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Using biomechanics to investigate the effect of VR on eye vergence system

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ABSTRACT

Vergence-accommodation conflict (VAC) is the main contributor to visual fatigue during immersion in virtual environments. Many studies have investigated the effects of VAC using 3D displays and expensive complex apparatus and setup to create natural and conflicting viewing conditions. However, a limited number of studies targeted virtual environments simulated using modern consumer-grade VR headsets. Our main objective, in this work, is to test how the modern VR headsets (VR simulated depth) could affect our vergence system, in addition to investigating the effect of the simulated depth on the eye-gaze performance. The virtual scenario used included a common virtual object (a cube) in a simple virtual environment with no constraints placed on the head and neck movement of the subjects. We used ocular biomechanics and eye tracking to compare between vergence angles in matching (ideal) and conflicting (real) viewing conditions. Real vergence angle during immersion was significantly higher than ideal vergence angle and exhibited higher variability which leads to incorrect depth cues that affects depth perception and also leads to visual fatigue for prolonged virtual experiences. Additionally, we found that as the simulated depth increases, the ability of users to manipulate virtual objects with their eyes decreases, thus, decreasing the possibilities of interaction through eye gaze. The biomechanics model used here can be further extended to study muscular activity of eye muscles during immersion. It presents an efficient and flexible assessment tool for virtual environments.

1. Introduction

Virtual reality (VR) headsets have become more affordable and accessible to a broader population that includes young adults and children. In a few years, it turned from expensive devices that needed extensive setup and expertise into an affordable, easy at-home setup headset which has a fast growing market of technologies and applications (Iskander et al., 2018b; Statista, 2016). Multiple VR applications have been developed in various fields. VR has been used in health care and rehabilitation (Rose et al., 2018) for patients suffering from stroke (Jack et al., 2001), Parkinson's disease (Mirelman et al., 2011) and even mental disorders (Freeman et al., 2017; Maples-Keller et al., 2017; Le and Beidel, 2017) among others (Hsu et al., 2017; McComas et al., 1998).

Multiple studies have been conducted on the effects of VR headsets or head mounted displays (HMD) on the visual system (Mon-Williams et al., 1995, 1996, 1998; 1993; Stanney et al., 1998; Turnbull and Phillips, 2017), since it's conception by Sutherland (1968) in 1968. Moreover, the prolonged immersion in virtual environments (VEs) is still associated with visual fatigue symptoms like eye-strain, nausea, dizziness, headache and double vision (Kuze and Ukai, 2008; Brunnström et al., 2017; Ohno and Ukai, 2000; Iskander et al., 2018b; Hua, 2017), despite of the rapidly developing technology. However, there is a limited number of recent studies investigating the effects of the modern consumer-grade VR headsets. In (Mai et al., 2017), visual discomfort was estimated using electroencephalography (EEG). In addition, a questionnaire (VRSQ) was developed to assess motion sickness in VR (Kim et al., 2018) which includes two components, the oculomotor and the disorientation component. VRSQ is based on the simulator sickness questionnaire (SSQ) (Kennedy et al., 1993). Ocular effect of VR was studied in (Turnbull and Phillips, 2017), they found that VR has no effect on the binocular vision status. In addition, there is evidence that VR headsets may not present a myopia-inducing stimulus. However, as per our knowledge, no studies targeted VAC in a consumer-grade VR headset.

Our vision system presents the world to us in a 3D layout where depth is perceived through monocular and binocular cues (Julesz, 1960). Time needed to perceive depth could take from a few milliseconds to a few minutes depending on the depth cues provided; smaller area size, and large parallax shift increase time required (Julesz, 1964; Emoto et al., 2004). When our fixation point changes from an object in one depth plane to another, our eyes moves in opposite

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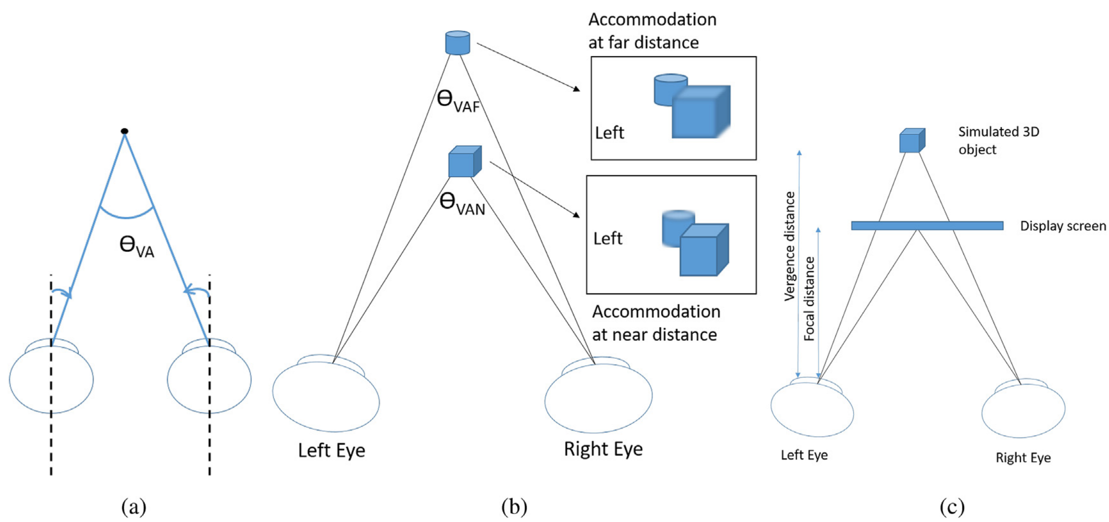

Fig. 1. (a) Vergence angle (θ_{VA}) is illustrated, where it is the angle between the visual axes of both eyes when they converge at a point. (b) The natural match between vergence and accommodation, in the real-world, is presented. Retinal image blur changes according to the accommodation depth which coincides with the vergence depth. The vergence angle at near distance (θ_{VAN}) is larger than the vergence angle at far distance (θ_{VAF}) (Hua, 2017). (c) Conflicting condition is presented where the vergence distance is different from the focal distance. The vergence distance depends on the simulated 3D object, whereas the focal distance depends on the display screen. This is one of the main sources of visual fatigue (Hoffman et al., 2008).

(disjunctive) directions (Rashbass and Westheimer, 1961; Howard, 2002). This disjunctive movement is called vergence. When the depth plane changes from near to far, our eyes diverge and similarly, when the depth plane changes from far to near, our eye converge. The vergence angle (VA) is the angle between the visual axes of both eyes as shown in Fig. 1(a), thus VA approaches zero when the visual axes are parallel which occurs when the observer is looking at optical infinity (Leigh and Zee, 2015; Howard, 2002). VA increases when the observer's eyes converge, the nearest distance for comfortable convergence is about 25 cm (Leigh and Zee, 2015; Howard, 2002).

