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Virtual reality games on accommodation and convergence

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ABSTRACT

Increasing popularity of virtual reality (VR) gaming is causing increased concern, as prolonged use induces visual adaptation effects which disturbs normal vision. Effects of VR gaming on accommodation and convergence of young adults by measuring accommodative response and phoria before and after experiencing virtual reality were measured. An increase in accommodative response and a decrease in convergence was observed after immersion in VR games. It was found that visual symptoms were apparent among the subjects post VR exposure.

1. Introduction

Virtual reality (VR) is a simulated environment where the visual content and alternatively different senses are entirely computer-generated and the participant's performance alters the appearance of the environmental status. The visual stimulus and other sensory channels such as touch, smell, sound, and taste are presented by a combination of virtual and augmented reality systems (Rebenitsch and Owen, 2016).

Virtual reality has been rapidly developmental in the recent years, particularly the VR headsets, which are used by attaching a smartphone that contain the VR game and mounting it on the head, thus providing users with a virtually immersive experience (Desai et al., 2014).

The current study uses a VR game as the stimulus as it is perceived to be more appealing to the user, enhancing maximum immersion; furthermore players show a higher anxiety level which would enhance their post VR-gaming response (Pallavicini et al., 2018). VR gaming blocks out the external environment whilst promoting sensory immersion due to the enlarged field of view (FOV) of the VR headset, providing users with a greater immersion experience (Martel and Muldner, 2017).

The accommodation and vergence systems are reflexively linked, interacting with each other through accommodative vergence and vergence accommodation; where accommodation is stimulated by retinal blur whereas vergence is stimulated by depth (Hung, 2001). Accommodation and convergence are simultaneously occurring ocular systems that enable normal binocular vision. A disruption in one system could affect the other (Shiomi et al., 2013). The demand exerted on the accommodation and vergence systems by VR results to a reduction in visual performance due to the ocular discomfort experienced (Barnes, 2016). Moreover, discomfort in stereoscopic viewing is caused by the need of quick adaptation from the vergence system, despite the conflicting accommodation system (Hoffman et al., 2008; Lambooij et al., 2009).

Studies have found a significant effect of VR on accommodation and convergence (Mon-Williams et al., 1993; Kooi and Toet, 2004; Rebenitsch and Owen, 2016), caused by a disruption in how these two systems work together. Shiomi and his colleagues found the incidence of mismatch between accommodation and convergence which resulted to complaints of visual fatigue after users were immersed in the VR world for a period of time (Shiomi et al., 2013).

This paper presents investigations on how the accommodative and convergence systems are affected after using the VR headset for a period of time.

2. Methods and materials

2.1. Subjects

Thirty four subjects participated in this study, out of which 21 were male and 13 were female, with age ranging 18–28 years and mean age of 23. All the subjects had distance visual acuity of 6/6 or better, of which 21 were spectacle wearers; normal color vision (correct

Abbreviations: VR, Virtual Reality; 3D, 3-Dimensional; FCC, Fused Cross Cylinder; SD, Standard Deviation; approx, approximately; AC/A, Accommodative-convergence/ Accommodation; VAC, Vergence-accommodation conflict; HMD, Head mounted display; FOV, Field of view; D, Diopters; mm, milimeters; cm, centimeters; m, meters; min, minutes

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Fig. 1. VR Shinecon® headset was used as the simulator during the research.

identification of all plates using the Ishihara 24 Plates Edition©); stereo acuity of 50 seconds of arc or better with The Netherland Observation (TNO) plates; near point of accommodation within estimated range of at least 12.5 cm and near point of convergence with break (5–7 cm) and recovery (7–9 cm); horizontal phoria ranged from 1^{Δ} esophoria to 3^{Δ} exophoria at distance and 0 to 6^{Δ} exophoria at near.

2.2. Instrumentation

The accessory used during this research was the VR Shinecon® headset with adjustable inter-pupillary distance as shown in Fig. 1. The headset provided a field of view of 90–110° with a 360° panoramic view to the user. The VR Shinecon® focal power of the lenses for both sides were approx. 16D, and the disparity was achieved by the offset of the display on the phone (Fig. 2). The focal distance of the VR setup were at a given range of approx. 55–75 cm.

