The relationship between cybersickness and eye-activity in response to varying speed, scene complexity and stereoscopic VR parameters

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Abstract

Eye trackers are non-invasive devices that can be integrated into VR head-mounted displays and the data they seamlessly provide can be instrumental in mitigating cybersickness. However, the connection of eye-activity to cybersickness has not been studied in a broad sense, where the effects of different VR content factors causing cybersickness are examined together. Addressing this gap, we present an extensive investigation of the relationship between eye-activity and cybersickness in response to three major cybersickness factors – navigation speed, scene complexity and stereoscopic rendering – simulated in varied severity. Our findings reveal multiple links between several eye-activity features and user-reported discomfort reports, the most significant of which are associated with speed levels, highlighting the relationship between feeling of vection and eye-activity. The evaluation also established significant differences in eye-activity response with different stimulus types and time spent in VR, suggesting an accumulation effect. Furthermore, the regression analysis hints that blink frequency can be utilized as a significant predictor of cybersickness, regardless of time spent in VR.

Keywords: virtual reality, cybersickness, eye-activity

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1. Introduction

Today, most virtual reality (VR) setups make use of head mounted displays (HMDs) in order to immerse users within the virtual environment

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(VE). Thanks to affordable commercial VR kits and easy-to-use game engines with VR capabilities, the technology has become more accessible and engaging (Celikcan, 2022). Nevertheless, the medium still has important issues remaining to be resolved. Among these, the most notorious one is cybersickness (LaViola Jr, 2000). This affliction is mainly associated with VR applications and presents itself with symptoms similar to motion sickness and simulator sickness. Yet, cybersickness is different as it can arise during VR experience without any real (physical) movement while motion sickness and simulator sickness occur in systems with real-life movement. Cybersickness may present itself in many symptoms including headache, eye strain, nausea and disorientation (Rebenitsch and Owen, 2016). It is theorized that the conflict between the visual and vestibular systems in response to the purely visual motion is a major contributor to the discomfort (Kim et al., 2021). This is supported by the studies that show a connection between environment realism and presence of cybersickness (Liu and Uang, 2011). As these symptoms are detrimental to user experience, they diminish the accessibility of VR applications.

Vergence-accommodation conflict (VAC) (Hoffman et al., 2008) is another major contributor to cybersickness in VR experiences where stereoscopic cues are used to create the illusion of three-dimensional environments. The discomfort arises due to the conflict between the distances of vergence location, where the eyes converge or align over the object of interest, and accommodation location, where the eye lenses adjust to in order to focus vision. This conflict does not usually occur in normal vision as the two distances match, however when stereoscopic vision is emulated by VR displays such as contemporary HMDs, the vergence distance can change but the accommodation distance stays constant on the display. The conflict causes a feedback loop that leads to discomfort, especially with extended use.

The Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) has been widely used as a tool for assessing cybersickness. The questionnaire returns subscores labeled as nausea (SSQ-N), oculomotor (SSQ-O), and disorientation (SSQ-D) as well as an overall ailment score (total score, SSQ-T) in response to questions about 16 different symptoms and their severity. The use of SSQ has been criticized for its length, as the time required to administer it may lead to the attenuation of cybersickness symptoms (Ames et al., 2005). Accordingly, some studies (van Emmerik et al., 2011) moved towards including single-question probes to quickly capture immediate discomfort. In this study, we employ SSQ and a single-question discomfort query together to capture both long-term and immediate effects of cybersickness factors.

Cybersickness has been studied using biofeedback measures such as electroencephalograms (EEG), electrocardiograms (ECG), and skin conductance to examine the relationship between physiological signals and the severity of experienced discomfort (Kim et al., 2005). A thorough understanding of this relationship could allow for the development of systems that can accommodate the VE for discomfort mitigation without interfering the user for explicit input. Such systems could increase the accessibility of VR applications by facilitating better utilization of VR stimuli.

In this study, we investigate the influence of major VR content factors on user-reported cybersickness and their link to five eye-activity features (fixation count, saccade count, blink count, mean fixation duration and change in pupil size). Our study aims to address two primary research questions:

- How does the selected set of eye-activity features relate to cybersickness experienced with VR-HMDs in response to varying stimuli of navigation speed, scene complexity and stereoscopic rendering parameters?
- How is this relationship affected by the duration of exposure to VR?

To this end, we evaluate the following hypotheses:

- The change in persistent cybersickness differs with each passing session (H1)
- Eye-activity features are linked to immediate cybersickness (H2)
- Eye-activity features are linked to persistent cybersickness (H3)
- Eye-activity features show different responses to cybersickness in different sessions (H4)
- Eye-activity features show different responses to cybersickness invoked by different factors (H5)
- Stimuli levels and eye-activity features are predictors of immediate cybersickness (H6)

These hypotheses were tested with data from our user experiment, where the set of independent variables included VR content parameters associated with the three content factors under consideration - i.e., navigation speed, level of scene complexity and the two stereoscopic rendering parameters (interaxial-distance and zero-parallax distance) - and duration of exposure to VR. The results are reported in Section 4 and discussed in Section 5.

