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Beyond Feeling Sick: The Visual and Cognitive Aftereffects of Virtual Reality

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ABSTRACT Despite continued improvements in virtual reality (VR) technologies, many people still experience adverse symptoms from using head-mounted displays (HMDs). Typically, these symptoms are monitored through self-report measures, such as the Simulator Sickness Questionnaire (SSQ); however, by only using subjective measures many symptoms may be overlooked. In an application-based study, we investigated visual and cognitive aftereffects of using HMDs and their relationship to the reporting of sickness on the SSQ. Visual (accommodation and vergence) and cognitive (reaction time and rapid visual processing) assessments were employed before and after participants engaged in a 30-minute VR table tennis game (VR group, $n = 27$) or went about their daily activities (control group, $n = 28$). The data showed changes in accommodation but no concurrent changes in vergence, which likely stems from decoupling accommodation and vergence in VR. Furthermore, larger changes in accommodation were linked to more severe sickness symptoms suggesting that decoupling accommodation and vergence could be more adverse than previously thought. The VR group also had slower decision (cognitive) times, but movement times were unaffected. These findings go beyond the typical self-reporting of sickness in VR studies. Moreover, we demonstrate that even in a high-quality commercial virtual environment, users may experience visual and cognitive aftereffects that may negatively influence their experience with subsequent activities in the real world. Developing an understanding of how VR aftereffects may influence later activities could help to minimise the risk of using HMDs for various applications and may be valuable to obtain a better understanding of user issues and VR safety.

INDEX TERMS Aftereffects, motion sickness, depth perception, vergence-accommodation conflict.

I. INTRODUCTION

The oculomotor system performs an essential function in depth perception and adaptation to environments. In natural viewing conditions, the left eye sees a left view of the world, and the right eye sees the right view. The brain fuses these two offset viewpoints to create one seamless three-dimensional perspective of the world—this is called binocular vision. During binocular fixation, oculomotor functions, such as vergence and accommodation, are responsible for achieving a single and clear focal point. Vergence is the rotation of the eyes inward towards a focal point; this is important for obtaining a single (i.e. fused) image at the point of fixation. Vergence errors lead to diplopia (double vision). Accommodation is the contraction of the ciliary eye muscle to achieve focusing power resulting in a clear image at a near fixation point—errors in accommodation lead to blurry vision. Vergence and accommodation are tightly coupled so that changes in viewing distance lead to changes in both mechanisms [1]. Naturally, vergence and accommodation occur at the same point of fixation. Hence, the vergence-accommodation coupling can increase the speed at which clear binocular fixation occurs [2].

A high-quality stereoscopic head-mounted display (HMD) will be capable of simulating depth that resembles the spatial properties of the real world; however, current technology

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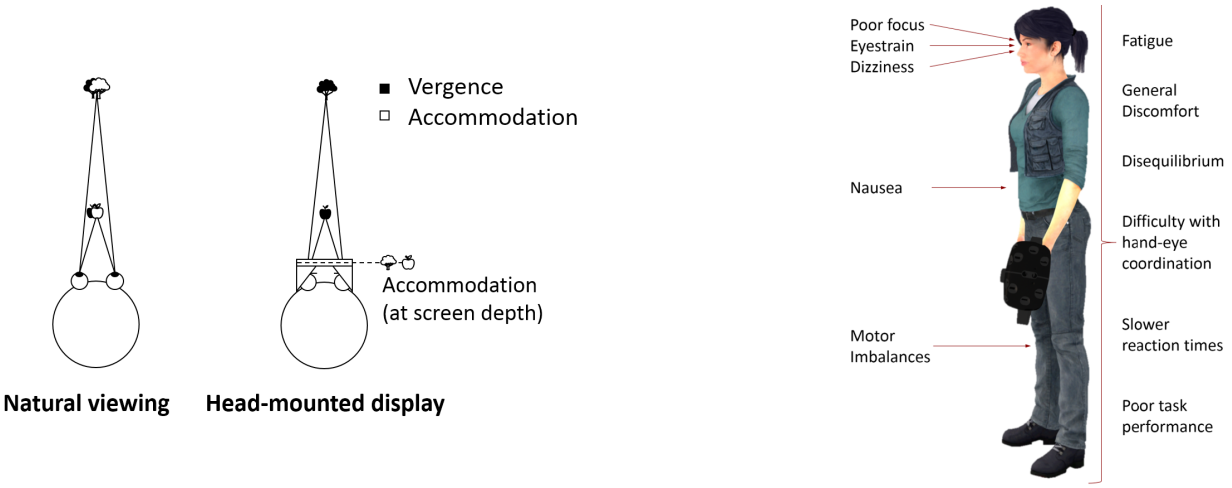

FIGURE 1. Decoupling of the oculomotor system in VR (left) and common VR sickness symptoms (right). Vergence and accommodation are naturally oriented to the same point, but this is not so in VR. Vergence can be at any of the various simulated depths in a virtual environment, but accommodation always occurs at screen depth. This temporary dissociation of vergence and accommodation introduces unnatural conflicts in visual processing, which are linked to symptoms such as headaches and visual fatigue. Figure on the left adapted from [3].

is not capable of replicating how humans see and perceive depth under natural viewing conditions. Binocular vision is simulated by displaying left and right offset images to each eye of the user. Accordingly, the visual system fuses the left and right images to create a single three-dimensional virtual environment. Simulated depth is created by altering the offset (disparity) between the left and right images projected to each eye. If the disparity is small, an object will appear close, and if the disparity is large, the object will appear further away. Accordingly, vergence can take place at various depths simulated in the virtual environment. Accommodation, however, typically occurs at screen depth, and is different from depths simulated during a VR experience (see Fig.1). This dissociation between vergence and accommodation in VR introduces unnatural visual conflicts that may lead to aftereffects such as visual fatigue, headaches, and readaptation difficulties [2].