Another depth change related eye response is the change to the shape of the lens. The dioptic power of the lens increases to deblur the image and to bring it back to focus, which is called accommodation (Leigh and Zee, 2015). Vergence and accommodation work together to create a single sharp image of the object, they roughly proceed each other and are controlled with a negative feedback mechanism. The vergence is controlled through the extraocular muscles while the accommodation through the ciliary muscles and the lens (Miles et al., 1987; Leigh and Zee, 2015).

Immersion in virtual environments causes a conflict between the two systems, the vergence and the accommodation (Hoffman et al., 2008). The conflict is due to the flatness of the display, while an illusion of 3D space is presented to the user. The 3D displays present depth cues through the simulated scene, which include binocular disparity, occlusion, shading, size (Hua, 2017; Hoffman et al., 2008). However, the focus cues and blur in the retinal image is tied to the flat display not the simulated scene and thus the conflict arises (Hoffman et al., 2008). In the absence of focus cues, that stimulate accommodation, the eyes see a clear focused image wherever it looks, thus, no change in accommodation is stimulated. However, there are depth cues, like objects size variation, image disparity and others, stimulating a vergence eye movement. This causes a mismatch, vergence-accommodation conflict (VAC), which, with prolonged use, produces visual fatigue. Fig. 1(b) and (c) illustrates the vergence-accommodation relationship under matching and conflicting conditions.

Many studies investigated the effect of vergence-accommodation conflict on the ocular system and especially the vergence eye movement system (Hoffman et al., 2008; Vienne et al., 2014) through measuring changes in the vergence and accommodation system. However, they used specific controlled apparatus to induce VAC conditions or natural matching conditions or used 3D stereoscopic displays (Lin and Widyaningrum, 2018; Lambooij et al., 2009; Aznar-Casanova et al., 2017). In this work, we propose using eye tracking and biomechanics simulation to study vergence angle.

Biomechanical analysis is used to simulate gait and other human movements (Delp et al., 2007; Rajagopal et al., 2016), and we have extended that to ocular movement through an ocular biomechanical model (Iskander et al., 2018c, a). Using ocular biomechanics simulation is an easy, more flexible alternative to complex experimental setups. It could provide accurate estimates to eye movements under different conditions. We use the ocular model to simulate the natural (non-VAC) viewing environment and calculate the vergence angle in this case.

Another aspect of VR immersion which can be affected by simulated depth is eye-gaze interaction. There is a growing trend in using eye-gaze as an interaction method during immersion (Blattgerste et al., 2018; Tanriverdi and Jacob, 2000; Sitzmann et al., 2018; Velichkovsky et al., 2014; Piumsomboon et al., 2017; Pfeiffer, 2008). The main challenge in using eye-gaze is the Midas touch problem (Jacob, 1995), which is how to differentiate the voluntary eye movement from the involuntary movements to avoid incorrect response to involuntary eye movements. Fixation dwell time is the most common detector used in object selection using eye-gaze in VR (Blattgerste et al., 2018; Piumsomboon et al., 2017). Therefore, if users find it hard to perceive the correct depth through the vergence of their eyes or find it difficult to maintain a constant fixation on an object, it will affect their eye-gaze interaction performance and may lead to increased visual fatigue and frustration.

1.1. Contribution and scope

The main objective of this paper is to study the effect of consumer-grade VR headsets using simple virtual objects and environments that is similar to virtual environments commonly used. Studies had targeted 3D stereoscopic displays and complex experimental setup that induces VAC yet there is a lack in studies using commercial headsets that are commonly used by young adults. In addition, most studies used a chin-rest to prevent or restrict head movements. Limitations on head movement are not found in VR immersion scenarios.

We designed a simple VR environment where users need to focus on a cube that changes position and depth (distance further/nearer to the user). To study vergence, users had to fixate on an object at different depths. This also helped us study the effect of depth on eye-gaze