A smart phone, Lenovo K6 Power with dimensions 141.9 × 70.3 × 9.3 mm and screen size 5.0 inches was attached to the headset which was then mounted on the subject's head. The screen was set to 50% brightness.

The VR game Galaxy Wars, available on Google PlayStore, was the game simulator used as it offers an intense and continuous motion gaming experience in combat. The content varies significantly from the nearest virtual plane to be at 3 m up to 500 m. The sky box (larger content) had the furthest virtual plane at about 3000 m. The illumination of the game in its display was in the range of 0.4–3.9 lux.

2.3. Procedure

All the subjects played the game Galaxy Wars, for 30 min. The lights in the test room were switched off (approx. 2.5 lux) to avoid reflections and the subjects were seated on a rotating stool to aid movement.

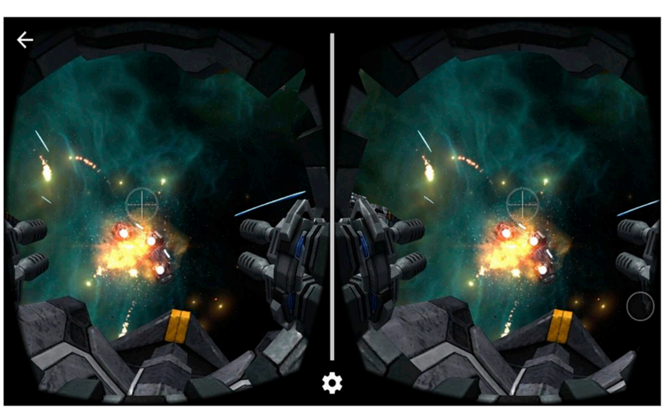

Fig. 2. Virtual reality game: Galaxy Wars screenshot.

Prior to the VR simulation, accommodative response, horizontal and vertical phoria measurements at distance and near were taken. A phoropter, under good illumination (approx. 572 lux), was used to conduct the Fused Cross Cylinder (FCC) test to measure accommodative response. The target was a cross-hatch chart set at 40 cm. Cross cylinder lenses of ± 0.50 D with the minus axis set at the vertical meridian were presented binocularly in front of the subject's eyes. Initially, if horizontal lines were reported clearer, spherical lenses of +0.25 D were added binocularly until the vertical lines became clearer or the lines in both meridians were equally clear. This is an indication of lag in accommodation. However, if vertical lines were reported clearer when first presented with the FCC, spherical lenses of −0.25 D were added binocularly until horizontal lines became clearer or both meridional lines were equally clear. A lead of accommodation is indicated in this case.

The vergence stability was measured using the horizontal and vertical phoria test at 6 m and at 40 cm. The test was carried out using a Maddox rod, a high-powered cylindrical lens that prevents fusion of the eyes as a point source of white light creates a thin red line. Subjects had to report esophoria for convergent visual axes and exophoria for divergent. The test was carried out in darkness whereby the Maddox rod was situated in front of the right eye and the white point source light shone on the left eye at 40 cm. Distance phoria was measured by placing the Maddox rod in front of the right eye and shining the point source light on the mirror situated at 3 m. Subjects were expected to report the position of the red line with reference to the white point source light. If the line and dot of light coincide, there is no phoria, if the line is reported to be on the right of the dot, it is esophoria, and when the line is to the left of the dot, it is exophoria. Prism bar would be added in front of the eye until the line and the dot coincided, giving the phoria value. The test compared the pre and post phoria values to determine any changes in convergence. The sequence of measuring accommodative response and phoria was randomized to avoid bias. Accommodative-Convergence to Accommodation (AC/A) ratio was then calculated to observe the relationship between the two systems (accommodation and vergence).

Immediately after the 30 min of VR exposure, the accommodative response and change in vergence status were re-measured using the same method of FCC and Maddox rod; maintaining the same measuring procedure. It took approx. 5 min to take the accommodative response and the phoria measurements after the VR immersion. The AC/A ratio was also recalculated for each subject. Subjects were also asked to report any feelings of discomfort, such as nausea, headache and dizziness.