Through the use of stereoscopic displays, the artificial decoupling of accommodation and vergence has been hypothesised to be an underlying factor in the occurrence of visual fatigue (see: *Lambooij et al.,* [4] for a review). Visual fatigue, however, is primarily captured through self-reported symptoms of tiredness, visual disturbances or discomfort [2], [5], [6], it is uncertain what visual fatigue after VR really is. Objective measures of visual fatigue in the vision literature are somewhat elusive, particularly because there is no agreed upon definition of visual fatigue across disciplines [4], [7]. Outside of the VR literature, studies that have attempted to link eye-movements and self-report measures of visual fatigue, have either been unable to do so or not found any consistent relationship [8], [9]. Notably, studies that have had success at linking fatigue and saccadic velocity, have operationalised fatigue as a reduced alertness/vigilance. Most of these studies, commonly report a relationship between reduced alertness with a decrease in saccadic velocity [10]. If self-report symptoms of visual fatigue after VR-exposure are linked to alertness instead of symptoms of visual dysfunction, then it is possible that visual fatigue after VR has cognitive origins [7].

The literature on cognitive aftereffects from VR is sparse and inconsistent, thus it is challenging to pinpoint what aspects of cognitive performance is affected. The findings from research examining VR aftereffects on specific areas of cognitive functioning such as mental rotation, visual-spatial working memory and visual search; vary between studies [11]–[13]. Decreases in reaction time after VR immersion have been reported across several studies [13]–[15], but the mechanisms affected by VR is still under debate. Nesbitt *et al.*, [14], found an association with increased reaction times and VR sickness, however, this was only for one of their two VR rollercoaster scenarios. These selective cognitive aftereffects may suggest that VR content could play a role in the onset or severity of cognitive symptoms. Other researchers have found increases in reaction times after VR but have not found associations with VR sickness [11], [13]. Hence, the inconsistency in findings raises another important issue about the source of cognitive aftereffects. Commonly used reaction time measures primarily engage cognitive and motor mechanisms. When a participant makes a speeded response in a reaction time task they engage both mechanisms and the output from the task is typically a combination of both. In the context of VR aftereffects, it is unclear if increased reaction times are a result of affected cognitive or motor mechanisms or a combination thereof. The discrepancy between studies may relate to the different demands placed on cognitive and motor mechanisms from various VR experiences, thus these demands may account for the inconsistent results found in the literature. An alternate explanation that has been proposed is that some cognitive aftereffects such as a decrease in hand-eye coordination may stem from visual, motor or vestibular adaptation in a virtual environment [13], [15], [16].

Adaptation to a virtual environment may contribute to virtual reality sickness [16]–[18]. Virtual reality sickness can be triggered by perceived self-motion in a virtual environment that may be different from true motion in the real world and can lead to symptoms of nausea, eye strain, headaches, dizziness and disorientation [16], [19]–[21]. When an individual puts on a VR headset and becomes immersed in a virtual environment, their brain integrates the new spatial characteristics of the virtual environment. By integrating this new information, adaptation to hand-eye coordination, visual perceptions, and balance are imposed [16]. Upon exiting VR and returning to the real world, an individual's oculomotor system will need to readapt back to the real world. Immediately after VR exposure, a person will need to reintegrate the spatial characteristics of the real world to readapt. During this time, individuals typically experience aftereffects with hand-eye coordination [16], [17], visual perception [5], [22] and balance [23], [24]. Accordingly, both adaptation [17] and readaptation [16] are related to symptoms of VR sickness. Repeated VR exposure has been thought to reduce VR sickness symptoms in certain individuals [25]–[27]. Some researchers have suggested that reduced symptoms may indicate a more advanced level of adaptation that may put these individuals at greater risk [16], [18], [21]. Thus, it is necessary for objective measurements of visual and cognitive aftereffects to be studied in relation to and independently from self-report symptoms of VR sickness.