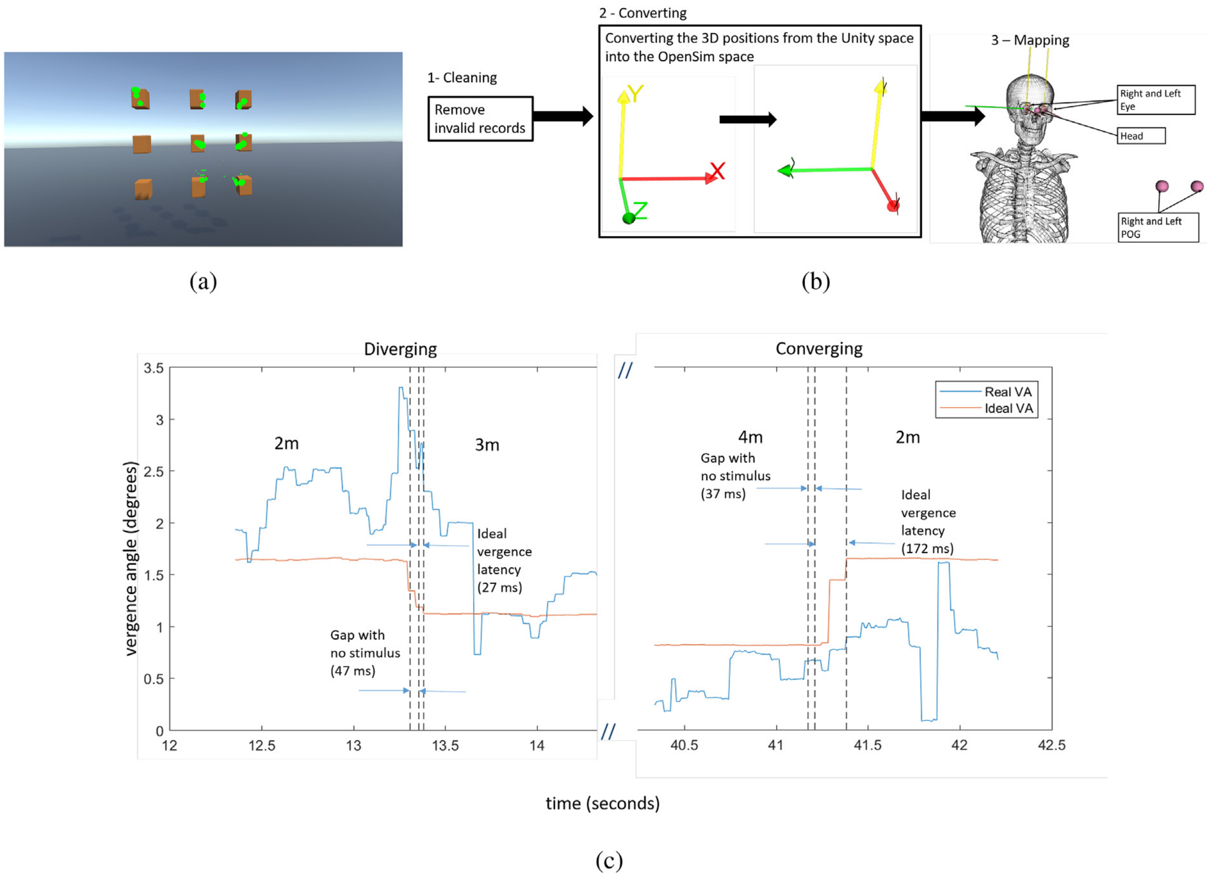

Fig. 2. (a) The VR scene used in the experiment with the eye gaze points overlain as green circles. The green circles were not shown to the user, to avoid distraction. The nine positions of the cube are shown here, however during the experiment only one cube was visible at any instance. (b) The pre-processing process illustrated. It included 3 steps, cleaning, converting and mapping. The biomechanical model (Iskander et al., 2018c, a) used in the analysis incorporates a head and neck model (Vasavada et al., 1998) and two eye models (Iskander et al., 2018c). The five markers are shown on the model, two for the eyes (right and left), two for the point of gaze (POG), and one for the head (Iskander et al., 2018a). (c) Vergence angle computed from the real recorded eye movement and the simulated ideal eye movement. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

performance, i.e. the ability to choose an object by fixating on it. We used discrete depths to be able to measure vergence correctly, taking into consideration vergence latency (Leigh and Zee, 2015; Howard, 2002; Rashbass and Westheimer, 1961). The subjects required time to fixate on the object at a certain depth before moving to another depth and simulating a new vergence movement. Therefore, during the experiment the depth is kept constant for 1.5 s.

The experiment includes two consecutive stages, the first stage, saccadic section, the virtual object moves from one position to the next stimulating saccadic eye movements and also moves in different simulated depths causing an accompanied vergence eye movement. In the second stage, the smooth pursuit section, the virtual object moves at two different speeds with no change in simulated depth, thus, simulating smooth pursuit eye movement. Fig. 2(a) shows the virtual object used and eye gaze is overlain on the scene.

Through recording the head and eye movement along with gaze data of subjects during immersion, we are able to compute the vergence angle through inverse kinematics using a biomechanical head and eye model (Vasavada et al., 1998; Iskander et al., 2018c), as shown in Fig. 2(b). The head and neck biomechanical model (Vasavada et al., 1998) was used to compensate for head movements, since the subjects were free to move their heads.

The study is done in two folds. First, we investigate the change in eye movement (vergence angle) with change of simulated depth and speed of stimulus. Next, we investigate eye-gaze performance relation to stimulus simulated depth and speed. In the case of the eye movement, we compare it with simulated ideal eye movement (ideal vergence angle) that represents a natural non-conflicting scenario. We make use of biomechanics simulation to simulate the ideal eye movement based on the recorded head and eye position of each subject.

The main contribution of this paper is to present a better understanding of depth effect in the commercially available VR headsets. This may help virtual environments designers build better interactive environments where eye-gaze can be used in interaction and manipulation of the VR environment. We also, propose using ocular biomechanical analysis to simulate eye-movement under different conditions instead of using complex experimental setups. We simulated natural viewing conditions (non-conflicting) using an ocular biomechanical model and eye and head tracking data.

The paper is organised as follows. Section 2 describes the experimental procedure, the participants and the apparatus used. The visual task and the biomechanical simulation are also described here. Section 3 presents the statistical analysis results of the different tests performed. And finally a discussion is presented in Section 4 and a conclusion in Section 5.

2. Methods

In this section, we describe the design of the experiment and the processing and analysis done on the collected data.

2.1. Participants

Twenty six subjects participated in the study with no physical or visual health problems; the age range was 21–45 years (M = 29.46, SD = 7.5). 34.6% of subjects normally wear glasses, however, only 11.538% wore the glasses during immersion. When asked about their previous experience in VR, 38.46% has no previous experience, 38.46% had brief VR experience of a few hours and 23.08% had more experience in VR. Prior to the experiment, each subject gave their written consent to perform the experiment. The ethics clearance was obtained from the Human Ethics Advisory Group (HEAG) of the Faculty of Science Engineering and Built Environment, Deakin University, Australia.

2.2. Apparatus

The VR environment was developed using Unity and simulated using HTC Vive. The HTC Vive has resolution of 1080x1200 pixels per eye with a refresh rate of 90 Hz and a field of view (FOV) of 110°. The Tobii eye-trackers were embedded inside the HTC Vive headsets (Tobii Tech, 2017) and were used to collect eye movement data. The Tobii trackers have 120 Hz. Calibration was done at the start of the experiment, through a 5 point procedure. Data collection and storage was done through a C# custom developed Unity application using Tobii development kit.

The Tobii development kit provides the 3D position of each eye in addition to the direction of line of sight in 3D. The data is recorded and stored in comma-separated format with a validity flag associated with each value. Records with an invalid flag are ignored. Head 3D position data is also collected, through head tracking provided by the HTC Vive development kit.

2.3. Visual task

The VR scene was a simple open horizon scene with a cube (12x16x18 cm^3), acting as the fixation target, appearing at different locations. The experiment had two sections, the saccadic part which took approximately 82 s. This was followed by a smooth pursuit part that took approximately 100 s.

In the saccadic part, the cube appeared at a position for 1.5 s then disappeared to reappear in another position. The cube assumed one of 9 positions as shown in Fig. 2(a). This procedure is repeated 5 times for different simulated depths. The simulated depth conditions used were 1.5m, 1.75m, 2m, 3m and 4m. The cubes started at 2m depth, then moved further to 3m then 4m, followed by returning to 2m depth. After that, the cube assumed 1.75 depth, then 1.5m depth. Nearer planes were not used to avoid discomfort and avoid the need to move the head backwards, as subjects may tend to move their head backward when faced with a very near object. Since we did not want to restrict head movement, we avoided any condition that may cause large head movement.

In the smooth pursuit part, following the saccadic movement, the cube did not change the simulated depth condition, it was constant at 2m. The cube started at one of the nine positions and moved slowly between the nine positions. This is repeated two times at a speed of 2 $deg.\ s^{-1}$ and 4 $deg.\ s^{-1}$ respectively, measured in visual angle per second.

2.4. Experiment procedure

After greeting the subjects, they were briefed on the experiment requirement and objective. After their consent was received, they were seated and their interpupillary distance (IPD) was measured, then the VR headset was put on and the IPD adjusted. After the calibration, the experiment started with the saccadic section followed by the smooth pursuit section.