Overall, the main contributions of this study are as follows:

- The effects of three major VR content factors - navigation speed, scene complexity and stereoscopic rendering parameters - on cybersickness are explored conjointly by evaluating responses elicited by the same VE using both eye-activity feedback and subjective discomfort reports.
- The study presents an innovative experimental design realized with a sample of 33 participants immersed in a VE designed to gradually induce discomfort by simulating the factor types in isolation while their eye-activity features are collected.
- By conducting the experiment in three repeated sessions, the time spent in VR is also taken into account to assess the accumulation of cybersickness.
- The study employs two self-reported measures of cybersickness: immediate levels of discomfort taken via responses to immersive single question probes and persistent levels of discomfort taken via responses to SSQ forms.
- In light of the collected measures, an extensive analysis of the relationship between the eye-activity and cybersickness is provided.

2. Related Work

Kolasinski's study (1995), one of the earliest works on cybersickness, identified multiple factors including frame rate and tracking errors as the main causes of cybersickness. Rebenitsch and Owen (2016) compiled a review about the subject, with an extensive overview of the research done in the field. According to their review, a large portion of the research focused on the factors within the VE contributing to the discomfort. In a more recent work (2021), they also proposed multiple statistical models that can be used to estimate reports of cybersickness using either demographic information from the user or hardware/software factors of the application. They reported that demographic factors explained 44.2% of the adjusted variance in a linear model while the hardware/software factors explained 55.3%.

In this work, we focus on three content factors of cybersickness: navigation speed, scene complexity and stereoscopic rendering. All three have been established as major cybersickness factors that can be controlled by software (Rebenitsch and Owen, 2016; 941, 2021; Lawson et al., 2022). So et al. (2001) reported that navigation speed in a VE had a significant effect on the oculomotor subscore of SSQ and thus related to eye and vision related symptoms. Agic et al. (2020) investigated the effects of movement speed on cybersickness and biometrically measured stress. They did not find a significant difference of symptoms or stress with respect to speed, however they reported some correlations between demographic and measured information, such as gender and physical discomfort while wearing the HMD. On the other hand, Keshavarz et al. (2019) found that both the duration and the intensity of vection (the sense of movement felt by the user purely based on visual stimulus) was connected to the speed of navigation. They also reported that crowdedness of the environment contributed to the intensity of the vection felt. Terenzi and Zaal (2020) investigated reactions to particle fields with different acceleration and optic flow variations. They found that different thresholds of discomfort were associated with different flow fields. Kavakli et al. (2008) compared SSQ scores of two groups of users exposed to two different VEs, one with a realistic city and another rendering only the lines of this city. While they reported higher SSQ results at the end of exposure for the realistic city group, these findings were not statistically significant. Similarly, Pouke et al. (2018) immersed users in two VEs for them to walk in, one being a realistic version and another being a cel-shaded version of the same outdoor museum. However, they did not observe significant differences in reported motion sickness between the realistic and cel-shaded versions.

Scenes with roller coasters were used for several studies for their ability to feature high speed scenes with multiple rotations to induce cybersickness. Wibirama et al. (2018) reported that users experienced more severe symptoms of cybersickness on the higher speed footage of a real roller coaster rather than the slower one without real-world footage. Nalivaiko et al. (2015) also reported their more realistic simulation of a roller coaster caused more nausea in the users.

The type of display used such as an HMD or a flat display and the content on it were also shown to have a significant effect on cybersickness. Yildirim (2019a) looked into player enjoyment and feeling of cybersickness with different display types and reported more discomfort when using HMDs. Yildirim (2019b) also evaluated different game genres (racing games and first person shooters) with different display types. Both genres caused significantly different ratings of discomfort between display types, in line with the previous research. Wibirama et al. (2019) compared user activity (playing or spectating) in games. They also evaluated type of movement in the games (flow-like motion as in racing games or fast, unpredictable movement as in shooter games). They reported higher sense of discomfort in games with unpredictable movement and spectating rather than flow-like movement and actively playing, respectively. Kwok et al. (2018) compared combinations of two different speeds in two types of VR display (HMD and CAVE systems). They reported significant difference in both discomfort and misery scores related to different speeds. The authors also reported a non-significant difference between display types, but only when the speed was low.

Eye tracking is a non-invasive means of acquiring rich and timely biometric feedback. It has been used by several works (Chen et al., 2017; Snowden et al., 2016; Tichon et al., 2014) in evaluating virtually created environments and the emotional responses they elicit. Eye tracking has also been used to evaluate cybersickness, though to a lesser extent compared to other biometric measures such as ECG or EEG (Celikcan, 2019; Kim et al., 2008). Nonetheless, the increasing availability of VR-HMDs with embedded eye trackers and its non-invasive nature make eye tracking a particularly valuable tool for cybersickness research. The eye-activity data provided through easy-to-use software interfaces can offer objective insight into cybersickness in contrast to subjective questionnaires. Cebeci et al. (2019) investigated the effects of VEs with different emotional stimuli on the biometric responses from the viewers as well as cybersickness. They reported that eye-activity features such as number of fixations and saccades correlated with the changes in SSQ scores in addition to emotional changes. Similarly, Bahit et al. (2016) discovered a correlation between the amount of fixations and level of cybersickness in simulation of driving in the morning while being sleep-deprived, with severe symptoms reducing visual attention. Wibirama et al. (2018) used three-dimensional gaze tracking in their aforementioned roller coaster VEs and reported more frequent depth oscillations for participants with higher scores on the SSQ. Lopes et al. (2020) evaluated pupil movement and blink frequency as a marker for cybersickness. However, they reported that the blink data did not show any statistically significant difference for the presence of discomfort and the pupil position data was deemed inconclusive.

