects their tracked head (and hand/body) movements have on their perceptual experiences – particularly as all VR systems have a finite head-to-display lag (also known as motion to photon latency). Previously, Allison, Harris and Jenkin (2001) found that human observers could tolerate significant display lag before the virtual environment became perceptually destabilized. In that study, significant display destabilization was only perceived when observers executed high-velocity head movements (which revealed the inconsistencies between their head and display motion). However, other researchers have proposed that moderate head-to-display lags (e.g., of 40 - 60 ms) can impair perception of simulator fidelity (Adelstein, Lee and Ellis, 2003), and that even shorter display lags (< 20 ms) can be perceptible to well-trained human observers (Mania et al., 2004). Detection thresholds for display lag in these active head movement studies were lower than the reported detection thresholds for passive participant rotations in an oscillating chair (Moss et al., 2010). Given this variability in the findings from previous studies, it is important to consider how head-to-display lag affects perceptual experiences in HMD-VR.

To our knowledge, no studies have systematically examined how this head-to-display lag affects the experiences of vection and presence induced by HMDs. However, a number of studies have examined the effects display lag on cybersickness (i.e., the feelings of motion sickness in HMD-VR – La Viola, 2000; Palmisano et al., 2017). Moss et al. (2011) instructed participants to view a real live video scene through an HMD and found that cybersickness was not affected by increased display lag. Similarly, St Pierre (2015) found that: 1) adding a constant display lag of 270 ms did not significantly alter cybersickness (compared to the baseline lag condition 70 ms); and 2) introducing a variable 0.2 Hz display lag increased cybersickness. In another study also using live video, Kinsella et al. (2016) found that 0.2 Hz varying lag generated greater sickness than 1.0 Hz varying lag and 100 ms fixed lag conditions. However, contrary to the view that only variable display lag affects the user's well-being, Feng et al. (2019) recently found that adding constant lag to the very low baseline latencies of the Oculus Rift CV1 and S HMDs (estimated at < 5 ms) significantly increased cybersickness. This disruptive effect of display lag was later found to be even larger under binocular, compared with monocular, viewing conditions (Palmisano et al., 2019). These effects of display lag on cybersickness can be attributed to the very low initial display lag levels and may be enhanced by use of virtual (as opposed to live video) content in HMDs.

In the past when studies have measured vection or presence in HMD VR, the baseline system latencies were (or would have been) quite high (e.g., 37.9 ms in Kim et al., 2015 and 72 ms in Palmisano, Mursic and Kim, 2017). Below we will briefly review some of the past HMD studies on vection, as well as some studies on the perceptual effects of head-display lag using large external displays.

Kim and colleagues (2015) showed that the Oculus Rift DK1 HMD could induce compelling vection when observers made angular yaw head rotations at approximately 1 Hz in time with a metronome. They found that synchronized head-display motion generated stronger vection than no compensation, which in turn generated superior vection to inversely-compensated motion. This dependence of vection on head-to-display synchronization was observed despite the Oculus Rift DK1 HMD having relatively long system latencies, ranging from 37.9 ms up to 196.7 ms depending on the scene complexity and rendering mode (Kim et al., 2015). However, this Kim et al. (2015) study did not systematically determine the effects of increasing display lag on vection and presence, nor did they use an HMD system that could achieve an extremely low baseline display lag.

A number of studies have used large external displays to examine how display lag affects the strength of vection. They found that vection decreased when the display moved in a contralateral (as opposed to ipsilateral) direction relative to the observer's oscillatory *linear* head movements (e.g., Kim and Palmisano, 2008; Kim and Palmisano, 2010; c.f., Ash, Palmisano and Kim, 2011). Technically, this contralateral display motion constituted a phase shift of 180˚ and a system lag of 500 ms. Another study by Ash, Palmisano, Govan and Kim (2011) systematically added display lags ranging between 0 and 200 ms to their baseline system latency of 113 ms. They found a negative relationship between ratings of vection strength and perceived lag; whereas higher perceived head-display lag generated lower vection strength ratings, lower perceived head-display lag generated stronger vection strength ratings. Vection was the lowest (and perceived lag the greatest) when head and display motions were approximately 60˚ to 75˚ out of phase (i.e., equivalent to display lags of 113+50 ms and 113+100 ms for head movements at ~1 Hz). Interestingly, lags above 90˚ (which were more consistent with counter-phase head-display synchronization) generated relatively strong vection and low perceived lags. These findings suggest that vection depends more critically on the temporal head-to-display lag (as opposed to the phase angle of the head-display synchronization).