The subjects were asked to fixate on the cubes as they appear and follow it as closely as possible. The cube colour changed when the eye gaze direction collides with the surface of the cube. The change of colour signified a correct hit which is used to calculate the eye-gaze interaction performance. The duration of the whole experiment was approximately 180 s (3 min) and thus, we assumed that the brevity of the experiment will eliminate fatigue and learning effect or ordering effect. That is why we did not consider blocking/counterbalancing techniques. All subjects performed the same task in the same depth order.

2.5. Data processing

From the recorded head and eye tracking data we calculated the vergence angle and eye-gaze performance metric.

2.5.1. Vergence angle

To calculate the vergence angle, we had to convert the recorded 3D position of each eye and line of sight of each eye into rotation angles. This was done through inverse kinematics using OpenSim platform (Delp et al., 2007) and our ocular model (Iskander et al., 2018c). The pre-processing stage is required to create data suitable for analysis through the OpenSim pipeline. The fields recorded through the Tobii eye trackers were the 3D position of the head and the eyes along with the 3D position of the eyes point of gaze (POG). The data pre-processing stage, illustrated in Fig. 2(b), included 3 steps, as follows.

Step (1): Invalid records are removed based on the validity flag. When the eye trackers fail to estimate eye position, the validity flag is set to false.

Step (2): The 3D positions from the unity space are converted into the OpenSim space. As shown in Fig. 2(b), there is a difference in the coordinate system used in Unity and Opensim. A simple transformation matrix was used to transform the 3D positions from the Unity space to the OpenSim space as shown in Eq. (1).

$$\begin{bmatrix} x_{os} \\ y_{os} \\ z_{os} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_u \\ y_u \\ z_u \end{bmatrix} \tag{1}$$

where x_{os}, y_{os}, z_{os} are 3D coordinates in OpenSim 3D space and x_u, y_u, z_u are 3D coordinates in Unity 3D space.

Step (3): The head, eye and POG 3D positions are mapped into the marker positions on the biomechanical model used.

Using the marker positions, generated in the pre-processing stage, we performed inverse kinematics using the biomechanical model (Iskander et al., 2018c; Vasavada et al., 1998) to compute the eyes rotational angles.

Inverse kinematics was performed twice, to get the real and ideal eye movement. The difference was in the position of the left and right POG markers, shown in Fig. 2(b). POG markers specify direction of gaze. Real eye movement was calculated using the data from the recorded eye movement while calculation of ideal eye movement is described below in Section 2.6. The vergence angle was then calculated as the angle between the two (right and left) visual axes at the point where they converge as shown in Fig. 1(a).

2.5.2. Eye-gaze performance

The eye-gaze performance was based on the collision between the combined gaze direction (average of both eyes) and the surface of the cube as shown in Fig. 2(a), when they intersect a hit is detected and the eye-gaze performance metric is calculated as the percentage of detected hit out of all recorded frames. The basic mechanism used in unity to detect collision was used.

The eye-gaze performance of each participant was calculated as follows. For each depth (d), where d ∈ [1.5, 1.75, 2, 3, 4]

$$\text{eye} - \text{gaze performance} = \frac{\sum_{i=1}^{m} hit_{id}}{m} {*}100, \tag{2}$$

where m is the number of eye data frames recorded for depth d, hit_{id} is 0 or 1 for the i^{th} frame of depth d.

2.6. Simulating ideal vergence

To assess the effect of VR on the vergence system, we simulated eye movement for each subject, where the position of the eye and head followed the recorded data. However, the line of sight was simulated such that it converged precisely at the virtual stimulus depth, thus creating an ideal non-conflicting case. Since the stimulus was not a single point but a cube with (12x16x18) cm^3, we used the center of the cube surface plus a uniformly-distributed random number to be the point of gaze, thus simulating a uniformly distributed scanning behaviour on the surface area of the cube. The vergence angle was calculated similar to the real vergence angle, and we considered it as the ideal vergence angle.

We compared the dynamics of the simulated ideal vergence behaviour to that of natural vergence behaviour (Leigh and Zee, 2015; Howard, 2002). The mean vergence latency was 166.5 ms. According to (Rashbass and Westheimer, 1961), the typical reaction time to a depth change is 160 ms. The vergence latency was calculated as the difference between the time the stimulus appeared and the time the vergence angle stabilised such that the vergence angle velocity dropped to approximately zero for 200 ms. The simulated ideal VA signal shows a low variability at each depth condition after the initail vergence latency duration as shown in Table 1 and Table 2.

Fig. 2(c) shows the dynamics of the simulated ideal vergence behaviour for participant S18. The figure shows two parts of the simulated eye movement. The first (left) part is the diverging case with the eyes diverging from 2m depth to 3m depth. The second (right) part is the converging case where the eyes where converging to a near depth of 2m. After the initial stage (vergence latency), the vergence angle was stable with very small variance.

3. Results

For the saccadic part, the real and ideal vergence angle were compared with the simulated depth as factors. We used 5 simulated depth conditions, 1.5m, 1.75m, 2m, 3m, and 4m. For the smooth pursuit part, only one simulated depth was used (2m) at two different speeds.

The distribution of the real and ideal vergence angles were found to be non-normal for all simulated depths, using Kolmogorov-Smirnov test (Massey, 1951; Miller, 1956; Wang et al., 2003). Similarly, the eye-gaze performance distribution for each depth was also found to be non-normal. Therefore, all comparisons were performed using non-parametric Kruskal Wallis tests (McKight and Najab, 2010), with post-hoc comparisons using the Tukey HSD test (Keppel and Wickens, 2004) for multiple comparisons. As all 26 participants completed the experiments with 5 virtual depths, there was 4 degrees of freedom between factors and 129 total degrees of freedom for all measures. Correlations were performed using Pearson product-moment correlation. The dependent variables were the vergence angle and eye-gaze performance metric, whereas, the independent variable was the stimulus simulated depth/speed.

Table 1
Description of eye-gaze performance, real vergence angle and ideal vergence angle grouped by stimulus simulated depth during saccadic movement.

	Depth (m)	Median	Interquartile Range (IQR)	IQR/ Median
Eye-GazePerformance	1.5	64.23	25.87	0.402
	1.75	69.53	32.98	0.474
	2	46.73	27.33	0.584
	3	27.52	35.55	1.291
	4	11.14	20.23	1.815
Real VA	1.5	2.83	2.45	0.865
	1.75	2.5	2.38	0.952
	2	2.14	2.26	1.05
	3	1.74	1.85	1.06
	4	1.46	1.59	1.08
Ideal VA	1.5	2.07	0.26	0.125
	1.75	1.83	0.19	0.103
	2	1.63	0.14	0.085
	3	1.11	0.08	0.072
	4	0.85	0.06	0.0705

Table 2
Description of eye-gaze performance, real vergence angle and ideal vergence angle grouped by stimulus smooth pursuit speed at 2m simulated depth condition.