3D delivery of content, usually via stereoscopy, is an important part of VR applications. Hence, researchers also investigated VAC in these applications.

Kim and Lee (2011) investigated visual fatigue when users were shown 2D and 3D images and the effects on EEG signals. They found significant differences in EEG features, blink rate and eye fatigue between 2D and 3D delivery. Wang et al. (2019) proposed a trained model that can detect eye fatigue by using eye features up to 90% accuracy and reported a significant change in these features between the start and end of the experiment.

In contrast to the previous work, this study investigates multiple VR content factors contributing to cybersickness, including navigation speed, scene complexity, and stereoscopic rendering. Scene complexity, in particular, has received relatively little attention in prior research, which has focused more on realism (Kavakli et al., 2008; Pouke et al., 2018) than other aspects of scene complexity such as the number of objects in view, their color and movement patterns. While there have been studies that explored the link between VAC and cybersickness (Szpak et al., 2019; Zheng et al., 2019; Zou et al., 2015), to the best of our knowledge, no other work has examined the effects of different stereoscopic rendering parameters on cybersickness experienced with VR-HMDs. Simulated speed has been studied as a factor of cybersickness to a greater extent (Keshavarz et al., 2019; Nalivaiko et al., 2015; Kwok et al., 2018; Agić et al., 2020). Yet, just a few of these studies have assessed the eye response to speed-induced cybersickness using only a subset of the eye-activity features analyzed in this work. In addition, many studies on cybersickness and the associated physiological responses have made evaluations accounting for the time spent in VR but without considering the effects of other controllable factors (Kim et al., 2005; Bahit et al., 2016). Whereas, in this study, we investigate the relationship between cybersickness and eye-activity based on self-reports of discomfort in response to multiple VR content factors that are simulated by the same VE in varying severities, but in isolation. Furthermore, we present an extensive evaluation of this relationship by also regarding the time spent in VR and utilizing two self-reported measures of cybersickness in order to capture both immediate and persistent levels of discomfort.

3. Experiment

We have conducted a within-subject user experiment with a VE designed to induce cybersickness symptoms via the simulation of three types of VR content factors in varying degrees. For the sake of clarity, first we make a list of definitions that we use in the experiment design. Then, we discuss the components of the user experiment in the remainder of the section.

Scene: A specific version of the implemented VE that simulates one of the three factors to induce cybersickness in isolation from the other two.
Level: A stage of a scene during which a participant experiences the specific factor simulated by that scene at a predetermined stimulus intensity. Each scene comprises of a fixed set of levels that the participant experiences consecutively.
Trial: This refers to the period of data collection during which a participant is exposed to a single level of a given scene. Hence, a participant viewing a single level of a particular scene constitutes a single trial and they experience as many consecutive trials as the number of levels defined for that scene.
Session: A single cycle of the experiment in which a participant experiences all levels of all three scenes once.

3.1. Participants

Participants for the study were gathered via a campus-wide announcement at Hacettepe University. Participants volunteered by providing their available times using an online form. Prior to the experiment, participants were tested for the conditions that would make them insensitive to the simulated cybersickness factors. For this, they were required to take an Ishihara color blindness test, and a stereo blindness test where they were asked to identify a shape with a different depth in a red-cyan random dot stereogram image. They were also asked to provide confirmation that they were not susceptible to light induced epileptic seizures.

A total of 35 participants completed the experiment from start to finish. However, two of these participants did not report any discomfort during the study. As the goal of this experiment is to observe cybersickness on the eye-activity data, these two participants were considered outliers and their data were excluded from the study.

Thus, 33 remaining participants made up the study sample for the analysis. The sample was aged 18-42 (mean age 23.8±5.56, 7 females and 26 males). On average, the sample belonged to 29.7±22.7 percentile on the motion sickness susceptibility questionnaire (MSSQ), which indicates low susceptibility. The average level of VR experience of the sample was low (0.9±1.1 on a Likert scale from 0 to 4), while they showed moderate video gaming habits (2.1±1.4 on a Likert scale from 0 to 4).

3.2. *Experimental Procedure and the Virtual Environment*

The overall procedure of the experiment is outlined in Figure 1. During the experiment, participants were immersed in the VE for three such sessions back-to-back. This design allowed for the evaluation of time spent immersed in VR as a variable and thus to account for accumulation effects. In this experiment, in addition to eye activity, we also collected participants' brain activity feedback in the form of EEG signals. Due to the scope of the current study, we refer the reader to Ozkan et al. (2023) for details on the EEG-related aspects of the experiment and their analysis in connection to cybersickness.