One limitation of the Ash et al. (2011) study was again the very large baseline system latency. As a result, the explored head-display lag was limited in range from 40˚ to 112˚ in phase angle and from 113 ms to 313 ms in temporal latency. Another potential limitation of this study was the use of an external display scenario, where the visual display was fixed to the wall and viewed monocularly. This is unlike modern VR technology where the vantage points for both eyes are rendered separately and presented on an HMD display that adheres to the observer's own head movements with high fidelity. Previous research has shown that stereoscopic viewing improves linear vection in depth (Palmisano, 1996, 2002), and recent work has shown that stereo viewing also enhances the strength of circular vection (Palmisano et al., 2016). The HMDs used in VR should therefore generate superior vection because they support large-field stereoscopic viewing.

1.3 The Current Study

In the present study, we examined the perceptual effects of adding head-to-display lag to the Oculus Rift CV1 HMD. We used this particular HMD because of its anticipated low baseline head-display lag (under 10 ms). Specifically, we sought to determine whether vection and presence differentially depend on interactions between head movement speed and the inherent head-display lag. The magnitude of the difference in the user's physical and virtual head orientations should increase with both the head-to-display lag and the speed of their head movements. This in turn should increase his/her visual-proprioceptive conflict (Lee and Lishman, 1975). Based on past research (primarily using external displays) we predicted that increases in head-to-display lag and head-movement speeds would both reduce vection strength. While the effects of display lag on our other outcome measures had not previously been examined, we also predicted that increases in head-display lag and head-movement speed would decrease user feelings of presence in their visual environment.

2. METHOD

2.1 Participants

A total of 23 observers participated in the experiment. There were 14 females and 9 males with an age range of 18 to 42 years. All had normal or corrected-to-normal vision and no known or reported signs of neurological disorder. All reported feeling well at the start of the experiment. Procedures were approved by the biomedical Human

Research Ethics Advisory panel (HREA-B) at the University of New South Wales (UNSW, Sydney) and adhered to the principles in the Declaration of Helsinki.

2.2 The virtual environment

We used the Oculus VR software development kit (OVR) to render a 3D cloud of randomly positioned objects. The 3D point cloud was implemented in the same way as previous research (Kim and Khuu, 2014), except that we used circular objects with no local orientation. A total of 6,912 points were rendered for each eye's view using a combination of calls to OpenGL and the GLSL pipeline (GL Shading Language). Initially, a framebuffer object was created, which is an offscreen memory allocation representing the displayable image area. Custom Open GLSL vertex and fragment shaders were written to render the points to the framebuffers prior to displaying on the Oculus Rift HMD. This method of rendering the display was the most efficient approach to performing rendering operations close to real-time performance, as it relies on the GPU of the video card. When the head is held completely stationary, the display expanded radially to simulate smooth forwards self-motion at a velocity of approximately 3 m/s.

2.3 Estimating HMD system lag

The system was controlled by custom software written in Microsoft Visual C++ 2010 running under the Windows 10 operating environment on an H270 PRO ASUS configuration with intel i7-7700 CPU and 16 GB RAM. The video card was a Nvidia GeForce GTX 1050ti graphics adapter with 4GB RAM. We configured the system to work with the Oculus Rift CV1 HMD without the touch remotes. The initial calibration and positioning of equipment was performed according to the prescribed procedures in the Oculus setup manuals.

After setting up the system, we created a simple display to estimate the baseline HMD system lag using the same procedure as Kim et al. (2015). The scene was configured to render the optic flow display described above, but with the dots rendered invisible (the dots and the background were both rendered as mid-grey). Two additional dark spots were added to the scene (both 0.5° in diameter). The dark spot on the left remained fixed on the left-third central axis of the display, irrespective of the HMD movement (reference spot). The dark spot on the right was configured so that its vertical position was altered by yaw HMD movement (calibration spot), which helped minimize cross-talk during recording. A Blackfly S digital USB camera (effective frame rate of 400 fps) was used to track the image positions of the dark spots on one of the Oculus Rift's displays. We oscillated the HMD in yaw (about ±8°), taking care to ensure the image capture was maintained. A custom gimbal ensured that these HMD rotations were centred around the camera's image plane. The tracked vertical position of the reference spot was subtracted from the tracked vertical position of calibration spot to further minimize cross-talk generated by unintentional vertical displacements of the HMD device during yaw oscillation. Then the HMD system lag was estimated by computed the temporal cross-correlation between the peak positions of the dark calibration and reference spots (after cubic spline fitting to increase precision (1000 points)).