Various studies have attempted to investigate vergence-accommodation conflicts and aftereffects in stereoscopic HMDs, but the links between visual effects and VR sickness is still uncertain. Mon-Williams *et al.* [28] observed changes in near point of convergence after participants engaged in a 10 minute VR cycling task using an HMD. The authors found an increase in the distance at which participants eyes could converge. Moreover, about 60 percent of their sample reported symptoms of blurred vision, headaches, diplopia, nausea and sore eyes. A more recent study examined the visual aftereffects in adolescence after watching a 30-minute VR video in an HMD, and the researchers did not observe any changes to accommodation after VR [22]. Ha *et al.* [22] did, however, find myopic shifts in about 40 percent of their participants. The authors did not systematically report VR sickness symptoms, thus it is uncertain whether participants with visual disturbances also had other symptoms. Other studies have artificially altered accommodation and vergence in VR and noted that participants report greater fatigue with larger mismatches [6] and that it may have an influence on postural sway [29]. Recent research on the changes in accommodation and vergence in stereoscopic HMDs is sparse and insufficient to draw any strong conclusions from. Furthermore, many of these studies do not have a control group to compare against. It is known, that transient changes to accommodation and vergence may occur during everyday activities [30], [31]. Hence, it is essential that a control group is included in VR studies that examine aftereffects to make comparisons between changes resulting from VR-exposure and normal everyday activities.

Rapid advancements in virtual reality technology have led to inexpensive commercially available HMDs that have greatly enhanced user's immersion in a diverse range of applications in education [32], business [33], entertainment [34], and training [35]. Enhancing a user's immersion is essential for developing a superior virtual environment with seamless visual adaptation to a new environment. A seamless visual adaptation to VR with little or no aftereffects will give users a better experience and ultimately result in the continued use of the technology. Therefore it is important that VR aftereffects are well understood. This study uses an application-based approach to address the gap in the literature on visual and cognitive aftereffects from using commercially available HMDs. Two main discrepancies in the literature will be addressed with the proposed research: (1) potential aftereffects from decoupling accommodation and vergence in VR will be measured, and (2) investigating whether cognitive (decision) or movement times are affected from VR immersion. Any measurable aftereffects will be correlated with reported VR sickness to observe how closely subjective and objective symptoms are related. Establishing how visual and cognitive aftereffects may present in existing applications will be useful to researchers that are planning on developing novel virtual environments for specific purposes. Furthermore, developing an understanding of how VR aftereffects may influence later activities could help to reduce the risk of using HMDs for various applications.

II. METHODS

A. PARTICIPANTS

Sixty-two university students ($m = 38$; $f = 24$) were recruited to partake in this VR study. All participants provided informed consent and were reimbursed $20 per hour for their time participating in this study. Participants were split up into two groups: a virtual reality group and a control group (see: procedure for further details). One participant withdrew (f), and another 6 participants ($m = 5$; $f = 1$) were excluded from the study for having poor stereo acuity. The remaining 55 participants (VR = 27; control = 28) were included in the main analyses ($M_{age} = 21.60$, $SD = 3.13$). In the VR group, 52% ($n = 14$) of participants played computer or console games seldomly (equal to or less than once a month) and the remaining 48% ($n = 13$) participants played games often (weekly/daily). Individual data is available on the Open Science Framework at https://osf.io/bn3cq/ with more details. The UniSA Human Research Ethics Committee granted approval for this study.

B. MATERIALS AND APPARATUS

1) VR SETUP

A commercially available HTC Vive Head-mounted display (HMD) was used to administer a 30-minute virtual reality experience to participants. In our application-based approach,

participants played an existing off-the-shelf table tennis game called *Eleven: Table Tennis VR* (developed by For Fun Labs). Eleven Table Tennis VR was chosen primarily because the game offers a high-quality, responsive and realistic virtual environment that participants could engage with for at least 30 minutes. A high-end laptop with an Intel Quad Core i7-7820HK processor at 2.90GHz, 16 GB RAM and an Nvidia Geforce GTX 1080 8GB graphics card ensured that participants experienced the game at optimal performance. Eleven: Table Tennis VR simulates a virtual game of table tennis whereby users interact with a virtual table tennis setup and respond to a competitive AI opponent. The game utilised haptic, auditory and performance feedback which gave participants an immersive experience.

2) VISION MEASURES

Standard ophthalmological equipment was used to screen participants visual and stereo acuity and was also used to measure changes in participants' depth perception and vision. Visual measurements were taken for long- and near-vision, stereo vision, and eye movements such as accommodation and vergence. The Snellen and Fonda-Anderson chart were used to assess long- and near-vision, respectively. The Butterfly Stereo Acuity test (Vision Assessment Corporation, 2007) was utilised to ensure participants could see the virtual environment correctly and to examine any changes in stereovision. Furthermore, the Royal Air Force (RAF) near point rule was used to assess near point of convergence (NPC) and near point of accommodation (NPA) pre- and post-VR exposure. The RAF near point rule is composed of a 500 mm ruler-like square tube with a slider attachment bracketing a four-sided rotating cuboid. In this study, we only used two of the four sides: the Time Roman typeface to measure NPA, and the small black dot to measure NPC. At the one end of the RAF rule, there is a plastic 60 mm V-shaped cheek rest to comfortably sit on a participant's cheek and fit around their nose (see: [36] for further details on the RAF rule).