	Speed ($deg.\ s^{-1}$)	Median	Interquartile Range (IQR)	IQR/ Median
Eye-Gaze Performance	2	46.41	20.04	0.431
	4	37.86	18.91	0.499
Real VA	2	2.73	2.14	0.783
	4	2.82	2.22	0.787
Ideal VA	2	1.63	0.13	0.079
	4	1.64	0.24	0.146

3.1. Effect of simulated depth and speed on vergence angle (VA)

There was a significant effect of the simulated depth on the real VA at p<0.001 for the five depth conditions, [χ^2 = 17939.23, df = 4, p = 0]. Fig. 3(a) shows the box plot of the vergence angle grouped by the different simulated depths.

Post hoc comparisons using the Tukey HSD test indicated that the real VA for each of the simulated depth conditions was significantly different from the other four simulated depth conditions; results are shown in Table 1.

For the ideal case, the same tests were performed. There was a significant effect of depth on eye-gaze performance at p<0.001 for the five depth conditions, [χ^2 = 217656.66, df = 4, p = 0]. Fig. 3(b) shows the box plot of the ideal vergence angle grouped by the different stimulus depths.

Post hoc comparisons using the Tukey HSD test indicated that the ideal VA for each of the depth conditions was significantly different from the other four depth conditions; results are shown in Table 1.

Fig. 3(d) shows the medians of the real and ideal vergence angle at each simulated depth condition. The real VA was significantly higher than the ideal VA at each depth (p<0.001). The error bars denote interquartile range.

The simulated depth condition of 2m was visited twice during the experiment, once at the start and again during mid-experiment. Investigating the real vergence angle individually at each section of the experiment, we found that the first part had significantly higher real VA values than that at mid-experiment.

In Table 2 the medians of the real and ideal vergence angle at each stimulus speed during the smooth pursuit section of the experiment are shown. There is a significant difference between the real and ideal vergence angle (p<0.001) at each speed. The real VA exhibits higher mean and larger variability which is similar to the values shown at the same depth (2m) in Fig. 3(d).

3.2. Effect of simulated depth and speed on eye-gaze performance

There was a significant effect of depth on eye-gaze performance at p<0.001 for the five depth conditions, [χ^2 = 70.23, df = 4, p = 2.026e-14]. Fig. 3(c) shows the box plot of the eye-gaze performance grouped by the five groups representing the different stimulus simulated depths.

Post hoc comparisons using the Tukey HSD test indicated that the score for the 1.5 m depth condition was significantly different from all

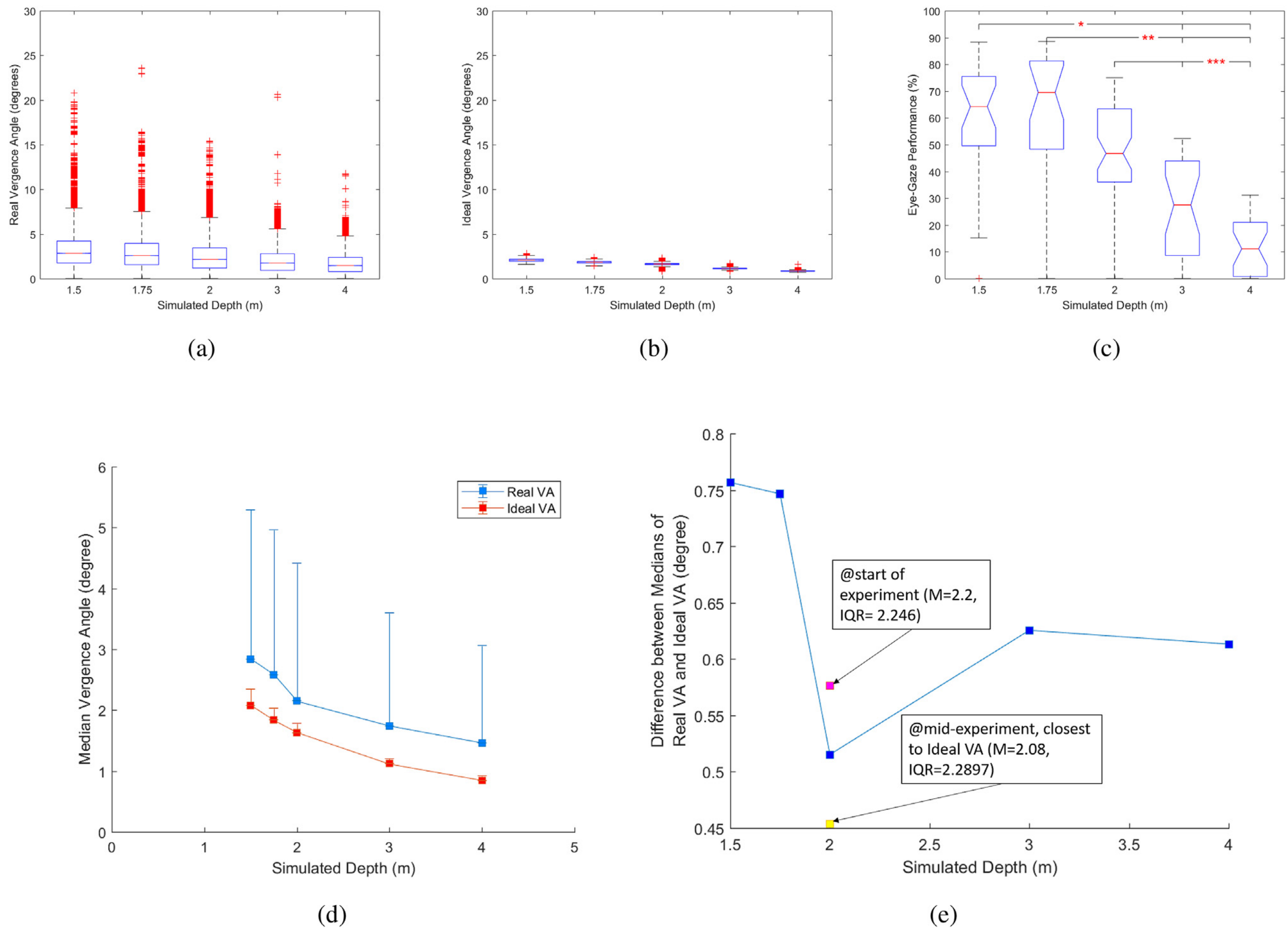

Fig. 3. (a) Box-plot showing the effect of simulated depth on vergence angle, in the realistic case, where the vergence angle is calculated from the subjective eye data and (b) idealistic case, where vergence angle is calculated from assuming the two eyes converging at the stimulus simulated depth. (c) Eye-gaze performance versus different simulated depths. * shows the significantly different depth conditions. (d) The relationship between depth and mean vergence angle for the real and ideal case. The real case shows higher median vergence angle and larger variability at each simulated depth than the ideal case. The error bars denotes interquartile range. (e) Difference between the medians of real and ideal VA. The 2m depth condition was visited twice during the experiment, at start and mid-experiment, the two squares (yellow and magenta) show the median of real VA at each case. The median and IQR values at each case is show too. Real VA at 2m depth condition (mid-experiment) exhibits the least deviation from ideal VA which may be attributed to being close to or inside the zone of comfort (Shibata et al., 2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