Since Wu, Dong and Hoover (2003) have shown that tracker-based system lags (like those associated with HMDs) can vary markedly over time, we examined how consistent our lag estimates were over time with the Oculus Rift CV1 HMD. We estimated the display lags in the current study based on 40 s recordings of both the baseline lag condition and the condition with the maximum imposed lag. These time-series data were then broken into 20 × 2 s windows in order to compute average head-display lag and the variation in this lag (95% confidence intervals (CIs)) for these two conditions.

2.4 Technique for increasing head-display lag

We modified head-to-display lag by shifting head movement data in time using a 1D memory array of finite length. As shown in Figure 1, the observer's head position in 6DOF was stored in a single block of memory at the current index (denoted t_i). Once written, the current index of the memory array was incremented to the next location ($t_i \rightarrow$

t_{i+1}). At this new location, the memory was read and used to overwrite the contents of the current head sensor data. By increasing the length of the array (n) above a value of 1, we progressively imposed temporal lag into our system. An array of one element in length would generate no added system lag because the sensor data written to the current element would be the same data read and used for updating the perspective views for the two eyes.

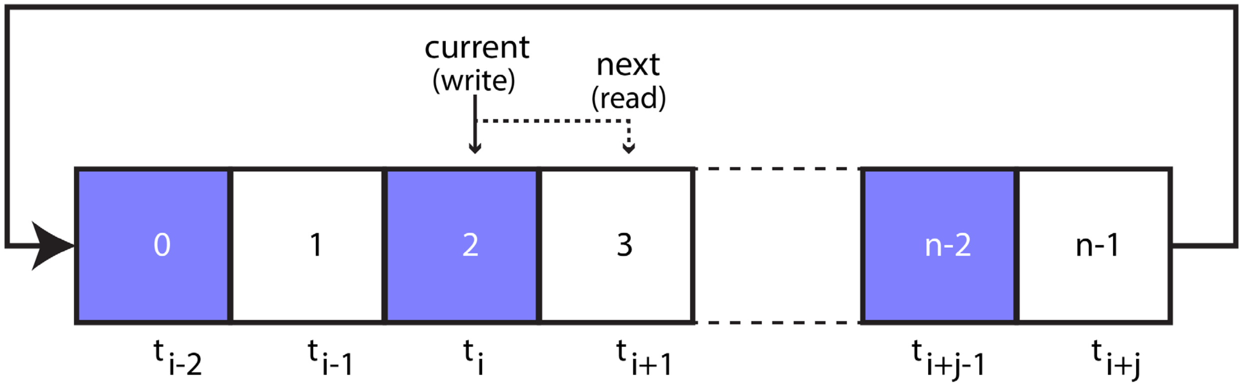

Fig 1. The memory buffer method used to impose head-display lag. The contents of the HMD sensor were written to the memory block at the current time index (t_i). The current index was then incremented to read the contents of the next element which were used to overwrite the current HMD sensor data. Incrementing beyond the last element in the array (i.e., n-1) resets the index to 0, ensuring continuity of the write/read operations. Note that increasing the total number of elements in the array (n) above 1 will increase system lag above the baseline benchmark.

2.5 Procedure

Participants were initially briefed on the requirements of the study. They were seated in a chair without arm supports and presented with audible metronome – sample tones at 1.0 Hz and 0.5 Hz – to gain practice with engaging in yaw head movements. They were instructed to adjust the posture of their head side-to-side in a way that was most "natural" and comfortable for them within the confines of their seating arrangements. The experimenter emphasised the importance of their head movements being consistent in amplitude (i.e., leftwards-rightwards extent) in response to the metronome across all conditions, which was presented in both the training and experimental sessions. To optimise participant comfort, no constraint of torso rotation was imposed in the current study.

Following sufficient practice in making these head movements (about 2-3 minutes), the participant was then reminded of the task. They were instructed to continually oscillate their head from side-to-side throughout each 40 s presentation of radially expanding optic flow. They were to attend to their overall experience of self-motion in depth (i.e., the illusion of forwards self-motion induced by viewing the display). Following each presentation of optic flow, the trial concluded with the participant being required to perform two psychophysical judgment tasks (as well as being checked to determine whether they felt sick or well).

The first of these tasks was to provide an overall estimate of vection strength for the trial on a 101-point scale (0-100) using a rating bar (e.g., Seno 2013). We only used overall ratings for gauging vection (and not latency) to maximize participant attention to optic flow throughout the stimulus presentation (however such ratings have been shown to correlate well with real-time indices of the vection time-course - see Seno et al., 2017). The second judgment task was to provide an overall estimate of the subjective experience of presence (i.e., "being there" in the simulated environment), which was reported on a 21-point rating bar (similar to IJsselsteijn et al., 2001). Ratings could range from 0 = feeling completely "not there" in the display; to 20 = feeling "completely there" in the display.