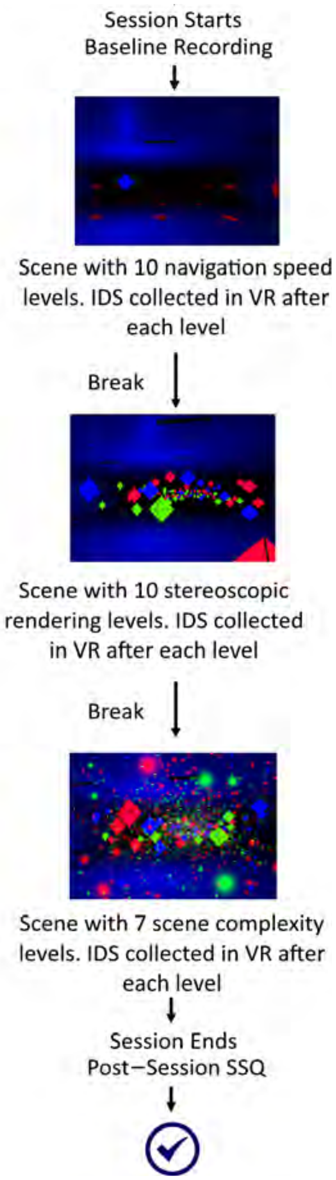


Figure 1: Flowchart of the experimental procedure for a single session. Each participant experienced three such sessions, in which the scenes were ordered in a 3x3 Latin square design. IDS stands for immediate discomfort score.

The VR application, including the VE, was realized in Unity and participants experienced it using an HTC Vive VR setup.

Prior to starting the experiment, participants were checked for the inclusion criteria and provided with information on cybersickness and its symptoms, the experimental setup and necessary controls. They were also informed of their right to quit the experiment any time in case they felt extreme discomfort. They filled a consent form, an MSSQ-Short form and a demographic information form that included VR experience level, video gaming habits, age, and gender.

The HMD helmet was fitted to their head after their interpupillary distance (IPD) was measured with a digital pupillometer and the HMD lenses were adjusted to match their IPD. Next, participants had a tutorial session, in which they were acclimated to the VE and learned how to report their intensity of discomfort felt during a level (henceforth called *immediate discomfort score*) on a scale from 1 ("none at all") to 7 ("extremely") via a pop-up VR interface (shown in Figure 2) using the HTC Vive Controller. Participants were explicitly informed that only a score of 1 indicated absence of discomfort and any discomfort should be reported with a higher score (2 or up) proportional to the severity of discomfort they feel. The tutorial was continued until they declared that they were confident in using the system. This was followed by eye-tracker calibration and pupil-size baseline recording (as detailed later in Section 3.3). An initial SSQ response was also taken before proceeding with the experiment.

Figure 2: Pop-up VR interface for immediate discomfort score reporting at the end of a level.

Afterwards started the actual experiment phase, where each cybersickness factor was simulated in a separate scene of the VE with its own set of stimulus levels, as detailed below. A sample frame from each scene can be seen in Figure 1, and additional frames are given in Figures 4 and 6. The supplementary video demonstrates a complete run of the three scenes comprising all simulated levels.

The VE was designed in the form of a corridor having a width of 11 Unity Engine units, which are taken as corresponding to meters in physical units. A point light placed at the center of the focus object served as the main source of lighting in the environment, while background objects and/or textures provided inferior auxiliary lighting, as detailed in the following subsections. Over the course of a level, participants were asked to follow a moving focal object, a glowing blue octahedron, which had a width of 0.4 Unity Engine units, as it moved down a dark wide corridor on a winding path for 10 seconds.

While moving, the focus object oscillated horizontally, requiring participants to shift their vision between left and right.

After each level was presented, participants were prompted to provide their immediate discomfort score. Once the score was obtained, the application proceeded to showing the next level of stimulus according to the predefined order of that stimulus set when participants indicated they were ready for the next level by pressing the designated hand controller button.

When all levels of a stimulus set were exhausted, a black screen was displayed for a minimum of 30 seconds to allow participants rest their eyes and recollect themselves. The scene for the next stimulus factor was initiated when participants pressed the same button as before, expressing their readiness to continue.

A session was concluded when all three scenes were completed. After this, participants were asked to remove the helmet and fill out an SSQ. A single session consisted of a total of 270 seconds of eye-activity data collected in approximately 9-10 minutes, which includes baseline recording and breaks in-between the levels where immediate discomfort scores were obtained.

After resting for at least three minutes, participants were reminded that they could stop at any time if they felt overwhelming discomfort, otherwise they could continue whenever they felt ready. At their request, they were re-fitted with the HMD and shown the VE for another session.

Once participants were exposed to the VE for a total of three sessions, the experiment was finalized. The order of the scenes across the sessions was arranged in a 3x3 Latin square design in order to offset any carry-over influence between different factor types.