other depth conditions except 1.75m and 2m depth condition. The 3m depth condition was significantly different than all other depth conditions except for the 4m depth condition. Also, 2 m depth condition was significantly different from only the 3m and the 4m depth conditions. The significance results are illustrated in Fig. 3(c).

There was no significant difference in eye-gaze performance between the 2m depth condition at the start of the experiment and that at mid-experiment.

Additionally, a Pearson product-moment correlation coefficient was computed to assess the relationship between the stimulus simulated depth and eye-gaze performance. The was a negative significant correlation between the variables, $r = -0.658$, $n = 150$, $p = 5.16e\text{-}20$.

There was no significant difference in eye-gaze performance between the saccadic movement at depth 2m and the smooth pursuit movement at the same depth condition. There is also no significant difference between eye-gaze performance at the different smooth pursuit speed conditions.

4. Discussion

With the wide spread of consumer-grade VR headsets and the increasing growth of VR applications, it is essential to study the effect it has on our ocular system. In this work, we are investigating the effect of changing simulated depth on our ocular system while using a commonly-used commercially-available VR headset. This will show the effects of the vergence-accommodation conflict common in consumer-grade HMDs on the vergence system. We also investigated the effect of simulated depth on VR user capability to focus on and hence choose an object using eye-gaze.

Real Vergence angle (Real VA) was computed from the data recorded during immersion in VR. We proposed a novel approach to estimate eye movement in natural (non-VAC) viewing environments through biomechanical simulation. The ocular biomechanical model used (Iskander et al., 2018c), has been validated previously in (Iskander et al., 2017, 2018a). We used the recorded head and eye position data of each subject to simulate looking precisely at the visual stimuli with no VAC, i.e. simulating a natural environment where vergence and accommodation match; through this simulation, we computed the Ideal VA. Using biomechanical simulation can be an interesting and more flexible solution to estimate eye behaviour in different situations instead of using complex and expensive experimental setups. It could also simulate different ocular motility diseases (Iskander et al., 2018c).

We found a decreasing relationship between the simulated depth and VA which confirms with the fact that eyes diverge as the distance to the object of interest approaches optical infinity (Leigh and Zee, 2015). We found that in VR, at a specific simulated depth, the vergence angles were significantly higher than in the ideal case. In addition, vergence angles had higher variability (shown in larger interquartile range) during immersion than in the ideal case as shown in Table 1. This shows an increased vergence load attributed to the vergence-accommodation conflict, where the constant accommodation due to lack of blur cues conflicts with the vergence movement stimulated by the change of simulated depth cues in the virtual 3D space (Vienne et al., 2014; Hoffman et al., 2008).

The vergence-accommodation conflict is a main source of visual fatigue, and from the results we can observe that it affects our ocular system by creating an excessive vergence eye movement, where vergence speed does not fall and stabilise after reaching a certain vergence angle which corresponds to the eyes converging to a certain depths. However, during immersion, the vergence angle assumed higher median values, which signified that it converged at a different perceived depth. Moreover, the variability of the eye movement was higher too. This, not only, leads to incorrect depth perception but also, leads to difficulty in fixating on objects at different depths.

Our initial assumption concerning the eye-gaze performance, was that the misperception of depth accompanying VAC will affect eye-gaze performance. Therefore, we studied the effect of the simulated depth on eye-gaze performance. We found that there is a relationship between simulated depth and eye-gaze performance, such that as the simulated depth increases, subjects found it difficult to maintain their fixations on the cube surface area. From that we could deduce that the increased simulated depth affects the ability to choose an object by fixating on it when the objects are further away. On the other hand, VA variability decrease with depth, which signifies more visual fatigue when fixating on nearer objects. It was also observed that at 1.75m depth, as shown in Fig. 3(c), there was an improvement in performance. As depth increased above 2m the performance decreased significantly and drastically.

The 2m simulated depth was visited twice by each subject, once at the start of the experiment and again mid-experiment. We hypothesised that Real VA should be the same however, we found that at the start the Real VA was significantly higher than during mid-experiment. This could be attributed to the initial phase of getting used to the virtual environment, where the subject's eye are adapting to the new environment and different accommodation cues. During mid-experiment, when 2m depth was revisited, the stimulus moved from 4m to 2m, causing a convergence which is often faster than diverging (Leigh and Zee, 2015), the real VA was at its closest to the ideal VA as shown in Fig. 3(e). We can assume from this that 2m depth may be close to or inside the zone of comfort (Shibata et al., 2011), where least deviation from ideal VA occurs. Using finer division of depths is useful for further investigation, into the zone of comfort and the depth of the field. The finding that at mid-experiment the 2m depth showed similar VA variability eliminated the assumption that fatigue may have occurred. Moreover, the order of the depths visited in the saccadic section of the experiment was 2m, 3m, 4m, 2m, 1.75m, and finally 1.5m. Consequently, the order of the nearer depths (1.5m and 1.75m) are after the further depths (3m, 4m) and the nearer depths produced better eye-gaze performance than the further depths. Thus, fatigue is not a factor affecting the decline in eye-gaze performance. In addition, eye-performance at 2m simulated depth was not different between start and mid-experiment.

We investigated the difference between saccadic eye movement and smooth pursuit at only one depth condition (2m), and found no significant difference between them in eye-gaze performance. The vergence angle and the eye-gaze performance were at the same level in both cases. Therefore, we can conclude that smooth pursuit eye movements did not enhance the eye-gaze performance.

There are multiple sources of error in the biomechanical simulation and analysis, starting with the accuracy of the eye trackers, then there is the errors added due to the inverse kinematics performed to change the 3D positions of head, eyes and direction of gaze into rotational eye movement. The Tobii eye trackers has 0.5° estimated accuracy (Tobii Tech, 2017). The root mean square inverse kinematics error for the ideal and real cases were and 5.8 mm and 5.8 mm, respectively; and 90% of the maximum error occurred in the head marker position. Therefore, we could safely imply that the results exhibits low probability of errors except for errors due to inattentiveness of subjects.