After completing these three judgment tasks for the trial participants were required to answer yes/no to the question: "Do you feel sick?". This was performed to check on the well-being of our participants during the experiment (similar to recent studies of HMD based cybersickness – e.g., Munafo et al., 2017). Any experience of dizziness, nausea or ocular discomfort (e.g., eye strain) was encouraged to be reported.

Trials were presented in a randomized order, and each participant performed a total of 12 trials in a block: Display lag (6 levels) × Head oscillation frequencies (2 levels). Based on the results reported below, the estimated imposed latencies for the six different levels of display lag were approximately: 6 ms (baseline), 47 ms, 88 ms, 130 ms, 171 ms and 212 ms (based on lag increments estimated at approximately 41.2 ms). Participation in this study required a total of 30 minutes to complete briefing, training and the experimental trials. Perceptual judgments and real-time sensor outputs from the HMD were logged to separate data files.

3.0 RESULTS

3.1 Head movement data

We first checked to see whether our participants had followed our instructions about making yaw head movements in this study. In yaw, the mean peak-to-peak head oscillation range for all participants was 55.8˚ for 0.5 Hz rotations (SD = 34.6˚) and 54.0˚ for 1.0 Hz rotations (SD = 30.0˚). In pitch, the mean peak-to-peak head oscillation range was 0.4˚ for 0.5 Hz rotations (SD = 3.3˚) and 0.6˚ for 1.0 Hz rotations (SD = 2.7˚). In roll, the mean peak-to-peak head oscillation range was 5.7˚ for 0.5 Hz rotations (SD = 5.6˚) and 5.4˚ for 1.0 Hz rotations (SD = 5.6˚). Three-dimensional changes in the angular orientation of the head during (0.5 Hz and 1.0 Hz) yaw head rotations are shown in Figure 2 for one representative participant.

We next examined how our participant's head movements were affected by the imposed display lag and the frequency of the metronome. A two-way repeated-measures ANOVA found no main effect of display lag ($F_{5,110}$=0.27, p = .93) or yaw head oscillation frequency ($F_{1,22}$=0.44, p = .51) on the peak-to-peak amplitude of yaw head oscillations. There was also no interaction effect between display lag and oscillation frequency on the amplitude of yaw head oscillations ($F_{5,110}$=1.52, p = .19).

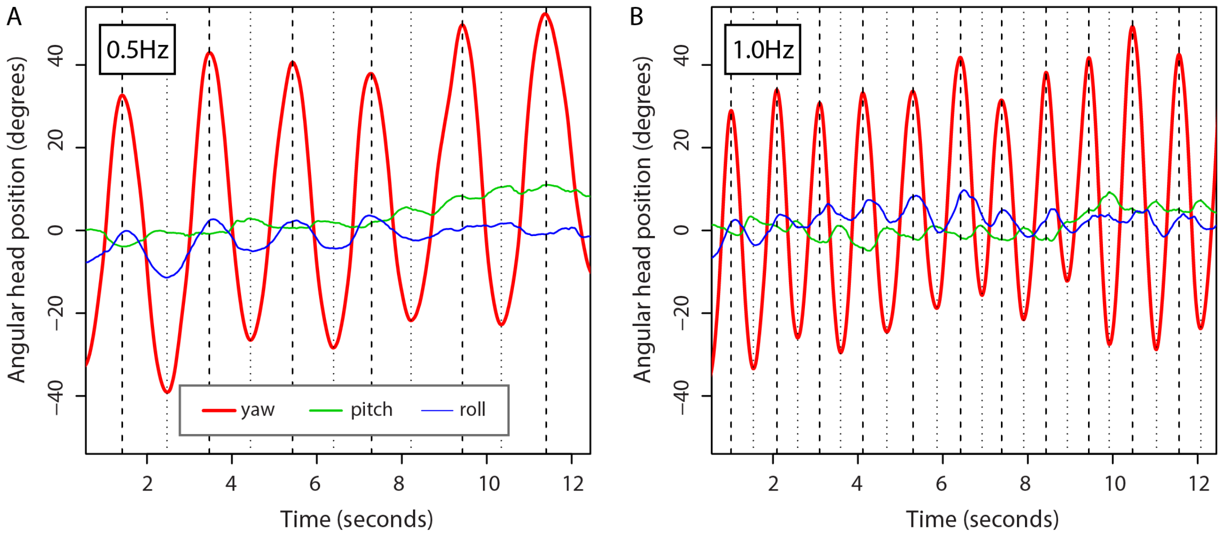

Fig 2. Angular head position during oscillation of the head in yaw at 0.5 Hz (A) and 1.0 Hz (B). Separate traces show orientation in yaw (thick red trace), pitch (thinner light green trace) and roll (thinnest dark blue trace). Vertical dashed and dotted lines indicate the points in time of peaks and troughs in the yaw head position, respectively.