3) COGNITIVE ASSESSMENTS

The CANTAB five-choice reaction time task (RTI) and rapid visual processing task (RVP) were administered on an Ipad 2 using the CANTAB application [37], [38]. The CANTAB version of the five-choice RTI focuses on measuring participant's speeded responses so that movement and decision aspects are dissociable. Because the five-choice RTI requires a participant to monitor five locations opposed to one, this version places greater demands on attention and cognitive load compared to simple one-target reaction time versions commonly used. The RTI consists of a circle (button) on the lower half of the screen and five circles on the top portion of the screen. The participant must hold down the button located at the bottom of the screen and wait for a yellow dot to appear in any of the five circles in the top portion of the screen. When a yellow dot appears, participants must release the button and touch the yellow dot as quickly as they can. Correct responses are used to calculate the mean duration from the time between the onset of the stimulus and the moment a participant released the button (i.e. decision time) and the time between button release and touch of the target (i.e. movement time).

The CANTAB Rapid Visual Processing (RVP) task assesses other domains of attention by measuring continuous performance and sustained attention. In the centre of the screen, single digits appear in a white box on a black background in a pseudo-random order at a rate of 100 digits per minute. On the right of the white box, target sequences of three digits are shown (for example, 2-4-6, 3-5-7, 4-6-8). When the participant sees any of the three target sequences, they must respond by selecting the button in the centre of the screen as quickly as possible. Nine target sequences appear every 100 digits. Key outcome measures for this task are A-prime and mean response latency. A-prime is a signal detection sensitivity measure that quantifies how accurate a participant is at detecting target sequences, the range of scores is from 0.00 (poor) to 1.00 (good). Mean response latency was calculated from correct trials only.

4) SIMULATOR SICKNESS QUESTIONNAIRE

The Simulator Sickness Questionnaire (SSQ) is the most widely used measure to assess simulator sickness, cybersickness and VR sickness; hence, we chose the SSQ to assess self-report symptoms of VR sickness [20]. The SSQ comprises of a 16 symptom inventory with a four-point rating scale from 0 (none) to 3 (severe). Kennedy clustered the 16 symptoms into three categories: nausea, oculomotor and disorientation. The nausea cluster comprises of 7 symptoms associated with feelings of stomach sickness such as increased salivation, burping and stomach awareness. The oculomotor cluster consists of 7 symptoms related to eyestrain, fatigue, and focusing. The disorientation cluster includes 7 symptoms related to dizziness and vertigo. The three subscales are not independent as the clusters include overlapping symptoms.

C. PROCEDURE

Prior to participation, participants either responded to flyers around the university campus about participation in a virtual reality study (VR group) or motor coordination study (control group). When participants signed up for the study they were volunteering to participate in a table tennis study (see [35]). The examination of visual and cognitive aftereffects detailed in this paper was a smaller, but necessary component of this VR study.

When participants arrived at the laboratory, they were given verbal instructions about the task and a participant information sheet. Participants then completed demographics questions, FLANDERS handedness inventory [39], and vision history form. The vision and acuity assessments were administered (approx. 8 minutes), and participants also completed the CANTAB Reaction Time (RTI) and Rapid Visual Processing tasks (approx. 15 minutes). After completing the questionnaires, participants in the VR group were guided to the virtual reality room and fitted with an HTC Vive headset.

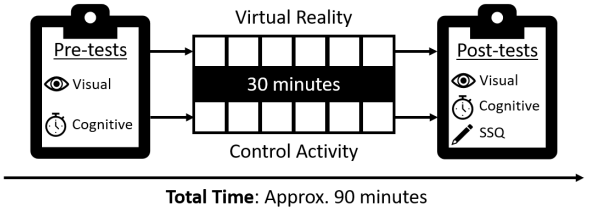

FIGURE 2. Showing experimental procedure and estimated time. The 90 minutes also included consent, verbal instructions, setup time and debriefing. The visual measures that were included are the Butterfly stereo acuity test, Snellen visual acuity chart, accommodation and vergence (RAF rule), and the cognitive tests that were included are the five-choice reaction time task (RTI) and rapid visual processing task (RVP).

The researcher provided verbal instructions on how to play Eleven: Table Tennis and a walkthrough on using the controls, menu and adjusting the headset. Once participants acknowledged that they understood the task they commenced a 30-minute VR experience. Immediately after participants took the VR headset off, they sat down and completed a second round of visual assessments and CANTAB tasks in addition to the Simulator Sickness Questionnaire [20]. In the control group, participants were instructed to 'go about their daily activities and return 30 minutes later for further assessments'. When participants from the control group returned, they were also given the visual assessments and CANTAB tasks again. At the end of the experiment, participants were reimbursed for their time. Overall this procedure took approximately 90 minutes to complete (see Fig.2).

III. RESULTS

Individual data is available on the Open Science Framework at https://osf.io/bn3cq/

1) VISION MEASURES

Accommodation and vergence measures were analysed in a mixed ANOVA with time (pre-test and post-test) as a within-subjects factor and group (VR and control) as a between-subjects factor (see Fig.3).