5. Conclusion

In this paper, we presented an investigation on the effect of VAC in consumer-grade HMDs on the eye vergence system and also on eye-gaze interaction performance in VR. We found that VAC affects our vergence system by increasing the vergence load, where the vergence angles has a higher variability than in natural viewing conditions which causes visual fatigue and also mis-perception of depth. We also found that increasing the simulated depth of objects may decrease the ability to fixate correctly on the object's surface. We proposed using ocular biomechanical analysis to simulate eye-movement under different conditions instead of using complex experimental setups.

There was a lack of documentation to specify the focal distance of the lenses used in HTC Vive, thus it was difficult to specify the zone of comfortable viewing according to (Shibata et al., 2011). However, from the results we could conclude that near viewing conditions gave users a better control on their eye-gaze to fixate on objects but increased the vergence load that was evident in increased variability while far viewing conditions were associated with less vergence load but decreased eye-gaze performance. Therefore, it is recommended to design virtual environments with interactive objects of bigger size (the used size was 12x16x18 cm^3) which lie at nearer planes (between 2m and 3m) rather than far away planes (more than 3m). The bigger size will enhance the eye-gaze performance while maintaining same vergence load. We also recommend that VR headset manufacturers publish design guidelines that describe zone of comfort and best depths to use for interactive objects like menus and avatars. In addition, it will be useful if they also make available the information about the lenses used. This was done by Oculus Rift (Yao et al., 2014; Oculus, 2017) and we hope that other manufacturers follow their lead.

Further investigation into the following is required in the future; the effect of smooth pursuit at different simulated depths and the effect of different object size (very large and very small), in addition to the effect of missing or distorted depth cues. Moreover, investigations into the comfort zone of the VR headset is required through testing the focal distance associated with the used lenses.

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References

Aznar-Casanova, J.A., Romeo, A., Gómez, A.T., Enrile, P.M., 2017. Visual fatigue while watching 3d stimuli from different positions. Journal of optometry 10, 149–160 3.
Blattgerste, J., Renner, P., Pfeiffer, T., 2018. Advantages of eye-gaze over head-gaze-based selection in virtual and augmented reality under varying field of views. In: Proceedings of the Workshop on Communication by Gaze Interaction. ACM, pp. 1.
Brunnström, K., Wang, K., Tavakoli, S., Andrén, B., 2017. Symptoms analysis of 3d tv viewing based on simulator sickness questionnaires. Qual. User Exp. 2 (1), 1.
Delp, S.L., Anderson, F.C., Arnold, A.S., Loan, P., Habib, A., John, C.T., Guendelman, E., Thelen, D.G., 2007. Opensim: open-source software to create and analyze dynamic simulations of movement. IEEE Trans. Biomed. Eng. 54 (11), 1940–1950.
Emoto, M., Nojiri, Y., Okano, F., 2004. Changes in fusional vergence limit and its hysteresis after viewing stereoscopic tv. Displays 25 (2–3), 67–76.
Freeman, D., Reeve, S., Robinson, A., Ehlers, A., Clark, D., Spanlang, B., Slater, M., 2017. Virtual reality in the assessment, understanding, and treatment of mental health disorders. Psychol. Med. 1–8.
Hoffman, D.M., Girshick, A.R., Akeley, K., Banks, M.S., 2008. Vergence–accommodation conflicts hinder visual performance and cause visual fatigue. J. Vis. 8 (3), 33 33.
Howard, I.P., 2002. Seeing in Depth, vol. 1 University of Toronto Press Basic mechanisms.
Hsu, S.-Y., Fang, T.-Y., Yeh, S.-C., Su, M.-C., Wang, P.-C., Wang, V.Y., 2017. Three-