3.2 Estimating Head-display lag

Results of our system latency benchmarking are shown in Figure 3. This figure shows correlations between the reference target's horizontal motion and the yaw-modulated target's vertical motion when two different system lags were imposed (i.e., the baseline lag and maximum imposed lag conditions). The peak in the correlation for the baseline lag condition indicates that the average benchmark system latency for our Oculus Rift HMD when presenting optic flow was 5.3 ms (±1.2 ms 95% CI). The peak in the correlation for the largest display lag condition is also shown in Figure 3 – the average lag for this particular condition was estimated to be 212.8 ms (±1.3 ms 95% CI). Thus, the effective range of the (average) lag imposed on the Oculus Rift based optic flow displays in this experiment was from 5.3 ms to 212.8 ms. The reported variability (95% CIs) appeared to be highly consistent across the full range of display lags that were imposed.

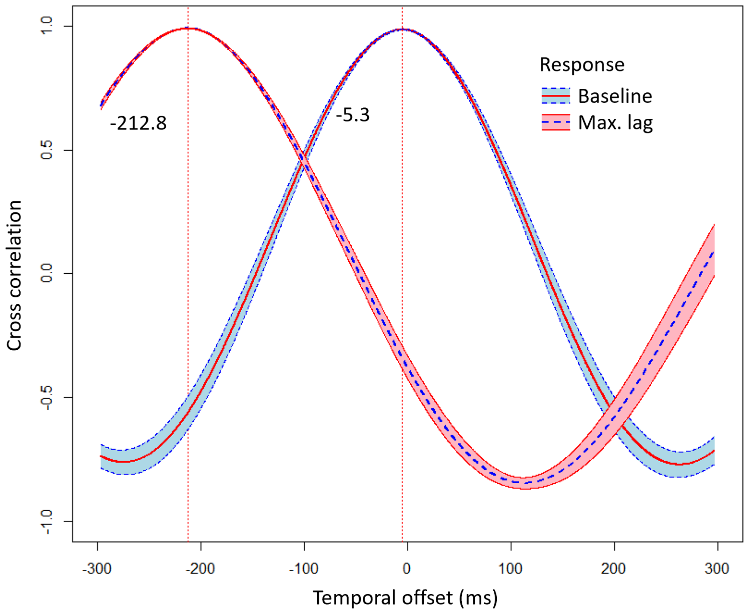

Fig 3. Cross-correlations in the time domain of targets used to estimate head-display lag. Mean cross-correlations plotted as a function of temporal offset in the yaw-modulated calibration signal relative to the change in position of the reference target. Separate curves and 95% confidence bands show data for the baseline lag condition (solid line) and maximum lag condition (dashed line). The dotted vertical lines show the location of the peaks in cross-correlation at baseline (-5.3ms ±1.2 ms 95% CI) and maximum latency (-212.8 ms ±1.3 ms 95% CI).

3.3 Effect of varying head-display lag on perceptual judgment tasks

Figure 4 shows sets of axes plotting the means and standard errors for the two dependent variables examined in this study (vection strength and presence). The results of repeated-measures ANOVAs are reported separately for each of the four outcome measures in the paragraphs that follow.