Details on how each of the three cybersickness factors was simulated in the VE are given below.

3.2.1. Navigation Speed

Ten levels of navigation speed (1.2, 2.4, 4.8, 9.6, 14.4, 19.2, 28.8, 38.4, 57.6, and 76.8 meters/sec for the consecutive levels) were used in the experiment, as shown in Figure 3. The speed of the focus object was set to match the designated navigation speed for each level. Additionally, for this scene only, red arrows pointing forward were added on the surface textures of the walls and floor to promote the sense of vection. An emission shader was applied to these arrows, making them unaffected by the scene lighting and visible independently from the focus object, which was the only other light source in the environment.

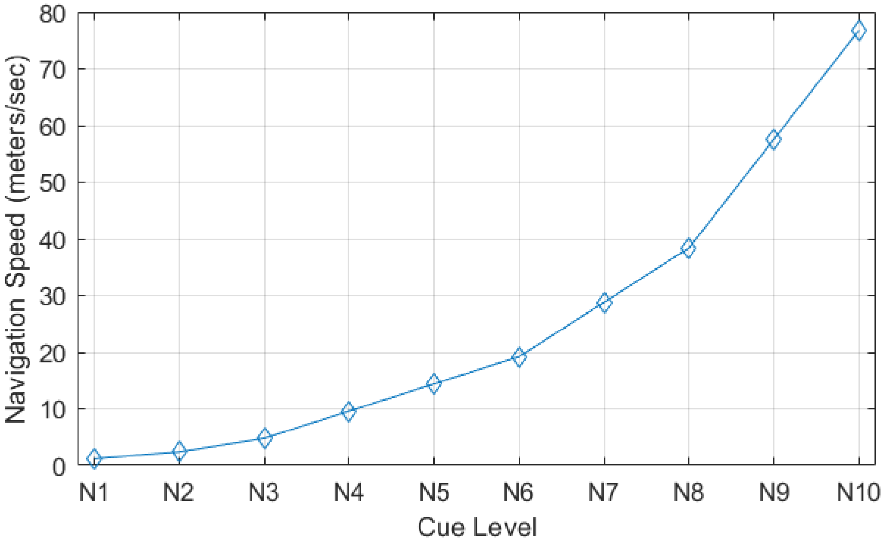


Figure 3: Plot showing the navigation speed values for each stimulus level.

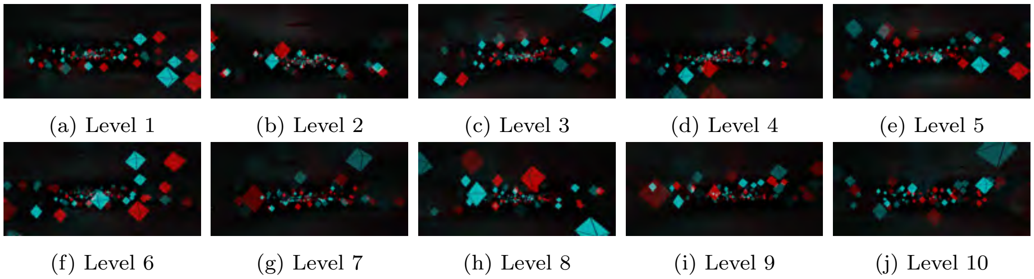
3.2.2. Stereoscopic Rendering Parameters

In our study, two major stereoscopic rendering parameters were considered: interaxial-distance, which is the distance between the two cameras rendering the scene, and zero-parallax -distance, which is the distance from the cameras where the captured points in each view appear at the same relative screen location, *i.e.*, without disparity. While today's commercially available HMDs, including the HTC Vive used in this study, keep these parameters fixed by default, it is possible to alter them using projection matrix manipulations (Avan et al., 2022) to create different levels of stereoscopic depth perception.

To evaluate the effects of different stereoscopic rendering settings in varying degrees of disparity and depth, 10 different pairs of interaxial-distance and zero-parallax distance (Table 1) were used in this scene. Only one of the two parameters was changed at a time between consecutive levels. Initially, the scene was rendered with a moderate interaxial-distance and a relatively short zero-parallax distance setting. Next, the zero-parallax -distance was increased first, followed by the interaxial-distance. After interaxial-distance was increased to its maximum level, the zero-parallax -distance was reduced again, causing severe visual strain while fusing the left and right views. The overall adjustment scheme of the two parameters through the 10 levels is il-

Table 1: Table showing the values (in Unity Engine units) used through the levels simulating stereoscopic rendering parameters and the corresponding disparity values observed for the focus object (in number of pixels for frames rendered in a resolution of 1415 by 674 pixels). The separate row at the bottom gives the default values of the stereoscopic rendering parameters, which are used with the scenes simulating navigation speed and scene complexity, and the corresponding disparity.