dimensional, virtual reality vestibular rehabilitation for chronic imbalance problem caused by ménières disease: a pilot study. Disabil. Rehabil. 39 (16), 1601–1606.
Hua, H., 2017. Enabling focus cues in head-mounted displays. Proc. IEEE 105 (5), 805–824.
Iskander, J., Hossny, M., Nahavandi, S., 2017. Simulating eye-head coordination during smooth pursuit using an ocular biomechanic model. In: Systems, Man, and Cybernetics (SMC), 2017 IEEE International Conference on. IEEE, pp. 3356–3361.
Iskander, J., Hossny, M., Nahavandi, S., 2018a. Biomechanical analysis of eye movement in virtual environments: a validation study. In: Systems, Man, and Cybernetics (SMC), 2018 IEEE International Conference on. IEEE (Accepted).
Iskander, J., Hossny, M., Nahavandi, S., 2018b. A review on ocular biomechanic models for assessing visual fatigue in virtual reality. IEEE Access 6, 19345–19361.
Iskander, J., Hossny, M., Nahavandi, S., Del Porto, L., April 2018c. An ocular biomechanic model for dynamic simulation of different eye movements. J. Biomech. 71, 208–216.
Jack, D., Boian, R., Merians, A.S., Tremaine, M., Burdea, G.C., Adamovich, S.V., Recce, M., Poizner, H., 2001. Virtual reality-enhanced stroke rehabilitation. IEEE Trans. Neural Syst. Rehabil. Eng. 9 (3), 308–318.
Jacob, R.J., 1995. Eye tracking in advanced interface design. Virtual Environ. Adv. Interface Des. 258–288.
Julesz, B., 1960. Binocular depth perception of computer-generated patterns. Bell Labs Tech. J. 39 (5), 1125–1162.
Julesz, B., 1964. Binocular depth perception without familiarity cues: random-dot stereo images with controlled spatial and temporal properties clarify problems in stereopsis. Science 145 (3630), 356–362.
Kennedy, R.S., Lane, N.E., Berbaum, K.S., Lilienthal, M.G., 1993. Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. Int. J. Aviat. Psychol. 3 (3), 203–220.
Keppel, G., Wickens, T., 2004. Simultaneous Comparisons and the Control of Type I Errors. Design and Analysis: A Researchers Handbook, fourth ed. Pearson Prentice Hall, Upper Saddle River (NJ), pp. 111–130.
Kim, H.K., Park, J., Choi, Y., Choe, M., 2018. Virtual reality sickness questionnaire (vrsq): motion sickness measurement index in a virtual reality environment. Appl. Ergon. 69, 66–73.
Kuze, J., Ukai, K., 2008. Subjective evaluation of visual fatigue caused by motion images. Displays 29 (2), 159–166.
Lambooij, M., Fortuin, M., IJsselsteijn, W., Heynderickx, I., 2009. Measuring visual discomfort associated with 3d displays. In: Stereoscopic Displays and Applications. vol. 7237. International Society for Optics and Photonics, pp. 72370K XX.
Le, T.-A.P., Beidel, D.C., 2017. Psychometric properties of a social skills assessment using a virtual environment. J. Psychopathol. Behav. Assess. 39 (2), 230–240.
Leigh, R.J., Zee, D.S., 2015. The Neurology of Eye Movements, vol. 90 Oxford University Press, USA.
Lin, C.J., Widyaningrum, R., 2018. The effect of parallax on eye fixation parameter in projection-based stereoscopic displays. Appl. Ergon. 69, 10–16.
Mai, C., Hassib, M., Königbauer, R., 2017. Estimating visual discomfort in head-mounted displays using electroencephalography. In: IFIP Conference on Human-Computer Interaction. Springer, pp. 243–252.
Maples-Keller, J.L., Bunnell, B.E., Kim, S.-J., Rothbaum, B.O., 2017. The use of virtual reality technology in the treatment of anxiety and other psychiatric disorders. Harv. Rev. Psychiatry 25 (3), 103–113.
Massey Jr., F.J., 1951. The Kolmogorov-smirnov test for goodness of fit. J. Am. Stat. Assoc. 46 (253), 68–78.
McComas, J., Pivik, P., Laflamme, M., 1998. Current uses of virtual reality for children with disabilities. Stud. Health Technol. Inf. 161–169.
McKight, P.E., Najab, J., 2010. Kruskal-wallis test. corsini Encycl. Psychol. 1–1.
Miles, F., Judge, S., Optican, L., 1987. Optically induced changes in the couplings between vergence and accommodation. J. Neurosci. 7 (8), 2576–2589.
Miller, L.H., 1956. Table of percentage points of Kolmogorov statistics. J. Am. Stat. Assoc. 51 (273), 111–121.
Mirelman, A., Maidan, I., Herman, T., Deutsch, J.E., Giladi, N., Hausdorff, J.M., 2011. Virtual reality for gait training: can it induce motor learning to enhance complex walking and reduce fall risk in patients with Parkinson's disease? J. Gerontol.: Ser. A 66 (2), 234–240.
Mon-Williams, M., Plooy, A., Burgess-Limerick, R., Wann, J., 1998. Gaze angle: a possible mechanism of visual stress in virtual reality headsets. Ergonomics 41 (3), 280–285.
Mon-Williams, M., Rushton, S., Wann, J., 1996. Investigating the reciprocal cross-links between accommodation and vergence: implications for virtual reality displays. Ophthalmic Physiol. Optic.
Mon-Williams, M., Wann, J.P., Rushton, S., 1995. Design factors in stereoscopic virtual-reality displays. J. Soc. Inf. Disp. 3 (4), 207–210.
Mon-Williams, M., Warm, J.P., Rushton, S., 1993. Binocular vision in a virtual world: visual deficits following the wearing of a head-mounted display. Ophthalmic Physiol. Optic. 13 (4), 387–391.
Oculus, V.R., 2017. OCULUS Best Practices. Oculus VR 36. https://goo.gl/CrjMoX.
Ohno, S., Ukai, K., 2000. Subjective evaluation of motion sickness following game play with head mounted display. J. Inst. Image Inf. Telev. Eng. 54 (887–891), 118.
Pfeiffer, T., 2008. Towards gaze interaction in immersive virtual reality: evaluation of a monocular eye tracking set-up. In: Virtuelle und Erweiterte Realität-Fünfter Workshop der GI-Fachgruppe VR/AR.
Piumsomboon, T., Lee, G., Lindeman, R.W., Billinghurst, M., 2017. Exploring natural eye-gaze-based interaction for immersive virtual reality. In: 3D User Interfaces (3DUI), 2017 IEEE Symposium on. IEEE, pp. 36–39.
Rajagopal, A., Dembia, C.L., DeMers, M.S., Delp, D.D., Hicks, J.L., Delp, S.L., 2016. Full-body musculoskeletal model for muscle-driven simulation of human gait. IEEE (Inst. Electr. Electron. Eng.) Trans. Biomed. Eng. 63 (10), 2068–2079.
Rashbass, C., Westheimer, G., 1961. Disjunctive eye movements. J. Physiol. 159 (2), 339.
Rose, T., Nam, C.S., Chen, K.B., 2018. Immersion of virtual reality for rehabilitation-review. Appl. Ergon. 69, 153–161.
Shibata, T., Kim, J., Hoffman, D.M., Banks, M.S., 2011. The zone of comfort: predicting visual discomfort with stereo displays. J. Vis. 11 (8), 11 11.
Sitzmann, V., Serrano, A., Pavel, A., Agrawala, M., Gutierrez, D., Masia, B., Wetzstein, G., 2018. Saliency in vr: how do people explore virtual environments? IEEE Trans. Vis. Comput. Graph. 24 (4), 1633–1642.
Stanney, K.M., Mourant, R.R., Kennedy, R.S., 1998. Human factors issues in virtual environments: a review of the literature. Presence 7 (4), 327–351.
Statista, 2016. Virtual Reality Hardware Market Size Worldwide from 2016 to 2020. https://www.statista.com/statistics/550461/virtual-reality-market-size-worldwide/.
Sutherland, I.E., 1968. A head-mounted three dimensional display. In: Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I. ACM, pp. 757–764.
Tanriverdi, V., Jacob, R.J., 2000. Interacting with eye movements in virtual environments. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM, pp. 265–272.
Tobii Tech, 2017. Tobii Releases Eye Tracking Vr Development Kit for Htc Vive. Tobii Press Release. https://www.tobii.com/group/news-media/press-releases/2017/5/tobii-releases-eye-tracking-vr-development-kit-for-htc-vive/.
Turnbull, P.R., Phillips, J.R., 2017. Ocular effects of virtual reality headset wear in young adults. Sci. Rep. 7 (1), 16172.
Vasavada, A.N., Li, S., Delp, S.L., 1998. Influence of muscle morphometry and moment arms on the moment-generating capacity of human neck muscles. Spine 23 (4), 412–422.
Velichkovsky, B.B., Rumyantsev, M.A., Morozov, M.A., 2014. New solution to the midas touch problem: identification of visual commands via extraction of focal fixations. Procedia Comput. Sci. 39, 75–82.
Vienne, C., Sorin, L., Blondé, L., Huynh-Thu, Q., Mamassian, P., 2014. Effect of the accommodation-vergence conflict on vergence eye movements. Vis. Res. 100, 124–133.
Wang, J., Tsang, W.W., Marsaglia, G., 2003. Evaluating Kolmogorov's distribution. J. Stat. Softw. 8 (18).
Yao, R., Heath, T., Davies, A., Forsyth, T., Mitchell, N., Hoberman, P., 2014. OCULUS VR best practices guide. Oculus VR 4.