For accommodation measurements, a significant main effect of time [$F(1, 53) = 12.707$, $p<.001$, *partial* $\eta^2 = .193$], and interaction of time and group [$F(1, 53) = 4.708$, $p = .035$, *partial* $\eta^2 = .082$] was found. There was no main effect for the between-subjects factor of group [$F(1, 53) = 2.674$, $p = .108$, *partial* $\eta^2 = .048$]. Independent t-tests demonstrated that VR and control groups were not significantly different at pre-test [$t(53) = .510$, $p = .612$], but were significantly different at post-test [$t(53) = 2.167$, $p = .035$]. Bonferroni corrected ($\alpha = .017$) paired t-tests showed that VR pre-tests [$M = 6.444$, $SE = .917$] and post-tests [$M = 10.556$, $SE = 1.460$] were significantly different [$t(26) = 3.757$, $p = .001$, *Cohen's d* $= .723$]. For the control group, paired t-tests showed that pre-test [$M = 5.786$, $SE = .909$] and post-test [$M = 6.786$, $SE = .968$] measurements did not differ [$t(27) = 1.073$, $p = .293$, *Cohen's d* $= .199$].

Convergence measurements were not significant for time [$F(1, 53) = 2.517$, $p = .119$, *partial* $\eta^2 = .045$], group [$F(1, 53) = 3.351$, $p = .073$, *partial* $\eta^2 = .059$], or interaction between time and group [$F(1, 53) = .049$, $p = .825$, *partial* $\eta^2 = .001$]. No further comparisons are reported as the ANOVA failed to reach significance.

2) COGNITIVE MEASURES

Change scores for decision and movement times were calculated by subtracting post-measurement scores to pre-measurement scores (see Fig.4). To make these results comparable to other studies, a combined mean of decision and movement times were also analysed. Several one-sample t-tests were performed to compare participants change scores against 0 (no change).

Regarding decision times, participants in the VR group [$M = 11.387$, $SE = 4.942$] were slower after VR [$t(26) = 2.304$, $p = .029$, *Cohen's d* $= .443$]. The control group [$M = -5.285$, $SE = 3.708$] showed no change [$t(27) = 1.425$, $p = .166$, *Cohen's d* $= .269$].

Regarding movement times, participants in the VR group [$M = -3.858$, $SE = 4.064$] were unchanged after VR [$t(26) = 0.949$, $p = .351$, *Cohen's d* $= .183$], as were the control group [$M = -6.240$, $SE = 5.515$] that also showed no change [$t(27) = 1.131$, $p = .268$, *Cohen's d* $= .214$].

Regarding overall RTs, participants in the VR group [$M = 3.765$, $SE = 3.085$] showed no change after VR [$t(26) = 1.220$, $p = .233$, *Cohen's d* $= .235$], and neither did the control group [$M = -5.763$, $SE = 3.166$] accordingly t-tests reflected no change [$t(27) = 1.820$, $p = .080$, *Cohen's d* $= .344$].

For the RVP task, A-prime was a key outcome measure determining participants level of accuracy for this task. Performance across the different groups was analysed in a mixed model repeated measures ANOVA with time (pre- and post-test) as within-subjects factors and group (VR or control) as between-subjects factors. The findings show that there was a main effect for time [$F(1, 53) = 48.396$, $p<.001$, *partial* $\eta^2 = .476$], but there was no interaction of time and group [$F(1, 53) = 0.300$, $p = .586$, *partial* $\eta^2 = .003$] was found. There was also no significant effect between groups [$F(1, 53) = .624$, $p = .433$, *partial* $\eta^2 = .012$]. Bonferroni corrected paired t-tests of participants performance at post-test [$M = .949$, $SE = .006$] compared to pre-test [$M = .915$, $SE = .007$] demonstrated higher accuracy regardless of which group participants were in [$t(54) = 6.663$, $p>.001$, *Cohen's d* $= .943$].

A change score was calculated for mean response latency by subtracting post-test from pre-test measurements for the RVP task. Differences between groups were analysed in an independent t-test and showed that the VR group [$M = -29.68$, $SE = 8.873$] and control group [$M = -56.40$, $SE = 21.862$] were not significantly different from one another [$t(53) = 1.117$, $p = .269$, *Cohen's d* $= .301$]. Moreover, one-sample t-tests showed that both the VR group [$t(26) = 3.345$, $p = .003$, *Cohen's d* $= .644$] and control group