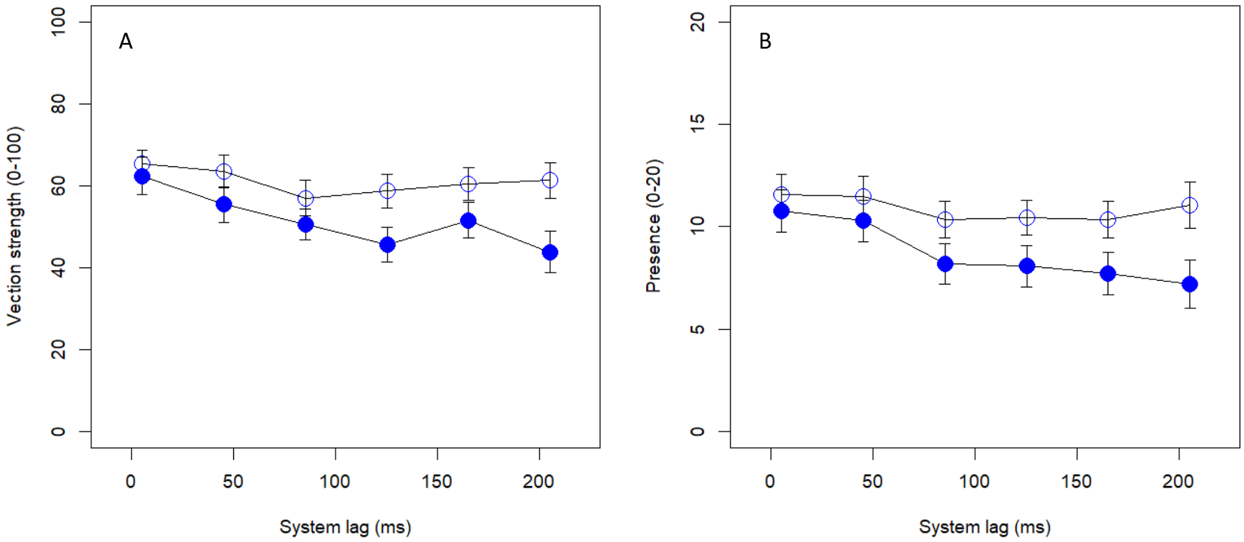

Fig 4. Outcome measures plotted as a function of display lag and head oscillation frequency. Separate plots show (A) Vection strength ratings, and (B) Presence ratings. Hollow points show data for 0.5 Hz conditions and solid points show data for 1.0 Hz conditions. Note that error bars are standard errors of the mean.

Vection strength ratings are plotted in Figure 4A as a function of display lag and the two frequencies of head oscillation. A repeated-measures ANOVA found a significant main effect of display lag on vection strength ($F_{5,110}$=4.17, $p < .005$). There was also a significant main effect of oscillation frequency on vection strength ($F_{1,22}$=16.71, $p < .0005$). There was no interaction effect between display lag and oscillation frequency on vection strength ($F_{5,110}$=1.97, $p < .09$).

Presence is also plotted in Figure 4B as a function of display lag and the two frequencies of head oscillation. A repeated-measures ANOVA found a significant main effect of display lag on presence ratings ($F_{5,110}$=2.98, $p < .05$). There was also a significant main effect of oscillation frequency on presence ratings ($F_{1,22}$=13.25, $p < .005$). There was no interaction effect between display lag and oscillation frequency on presence ratings ($F_{5,110}$=2.11, $p = .07$).

Cybersickness monitored in our self-reporting task generated YES/NO data that were converted to probability estimates of the likelihood that participants reported feeling sick on any given trial. A repeated-measures t-test found that the probability of reporting sickness was greater for the faster 1.0 Hz head oscillation condition, compared with the slower 0.5 Hz head oscillation condition (t_{22} = 2.98, $p < .01$).

3.4 Relationships between vection and presence

Like regression (Lorch and Meyers, 1990), correlational analyses assume that the data represents independent samples. Thus, we first obtained the average vection strength and presence ratings for each participant. There was a significant correlation between vection strength and presence for the 0.5 Hz head oscillation conditions ($r = +0.61$, $p < .005$). There was also a significant correlation between vection strength and presence for the 1.0 Hz head oscillation conditions ($r = +0.62$, $p < .005$). We plotted perceived vection as a function of presence for the two frequencies of head oscillation as shown in Figure 5. The thick solid line shows the line of best fit for the data averaged across head oscillation frequency. Note that the positive intercept implies that participants could experience vection even when they did not feel they were immersed in the display. One sample t-tests can then be used to assess significance of the slope and intercept parameters. We performed this analysis on our relationship between vection and presence. For the 0.5 Hz condition, we computed the average linear model (Vection strength = 1.48 * Presence + 51.8). Because there are multiple points for each participant represented in the plot (repeat data from different lag levels), Lorch and Myers (1990) prefers an analysis whereby a linear-least squares model is fit to each set of participant data. One sample t-tests found that the model slope was significantly different to zero (t_{22} = 4.48, $p < .0005$) and the model intercept was significantly different to zero (t_{22} = 4.00, $p < .001$). For the 1.0 Hz condition, we again computed the average linear model (Vection strength = 2.35 * Presence + 47.2). Again, one sample t-tests found that the model slope was significantly different to zero (t_{22} = 4.46, $p < .0005$) and the model intercept was significantly different to zero (t_{22} = 5.95, $p < .00001$).