Stimulus Level	**Interaxial Distance**	**Zero-Parallax Distance**	**Disparity**
Level 1	0.400	4.0	175
Level 2	0.400	6.0	140
Level 3	0.400	8.0	106
Level 4	0.400	10.0	95
Level 5	0.600	10.0	137
Level 6	0.800	10.0	160
Level 7	1.000	10.0	213
Level 8	1.000	8.5	226
Level 9	1.000	7.0	253
Level 10	1.000	5.0	270
Default	0.022	10.0	105


(a) Level 1 (b) Level 2 (c) Level 3 (d) Level 4 (e) Level 5

(f) Level 6 (g) Level 7 (h) Level 8 (i) Level 9 (j) Level 10

Figure 4: Sample frames demonstrating each pair of stereoscopic rendering parameters per level. The frames were converted first to grayscale and then to a red-cyan scheme for the sake of illustration clarity.

lustrated in Figure 5. Additionally, in order to increase the amount of depth cues, the scene was populated with smaller stationary copies of the focus object, randomly colored red, green or blue, in the background. Sample anaglyph frames from the levels are provided in Figure 4.

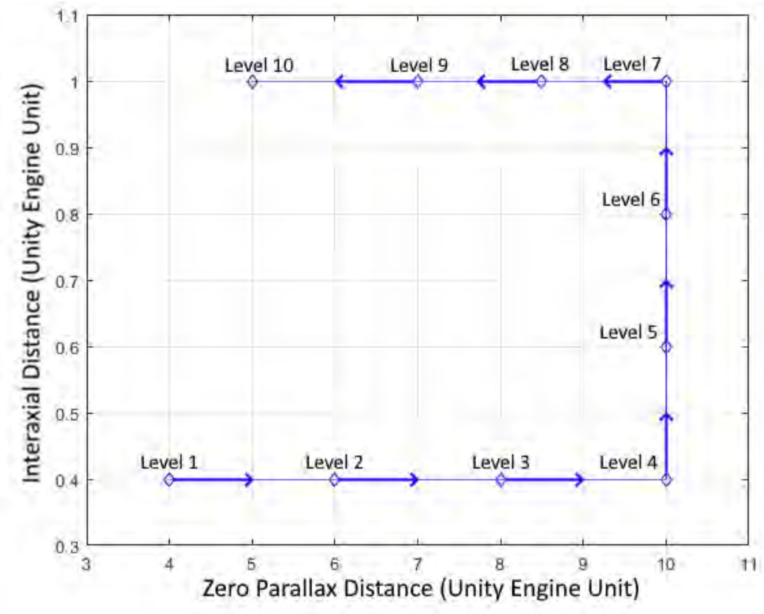
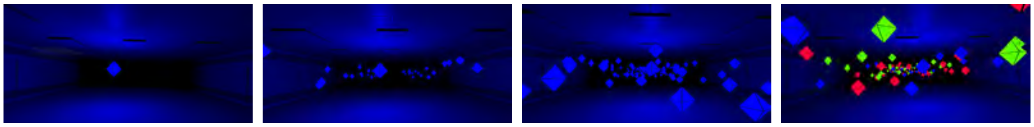


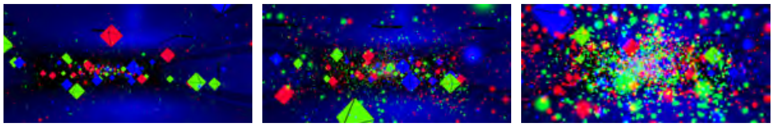
Figure 5: Directed chart showing the change of stereoscopic rendering parameters for each stimulus level.

3.2.3. Scene Complexity

Seven levels of scene complexity were simulated with increasing intensity. The first level consisted of only the empty corridor environment and the focus object. The second level employed 84 copies of the focus object, which were identical to the original and oscillated up and down periodically along the edges of the environment. The third level further increased the number of these copies by another 171, which were arranged in three additional lines along the corridor with increasing density towards the end. The fourth level did not add more objects, but randomly colored the copies red, green or blue, creating a more vibrant background. The fifth level added particle emitters to the copies directed towards the central path of the user, which produced 20 particles per second matching the color of the source object. At the sixth level, the particles were given extra intensity via HDR textures and a force field was activated to propel them directly at participants' view. Also, the amount of particles were increased to 50 particles per second. The seventh level substantially increased brightness of particles and boosted the emission rate to 75 particles per second, causing the particles to occupy most of the field of view at severe discomfort. A set of sample frames, one illustrating



(a) Level 1 (b) Level 2 (c) Level 3 (d) Level 4



(e) Level 5 (f) Level 6 (g) Level 7

Figure 6: Sample frames demonstrating the levels of scene complexity employed in the user study as explained in section 3.2.3.

each level, is provided in Figure 6.

It should be noted that the scenes simulating navigation speed and stereoscopic rendering parameters were kept at minimal complexity in order to isolate the effects of varying complexity on responses to the scene complexity trials as much as possible. Similarly, the navigation speed during the simulation of scene complexity and stereoscopic rendering parameters was kept at the same minimum value (1.2 meters/sec) that is used in the first level of the navigation speed scene and the stereoscopic rendering parameters were kept at the default values (given at the bottom row of Table 1) during the simulation of navigation speed and scene complexity levels.