3. Results and discussion

Paired *t*-test was used to independently analyze the mean pre and post accommodative response and horizontal and vertical phoria at distance and near as well as AC/A ratio. There was significant difference between the pre and post mean values of accommodative response [t (33) = 2.72, $p < 0.05$] (Table 1). The pre and post mean values of horizontal phoria at near [t (33) = 4.42, $p < 0.05$] were significantly greater compared to distance [t (33) = 5.17, $p < 0.05$] (Table 2). Wilcoxon Signed-Rank test revealed no statistically significant difference in median errors of vertical phoria at distance [z = −1.73, $p > 0.05$] and near [z = 0.81, $p > 0.05$] (Table 3). There was

Table 1
Mean and SD of changes in accommodative response.

	Mean (D)	SD	*p*
Pre accommodative response	−0.06	0.05	< 0.05
Post accommodative response	−0.22	0.06	

Table 2
Mean and SD of changes in horizontal phoria.

		Mean (Δ)	SD	*p*
Distance	Pre horizontal phoria	−0.41	0.36	< 0.05
	Post horizontal phoria	−1.65	0.32	
Near	Pre horizontal phoria	−3.62	0.72	< 0.05
	Post horizontal phoria	−6.56	0.98	

Table 3
Median and range of changes in vertical phoria.

		Median (Δ)	Range (Δ)	*p*
Distance	Pre vertical phoria	0.00	−2 to 1	0.86
	Post vertical phoria	0.00	−2 to 2	
Near	Pre vertical phoria	0.00	−3 to 1	0.41
	Post vertical phoria	0.00	−3 to 1	

Table 4
Mean and SD of changes in AC/A ratio.

	Mean (Δ/D)	SD	*p*
Pre AC/A ratio	4.76	1.51	< 0.05
Post AC/A ratio	3.91	2.39	

significant increase in the mean of AC/A ratio of pre and post VR gaming session [t (33) = 2.489, $p < 0.05$] (Table 4). Fig. 3 shows the frequency of participants having visual symptoms after playing VR for 30 min.

This paper investigated the mean errors in accommodative response and the status of vergence through phoria and AC/A ratio after using the VR headset for 30 min. The findings demonstrate an increase in accommodation and changes in vergence status. The accommodative response values indicate an increase in lead of accommodation after VR exposure, suggesting that, after a short period of VR gaming, the response of accommodation of the eyes to accommodative targets was greater. Accommodative response in humans is more prevalent of accommodative lag at near, indicating that the eyes do not accommodate fully to a stimulus presented at a near distance. However, as found in this study, the disparity of stereoscopic images on the VR unit has increased binocular disparity, inducing accommodative convergence which exceeds physiological accommodation lag, resulting to accommodation lead, similar to the findings by Iwasaki et al. (2009).

Turnbull and Phillips (2017) reveal minimal effect to the binocular vision system after 40 min exposure to VR HMD as compared to the real world equivalent task; the dissociated position of the eyes was not affected by the accommodative demand at both distance and near, implying no accommodative fatigue. This could be due to the stimulus; an outdoor island environment where participants were required to find treasures around the island and an indoor cabin with a documentary playing on a television mounted on the wall. Both of these tasks are less intense as compared to the combat game used in the current study. However, a thought-provoking finding of Turnbull and Phillips (2017) could indirectly be in agreement with the current study i.e. choroidal thickness changes. The significant increase in choroidal thickness after VR exposure suggests that a lead of accommodation did occur even with non-intense VR experience, however, not to the point of visual discomfort, since accommodative errors were not their major findings to suggest direct effect on VR immersion.

Our results are in agreement with a study by Roberts et al. (2018) in which they have shown that accommodative lag decreases (increase in accommodative lead) during near viewing tasks that require more cognitive effort. Notwithstanding, our VR gaming task primarily involved distances that are further than normal near viewing tasks, with the presence of accommodative stimulus approx. at 3–6 m, cannot be discounted. However, their findings suggested a significant difference in accommodative response among children population but not among adult population. This raises a question about the susceptibility of the accommodative system to visual cognitive demands.