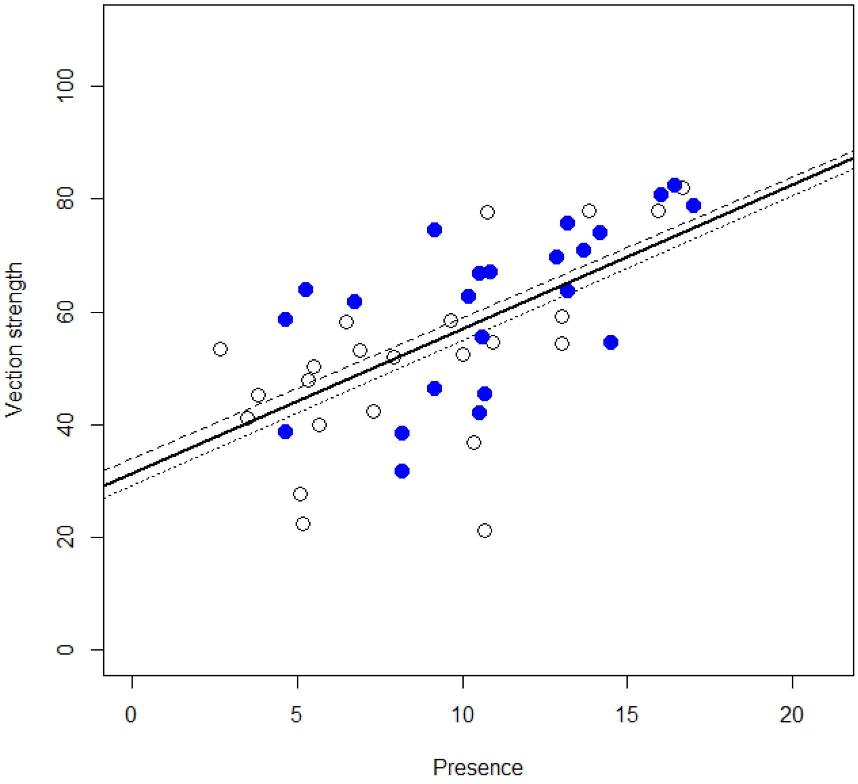

Fig 5. Vection strength plotted as a function of presence. Hollow points and dotted line show data points and line of best fit for the 0.5 Hz condition. Solid points and dashed line show data points and line of best fit for the 1.0 Hz condition. The thick solid line shows the line of best fit for data averaged across head oscillation frequency.

4. DISCUSSION

Our study presented our optic flow displays (simulating self-motion) to participants wearing the Oculus Rift CV1 HMD. As our system was found to have a very low baseline lag (~5.3 ms), this allowed us to assess the effects of systematically increasing head-to-display lag on both vection and presence. We found that increasing head-to-display lag significantly decreased both vection strength and reported feelings of presence. As predicted we also found moderate to strong correlations between vection strength and on presence in HMD-VR (for both the 0.5 Hz and the 1.0 Hz head movement conditions). The significant relationships that we observed in this study were similar to those previously reported by studies using large external displays. For example, Riecke et al. (2006) found that vection and presence ratings varied in similar ways with changes in the realism of the scene content. Both vection and presence ratings were strongest for simulations using the original intact scene images (of the Tübingen Market

Place) and were reduced in a similar fashion by scrambling these images. Although no direct cause could be inferred, Riecke and his colleagues proposed that vection might be rated more strongly when observers view displays that generate greater experiences of presence. A more recent study by Keshavarz et al. (2018) examined the relationship between vection and presence when simulated viewpoint oscillations were added to displays simulating self-motion in depth. They found significant correlations between vection and presence for conditions with simulated rotations in pitch and roll, but not for simulated rotations in yaw. It is worth noting that the oscillating optic flow in their study was displayed *passively* (i.e., it was not generated by the observer's own head movements). By contrast, the results of our study reveal a strong relationship between vection and presence for *actively* generated yaw head rotations. It is possible that this relationship arose because the increased head-to-lag reduced presence, which in turn reduced the potential for the simulation to induce vection in depth (based on the assumption that it is easier to perceive that you are moving through a virtual environment if you already feel present in that environment). However, contrary to this notion, we did find that some vection could still be induced when observers had presence ratings of zero (see the positive model intercepts in Figure 5).