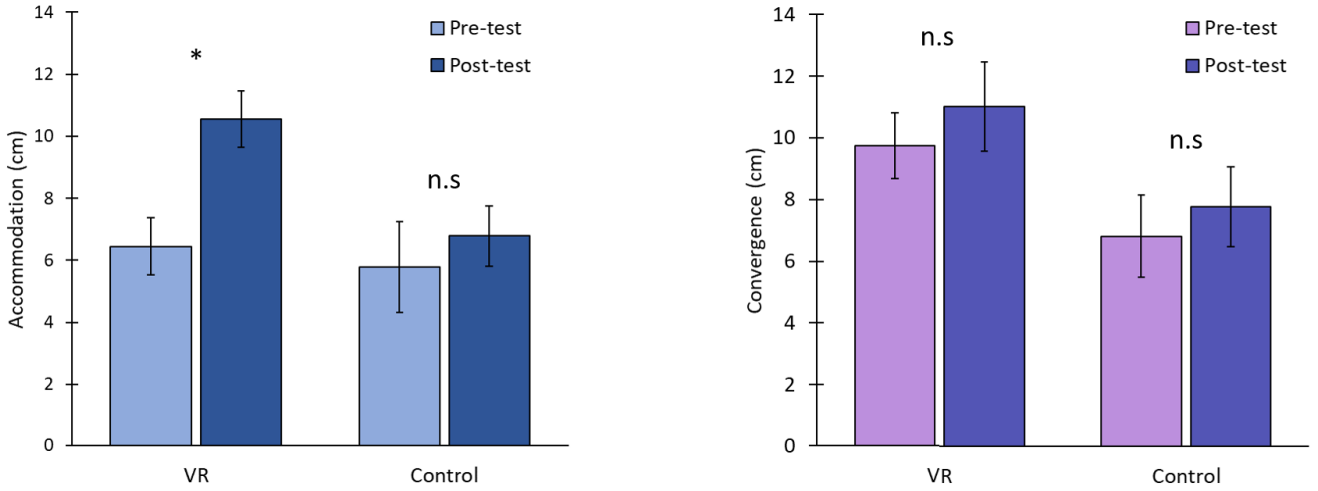

FIGURE 3. Figures demonstrating the changes in participants near point accommodation and convergence before and after VR. Note: Accommodation (left) changed after VR, but convergence (right) was not significantly different (n.s). This pattern of results is likely due to the decoupling of accommodation and vergence in head-mounted displays. Error bars indicate standard errors.

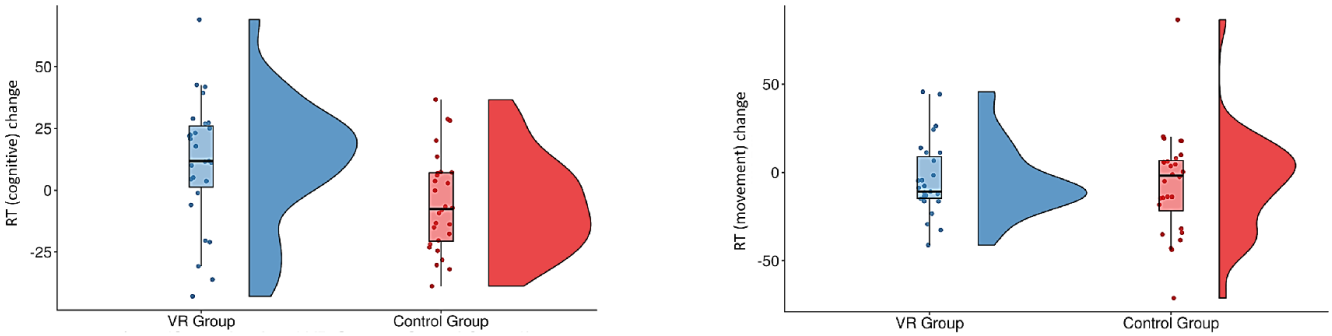

FIGURE 4. Raincloud plots [40] showing distributions, boxplots and raw data of participants change scores on the five-choice reaction time task (in milliseconds). Decision (left) and movement (right) times of the RTI have been analysed separately. Negative values represent a decrease in reaction times (faster), whereas positive values represent an increase (slower). VR group played table tennis in an HMD for 30 minutes ($n = 28$), and the control group ($n = 27$) which went about their daily activities.

[$t(27) = 2.580$, $p = .016$, *Cohen's* $d = .488$] became faster. Taking into account both key outcomes of A-prime and mean response latency, these data show that participants improved in accuracy and speed regardless of whether they were allocated to the VR or control groups.

3) SIMULATOR SICKNESS QUESTIONNAIRE

The mean weighted scores [20] and standard errors for the SSQ subscales and total scores are as follows: nausea 14.49 (2.81), oculomotor 20.21 (3.77), disorientation 17.53 (3.76) and total weighted SSQ score 20.36 (3.76). According to the total SSQ categorisations in [41], 29.63% of participants reported symptoms of serious concern and another 37.04% reported significant symptoms (see Fig. 5).

To assess whether participant's post-accommodation scores were related to reported sickness symptoms several correlations were run on the total SSQ scores and all three SSQ subscales. Post-accommodation scores and total SSQ scores were significantly related [$R^2 = .202$, $p = .019$]. The findings suggests that accommodation may be related to participants reporting of simulator sickness symptoms. To further understand this relationship and whether particular clusters in the SSQ were driving this relationship, correlations on the SSQ subscales were also employed. These analyses demonstrated that nausea [$R^2 = .232$, $p = .011$], and disorientation [$R^2 = .204$, $p = .018$] were related to post-accommodation scores, however oculomotor symptoms [$R^2 = .143$, $p = .052$], failed to reach significance.

Similar analyses were conducted using post-vergence measurements and neither the total scores nor subscales reached significance [R^2<.090, p>.129].

Correlations with change scores for RTI reaction times and SSQ total scores subscales scores failed to reach significance for decision times [R^2>.025, p>.433] and movement times [R^2>.078, p>.157].

Correlations with change scores for the RVP task and SSQ were closer to significance levels for total [$R^2 = .141$, $p = .054$], nausea [$R^2 = .119$, $p = .078$], oculomotor [$R^2 = .133$, $p = .062$], and disorientation [$R^2 = .123$, $p = .073$], however, did not quite reach significance.