One plausible explanation for our findings might be due to accommodation hysteresis. The sustained exposure of near tasks via VR headset may trigger the accommodative hysteresis. The constant changes of apparent viewing distance through the VR may evoke the level of accommodation response to be altered according to the apparent stimulus distance. This will lead to adaptive accommodative hysteresis, which will provoke the negative shift (lead) of the accommodative response (Hasebe et al., 2001).

The first notable vergence change seen in this study was exo-shift of the horizontal phoria. The horizontal phoria values indicated a shift towards exophoria at both far and near distances. Previous research reported a shift towards exophoria when playing games in 3D suggesting that it is due to the cross-link between accommodation and convergence; accommodation lead induces exodeviation (Pölönen et al., 2013). This dynamic relationship between accommodation and vergence systems is represented by the AC/A ratio. Our study showed that the AC/A ratio reduced significantly after VR exposure of 30 min. The decrement of the cross-links gain between accommodation and vergence may be contributed by the fact that while the exposure to VR games happened, the subjects were viewing images that were moving backwards and forwards in depth. This type of viewing has been found to decrease the gains of the cross-links (Mon-Williams and Wann, 1998), leading to an exo-shift of the horizontal phoria.

This study also indicated that the phoria at near was affected more than at distance. A probable explanation is that near responses are dominated by vergence movements due to the short latency period and smaller fixation disparity. The measurement of binocular disparity ought to be constrained to certain esteems to enable comfortable stereoscopic viewing (Bando et al., 2012).

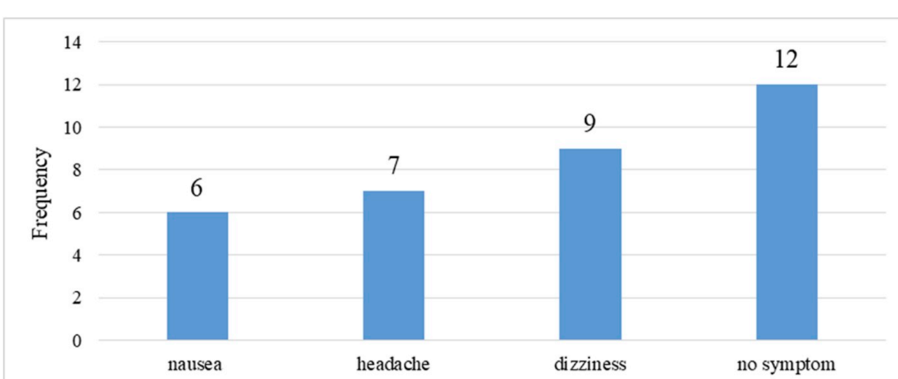

Fig. 3. Frequency of subjects with visual symptoms.

As for the vertical phoria, there was no indication of change at both distances, as there was no misalignment in the vertical plane during the use of VR headsets (Kalich et al., 2004). Vertical vergence adaptation is usually the result of a convergence-dependent gain alteration of the extraocular muscles of the vertical plane without respect to the position of the eye in the globe. The shift of vertical phoria requires a prolonged period of adaptation as experimented by Schor (2009). It was found that after 1 h of exposure of alternate fixation of targets separated horizontally as well as vertically, the vertical phoria only changed by 0.5^{Δ}. Thus showing an underlying adaptive vertical vergence mechanism that maintains the degree of disconjugacy of vertical saccades, and the change may only be observable if a longer period of adaptation is allowed (Ygge and Zee, 1996).