3.3. Collection and Processing of Eye-Activity Data

For evaluation, we used several prominent eye-activity features extracted from the data collected with a Tobii eye-tracker embedded inside an HTC Vive HMD. Eye-activity data collected with HMDs is robust and not prone to outside artifacts as HMDs provide an isolated environment, while the tracker can also adapt to low-light conditions automatically. Besides, as the tracker is securely attached to the HMD, it does not affect the user's immersion in the VE in any way, unlike other biofeedback alternatives such as EEG, ECG or galvanic skin response measurement devices/probes that need to be attached to the body.

The Tobii SDK for Unity enabled recording the gaze information and the measured pupil size in real-time. The data can be acquired with every frame rendered but it was sampled at a constant 50 Hz in the interest of keeping the samples uniform. Using PyGaze (Dalmaijer et al., 2014), an open source

eye-tracking toolbox, the raw data was converted into the following features of eye-activity:
- ***Fixation Count***, the number of instances where the gaze is fixated on a certain region during a trial.
- ***Saccade Count***, the number of instances where the gaze moves quickly from one point to another during a trial.
- ***Blink Count***, the number of eye blinks during a trial.
- ***Mean Fixation Duration***, the average duration of fixations recorded during a trial expressed in milliseconds.
- ***Pupil-Size Change***, per-frame change in pupil size relative to the baseline recording at the matching illumination level as averaged over the duration of a trial.

To measure pupil-size change, a personal baseline recording was conducted for each participant at the start of each session. This involved showing the participant a blank, completely dark background, and gradually increasing the brightness in even steps to establish a baseline level of pupil diameter per brightness step. The mean pupil diameters of the user sample are shown per brightness step in Figure 7. During each stimulus level, screenshots were

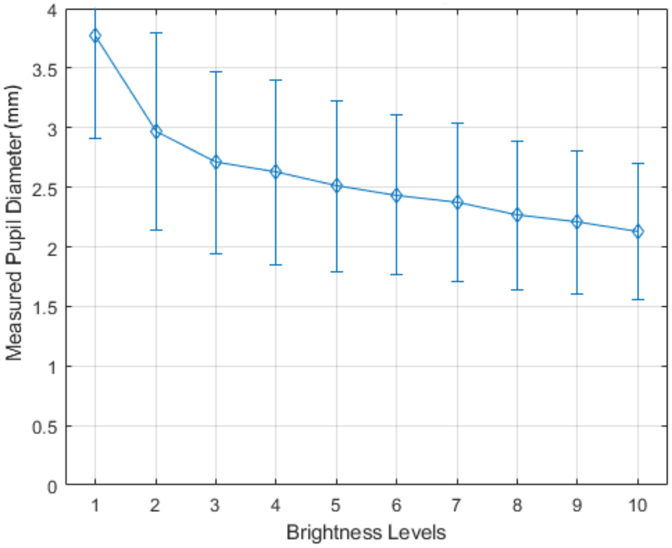


Figure 7: The average pupil diameter per brightness level captured with the baseline recordings.

taken at fixed intervals and the mean brightness of each screenshot was compared to the steps of the baseline recording to identify the closest match. The percentage difference between the pupil diameter at a given screenshot and the baseline diameter at the matching brightness step was then used to determine the change in pupil size at that instant.

The effect of various artifacts on the other collected eye-activity measures were mitigated during feature extraction. For saccade and fixation detection, the samples where a subject's either eye was closed were not taken into account. For blinks, fixations and saccades, individual minimum durations that are larger than the sampling rate (0.02 seconds) were used in order to eliminate false positives.

4. Results

In the user study, each participant completed 27 trials for the three cybersickness factors (corresponding to seven levels of scene complexity, ten levels of navigation speed and ten levels of stereoscopic rendering parameters) in each session (totaling 81 trials after three sessions). To have a binary measure of discomfort, participants were instructed to give an immediate discomfort score of 1 out of 7 only when they did not feel any discomfort upon the experienced trial. Accordingly, the trials that were rated with scores of 2 or higher were registered as the discomfort cases. Altogether, the whole sample of 33 participants completed a total of

- 693 scene complexity trials, 377 of which resulted in no discomfort while 316 reported discomfort;
- 990 navigation speed trials, 622 of which resulted in no discomfort while 368 reported discomfort;
- and 990 stereoscopic rendering trials, 381 of which resulted in no discomfort while 609 reported discomfort.

Over the collected data, the evaluation was carried out based on the posited hypotheses.

4.1. The change in persistent cybersickness differs with each passing session (H1)

The changes between consecutive SSQ responses across the sessions were subjected to a one way repeated measures analysis of variance (RMANOVA)

Table 2: Statistics of the changes between pre- and post- session SSQ scores and the corresponding RMANOVA test results.