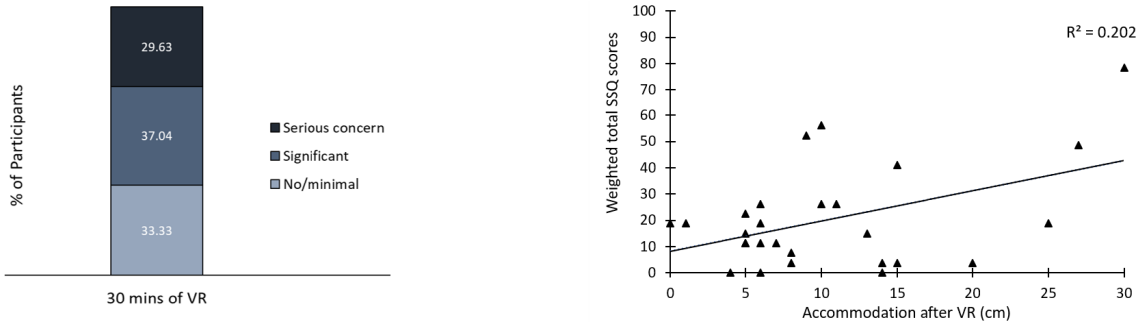

FIGURE 5. Percentage of participants from the VR group ($n = 27$) showing no/minimal, significant and serious VR sickness symptoms after 30 minutes of VR exposure (left). The categorisation of severity levels is based on [41] interpretation of the Simulator Sickness Questionnaire scoring. The categories are as follows: No/minimal symptoms (0-10), significant symptoms (11-20), and symptoms of serious concern (>20). Decoupling of the oculomotor system in VR leads to subsequent VR sickness symptoms. Post accommodation measurements correlated with total SSQ scores (right). Scores greater than 15 cm may indicate accommodation insufficiency.

IV. DISCUSSION

The aim of this study was to go beyond the self-report symptoms commonly reported in VR studies by investigating how HMDs may also lead to visual and cognitive aftereffects. Moreover, this study attempted to expand on these findings by examining the relationship of these aftereffects to VR sickness symptoms. A high-quality off-the-shelf game was selected to test the hypothesis that commercially sold HMDs may lead to visual and cognitive aftereffects. A battery of standardised visual and cognitive assessments were employed before and after participants engaged in a 30-minute table tennis game. Self-report symptoms of VR sickness were also measured using the SSQ. We observed changes in accommodation but not in vergence, which possibly stems from the aftereffects of decoupling accommodation and vergence in VR. Also, participants showed an increase in a decision-making reaction time task post-VR and compared to a control group. These findings show that objective measures of the visual and cognitive aftereffects of VR may provide insight beyond self-report measures of VR sickness. Establishing how visual and cognitive aftereffects may present in existing applications will be useful to researchers that are planning on developing novel virtual environments for specific purposes. Furthermore, these measures may also be valuable to obtain a better understanding of user issues.

In this study, the main findings regarding visual effects were changes in accommodation after VR. These changes in accommodation were significantly different from a non-VR control group that went about their daily activities. Notably, there were no concurrent changes in vergence (as one may expect in a real-world environment), this perhaps demonstrates the aftereffects of decoupling accommodation and vergence in VR (see Fig. 1). In a real-world environment, accommodation and vergence occur at the same depth. In VR, however, accommodation happens at screen depth and vergence occurs at any of the simulated depths. Previous studies that have shown aftereffects of accommodation and vergence have been criticised for not demonstrating aftereffects substantive enough to be of clinical concern [42]. For example, if participants presented with an accommodative spasm after VR this would warrant clinical attention. In the case of the present study, participants did not show aftereffects of clinical concern. Some participants accommodated outside of the normal range but did not report diplopia or other significant visual impairments. Although VR exposure did not give participants side-effects meeting clinical diagnoses, the decoupling of accommodation and vergence may have latent visual and cognitive effects.

A particularly intriguing finding was that the post-accommodation measurements correlated with total SSQ scores and on nausea and disorientation subscales. These findings may suggest that vergence-accommodation conflicts could lead to symptoms beyond visual fatigue—which is commonly reported [4], [6]. Even though these changes in accommodation did not meet clinical significance, they may still be of importance as they correlate with the SSQ (see Fig. 5). An individual's susceptibility to aftereffects may be influenced by factors such as repeated exposure [41], [43], and VR content [14], [34]. Investigating how long these effects last for would be an important step in understanding the potential risks associated with individual changes and symptoms after VR.