These accommodation and vergence changes found in this study raise an interesting discussion on the vergence-accommodation conflicts (VAC) while using virtual reality devices. VAC caused by VR gaming is due to the conflict of depth cues, in which the depth cues for both accommodation and vergence systems do not match (Reichelt et al., 2010). As explained by Takatalo et al. (2011), user experiences during 3D gaming are different compared to normal stereoscopic displays. The concepts of immersion, fun, presence, involvement, engagement and flow are accumulated during the experience. Presence, also referred to as spatial presence (IJsselsteijn et al., 2000), which results in perceived realness and the attention aspects; keeps on changing during the gaming experience. Thus, the virtual image plane distance cannot be measured in a straightforward manner. Instead, one must recognize that during stereoscopic gaming, the stimulus' apparent position will keep on changing, hence leading to possible VAC conflicts. Apparent distances deem to be comfortable in the context of virtual reality display when the content zone of the apparent images falls within 0.5 m–20 m in a 70° field of view (Alger, 2015). However, Shibata et al. (2011) assumed that the maximum and minimum relative widths of the comfort zone were 0.8D (1.28 m) and 0.3D (3.33 m). Presumably, VR games are utilizing different distances compared to the assumed comfortable distance for viewing, in our case ranging from 3 m to 3000 m. Thus, VAC conflicts might have been aggravated by VR gaming compared to other VR tasks. In addition, the VAC conflict seems to be more aggravated by the nature of the viewing, in our case, the gaming experience. VAC caused more difficulty for visual performance when the conflicts changed rapidly, according to Kim et al. (2014). When the fixation distance changes rapidly, especially in the case of gaming, the offset between the vergence and accommodation stimuli constantly changes, presumably due to stimulation of the phasic component when the step change occurs.

While the acommodation depth cue remains static (constant distance to the screen), the vergence depth cues change. The change in angular distance and different convergence demands (moving images) create a difference in cues for vergence depth, contributing to the conflict between accommodation and vergence systems. Our results show that both of the systems did change after the use of VR headset, indicating that there is a conflicting depth stimulus to both systems to maintain single and sharp binocular vision. However, as observed in our study, this conflict appeared to be resolved by the dynamic relationship between accommodation and vergence systems (AC/A ratio), counter-acting the cross-links that attempt to drive vergence to be consistent with accommodation and vice versa (Kim et al., 2014). As the response of accommodation changes (increase in accommodation lead), the vergence system reduces in its response (by about 1 prism diopter).

The amplitude of relative accommodation and vergence cannot act independently, however, each system can be slightly out of phase under normal conditions (Rushton and Riddell, 1999). The mismatch in binocular fusion cues contributes to the perceived quality of the VR experience. Inconsistent accommodation and vergence cues are known to cause visual discomfort to VR headset users (Bando et al., 2012). In our study, majority of the subjects complained of symptoms of motion sickness such as nausea, headache and dizziness after the experiment. As explained by Kennedy and his colleagues, such symptoms arise from visually perceived motion in the absence of inertial motion, furthermore the diversity in symptoms to VR use come about as a result of variations in individual responses to motion environments (Kennedy et al., 2010). These results correspond with a study on motion sickness measurement index where nausea was the least common complaint, whereas disorientation was the most common visual symptom experienced by the subjects based on the Virtual Reality Sickness Questionnaire which was modified from the Simulator Sickness Questionnaire (Kim et al., 2018).

The sensory conflict theory states that motion sickness can occur when there are paradoxical cues from the vestibular and visual systems (Hasegawa et al., 2009). Furthermore, these symptoms occur due to conflict caused by the impression that the world is moving visually, whereas there is minimal physical movement of the body and the time lag for the virtual scene to be updated after head movement (Falahee et al., 2000). Visual fatigue can be caused by the large amount of motion and parallax during stereoscopic viewing as there is constant motion thus exerting an increasing demand on accommodative and vergence systems to maintain a clear and single image, as well as when the stereoscopic images were perceived outside the range of depth of focus (Yano et al., 2002, 2004).

4. Conclusion

The results illustrated that exposure to virtual reality gaming did affect accommodation and convergence systems. After immersion in virtual reality, subjects exhibited a lead in accommodation, where they tend to focus more than required, whereas convergence is receded as there is a shift towards exophoria, due to the loss gains in AC/A ratio. These errors in accommodation and convergence in turn lead to visual symptoms and discomfort among young adults. Due to these adverse effects from the VAC, it is important to have a correct setup of VR headsets for comfortable and more pleasurable experiences.

Investigations to measure the effect of VR gaming on accommodation and convergence when it is used over a period of time and not limiting the duration to 30 min. Modifications could be done by involving a wider range of stimuli instead of only one game each time to measure the extent of changes in accommodation and convergence errors. Further investigations could be conducted on children population to observe the effect of VR gaming on accommodation and convergence.

Conflicts of interest

The authors have no conflicts of interest to declare.

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