In this study it was possible that some of the variability in the responses across participants was due to eye movements. While we instructed observers to look ahead in the distance, no fixation point was provided to suppress their eye movements. Previous work has shown that active central fixation can impair the vection generated by angular viewpoint oscillation (similar to that used here), but not linear viewpoint oscillations (Kim et al., 2012). It is likely that if observers had made eccentric eye movements then vection strength would have increased rather than decreased. Indeed, Palmisano and Kim (2009) showed that vection could be increased significantly following periodic eccentric fixations relative to the expanding flow field. In a recent paper, Moroz et al. (2018) found that active ego-centric fixation reduced sensitivity to detecting modulations in head-to-display gain during both passive and active yaw rotations. They also found that world-centric fixation increased sensitivity to these modulations which may have increased susceptibility to cybersickness.

It has been suggested that undesired perceptual effects (such as cybersickness) could be caused by 'variability' in latency, rather than latency of HMDs per se (Moss et al., 2011; St Pierre et al., 2015; Kinsella et al., 2016). We performed calibrations at baseline and at the maximum level of lag imposed to ascertain how consistent the measured latency of the Oculus Rift CV1 was over our 40 s trials. We found that the estimated variability in sampled latencies was similar across the baseline (low latency) and highest system latency imposed in the study. This finding suggests that the effects of head-display lag on our vection and presence measures cannot be explained by variance in system latency over time. Rather, we propose that the perceptual effects that we observed were caused by differences in the orientation of the simulated and physical head orientations achieved over time. This proposal is supported by the finding that lower vection and presence measures were found when participants made faster head movements (i.e., 1.0 Hz compared with 0.5 Hz head oscillations).

The findings of the present study suggest that head-to-display lag affects vection and presence. There was a strong relationship between vection and presence, which could suggest these two percepts are perceptually related. Recent studies have shown that vection was strongest in conditions where simulated head orientation matched physical head orientation (Kim et al., 2015; Palmisano et al., 2017). Future work will hopefully determine whether differences in orientation between the physical and the (virtually-)perceived head orientation might account for declines in vection like those observed in the present study.

The potential effects of HMD constraints on perceptual experience should also be considered in future. Riecke and Jordan (2015) found that reducing the field of view (using an external or HMD display) reduced the latency of vection onset, and this effect was consistent across display types. However, they found no difference in vection strength with changes in field of view. In contradistinction, Basting et al. (2017) found a positive relationship between vection strength and the HMD's field of view. It is possible the differences between these studies can be attributed to differences in the type of simulated display motion and structure of the scene. It is possible that the amount of physical head movement could also explain these differences. For example, viewpoint perspective changes associated with lateral linear head displacement can prime the onset of vection (Palmisano and Riecke, 2018). Future work should be considerate of the potential effects on outcome metrics from an HMD's field of view and other constraints. Fortunately, field of view was unlikely to have influenced the results of the present study as display size was not varied in the process of presenting our virtual environment.

One potential further consideration for future research is the role that display lag may have on cybersickness. We monitored cybersickness using an insensitive YES/NO report and found that the likelihood of reporting cybersickness was significantly greater for fast head movements compared to slower head movements. However, these sickness task did not estimate severity of any reported cybersickness. Feng et al. (2019) found that increasing display lag increased cybersickness severity, but a small amount of cybersickness was reported for even very low latencies. They proposed that constraints inherent in the presentation of content on the display itself may generate cybersickness. In earlier work, Prothero (1995) proposed that background motion is important for cybersickness. The researcher found that introducing a stable visual background behind the virtual scene using a half-silvered mirror was sufficient to mitigate the effects of cybersickness, while preserving vection. More recent research has shown that cybersickness in HMD-VR appears to depend on stereoscopic disparity (Palmisano et al., 2019) and restrictions on the simulated depth of field (Carnegie and Rhee, 2015). It would therefore appear that stabilizing image content at different simulated depths might be critical for minimising cybersickness and its severity. Fortunately, there are also exciting approaches being implemented in augmented and mixed reality for optimizing fidelity in display alignment to minimize perceptual incompatibility when mixing virtual content with real-world visual information (Yokokohji et al., 2000; Freiwald et al., 2018).

Ultimately, the extent to which changes in perceived self-orientation can be readily measured will provide critical insight into the potential factors of multisensory conflict that may drive the perceptual advantages that users enjoy with extremely low system latencies (e.g., Riecke, Freiberg, Grechkin, 2015). These benefits will be ensured not by the future advances in adaptive latency reducing algorithms (e.g., time warp), but rather, the ongoing psychophysical research that will validate their effectiveness.

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