In a recent study, Ha *et al.* [22] measured near point accommodation after VR and did not find any noticeable changes. The authors split participants into two groups; one group watched a 3D movie and the other watched a VR application on a Samsung Gear VR. Several differences between our study and Ha *et al.*,'s study may account for the differences in post-VR accommodation measurements. Our study used an interactive table tennis game requiring participants to move in both the virtual and real worlds. Although this difference may appear subtle, it is well known that adaptation to novel environments increases with proprioception [16], [44]. Also, in our study participants played a game of table tennis that required participants to focus on the ball at rapidly changing

depths for most of the 30-minute VR session. If participants did not follow the table tennis ball in the VE then their performance would deteriorate, thus the demands of the VE would have led to continuous changes in vergence. There are several studies demonstrating that the rate of change of the vergence-accommodation conflict can cause visual discomfort [6], [45]. Kim *et al.*, [6] showed that slow changes in distance for a single stimulus produced little discomfort, whereas rapid depth changes led to more participants reporting visual discomfort. Other studies, such as [45], [46], also found similar effects whereby fast motion in depth led to discomfort. Kim *et al.*, [6] hypothesised that the cross-links between vergence and accommodation may explain these differences in discomfort for slow and rapid motion in stereoscopic displays (see: [47] for model). Rapid changes in vergence in the VR table tennis game may have led to accommodation aftereffects and could explain the differences between Ha *et al.*'s study and our experiment.

Various hypotheses on the origins of cognitive aftereffects have been suggested spanning across different disciplines. Nesbitt *et al.* [14] have suggested that VR sickness, particularly nausea, may impact on participants ability to perform in reaction time tasks. The authors propose that slower reaction times may not reflect impaired cognitive function, but rather participants who felt unwell performed worse. This hypothesis seems plausible, however, Mittelstaedt *et al.* [13] were unable to find any associations with nausea and performance on reaction time tasks. As an alternative explanation, Mittelstaedt *et al.* [13] proposed that a increase in reaction times after VR could reflect adaptation. During a VR immersion, an individual may experience adaptation to visual perception, motor coordination and vestibular systems. Mittelstaedt *et al.* [13] suggest that their VR simulator may have affected motor and proprioceptive senses resulting in reduced motor response speeds in the reaction time task. Other explanations of cognitive aftereffects pertain to attentional resources being diverted to address the visual-vestibular conflicts of VR experiences [15]. Visual fatigue has also been hypothesised as a potential driver of decreased cognitive performance [7]. Considering these different viewpoints on cognitive aftereffects, it seems that identifying whether decreased cognitive performance on a reaction time task is attributed to motor or cognitive changes will be a valuable insight for future research.

In our study, we sought to directly examine cognitive aftereffects by distinguishing between cognitive and motor performances. To investigate cognitive aftereffects we employed a decision-making choice reaction time task and rapid visual processing task. Primarily, we found participants had slower cognitive processing speeds on the five-choice reaction time task after VR and were also slower compared to controls. Interestingly, the VR group was only slower for the cognitive component of the task, but not the movement component. That is, participants were slower between the onset of the stimulus to the release of the button, but not for the movement component of releasing the button and touching the target. These data suggest that the factors driving aftereffects are likely related to attention rather than motor performance. Interestingly, the raincloud plots (see Fig 4) show that not all participants behaved uniformly. At a group level, most participants in the VR group showed slower decision times after VR, however, certain participants got faster after immersion. Understanding what drives these distinct aftereffects may be important to determine how VR devices could affect individuals differently. A prime suspect for such differences is VR sickness, but VR sickness was not statistically related to changes in decision or movement times. Although some studies have been successful in linking changes in reaction times with VR sickness [14], [15], other studies have not found these same links [11], [13]. In our study, we considered the possibility that different motor or cognitive mechanisms of the RT task may be driving the correlations found in studies like [14], [15], but we did not observe any correlations with VR sickness and decision times or movement times or even a combination thereof. Previous studies have also found specific motor-related aftereffects (i.e hand-eye coordination) [16], [24]. In our study, we did not observe support for these effects, however, it is possible that motor effects may become more obvious with movements towards the periphery. The aftereffects with decision times in the current study is a relatively novel finding. These cognitive aftereffects do not relate to VR sickness, thus is it unclear what is driving these findings. Various studies have used simple (single-target) reaction time tasks to measure vigilance [48], [49]. If the decision time effects are related to vigilance, one may expect that participants in the VR group would also demonstrate poorer sustained attention. In the sustained attention task (RVP) we employed in this study, no such effects were observed. Substantial differences of time from pre- to post-VR in the RVP task, shows that participants from both groups improved in speed and accuracy for this task. These large improvements may represent practice effects and future studies could consider including multiple baseline sessions or longer practice sessions to overcome this issue.

V. CONCLUSION

This study demonstrates both visual and cognitive aftereffects from engaging in a VR experience using an HMD. Visual effects include an increase in accommodation, decoupling between vergence and accommodation post-VR and a correlation between self-report symptoms of VR sickness and near point accommodation measurements after VR. Cognitive effects include changes in decision times that may be related to alertness and attention, however, there is still a great need for further research to determine who is affected and why. By establishing how aftereffects may arise in an application-based scenario, this research may be extended by making incremental changes to the virtual environment to build stronger links between what participants are seeing and relative aftereffects. Despite the recent popularity of HMDs, it is surprising that little is known about the visual

and cognitive aftereffects of using VR in HMDs. Particularly, given that most if not all commercial VR devices come with safety warnings and list of visual and cognitive symptoms a user may experience during or post-exposure to VR content. Moreover, understanding VR aftereffects may help to improve HMD technologies and user experiences, as well as help to establish a targeted safety protocol for a diverse range of users.

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