	After Session 1 M ± SD	After Session 2 M ± SD	After Session 3 M ± SD	Significance
Difference in Nausea (SSQ-N)	-4.04 ± 12.40	4.43 ± 10.95	12.14 ± 14.56	$F_{2,64} = 12.558$, $\mathbf{p < 0.001}$
Difference in Oculomotor (SSQ-O)	2.06 ± 14.83	10.56 ± 17.04	13.09 ± 16.33	$F_{2,64} = 4.283$, $\mathbf{p = 0.018}$
Difference in Disorientation (SSQ-D)	8.01 ± 19.38	9.28 ± 20.49	7.59 ± 20.90	$F_{2,64} = 0.053$, $p = 0.949$
Difference in Total SSQ (SSQ-T)	1.59 ± 13.99	9.40 ± 16.67	13.26 ± 15.84	$F_{2,64} = 4.728$, $\mathbf{p = 0.012}$

test. The results are shown in Table 2 along with means and standard deviations of the reported changes in SSQ scores for each session. A prominent increase is evident in nausea, oculomotor and total SSQ scores as the experiment progresses and the corresponding distributions are found to be significantly different.

4.2. Eye-activity features are linked to immediate cybersickness (H2)

Curves of the collected eye-activity features as averaged over the sample per session are given in Figure 8 separated by factor type. The curves show particularly noticeable trends when speed trials are concerned. The number of saccades, number of fixations and mean fixation duration attenuate as speed increases. In addition to this, variations across different sessions are observed, indicating an effect based on time spent in VR. Also, heightened measures of immediate discomfort are evident as the sessions progress, especially with the stereoscopic rendering parameters, indicating a lowered tolerance as more time is spent in VR. The recorded eye-activity shows mostly negative pupil diameter change, suggesting pupil constriction. This is mainly due to pupil near response (Mathôt, 2018; Kasthurirangan and Glasser, 2005) which is observed when the viewer focuses on a nearby point. As the study participants were instructed to keep their gaze on the nearby focus object, this is likely to have triggered pupil near response and resulted in constriction in general.

To see how the reported cybersickness in response to the experienced stimuli presented itself in the recorded eye-activity features, Pearson corre-

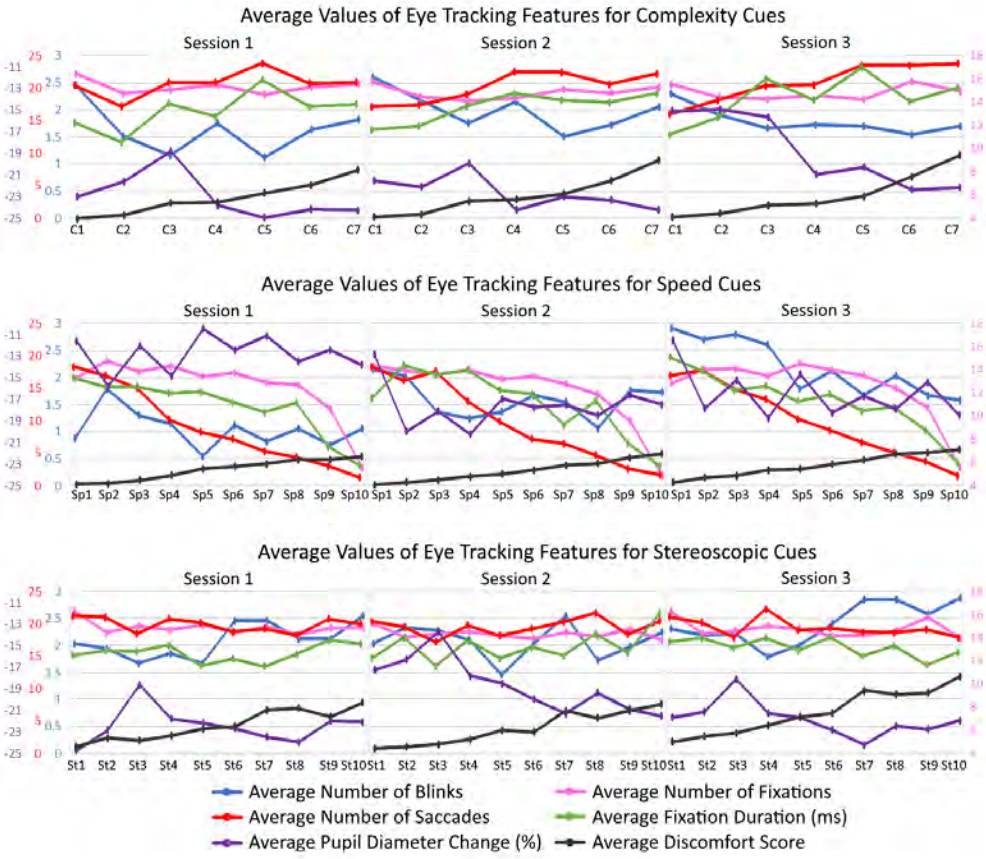


Figure 8: Curves of eye-activity features for the scene complexity, navigation speed and stereoscopic rendering trials as averaged over the subject sample. To facilitate the comparison, the curves are presented using the same vertical scale in all three graphs.

lation analysis was used. The trials were grouped up according to factor type and session order. The analysis revealed several weak but statistically significant correlations between the immediate discomfort scores and the eye-activity features. When participants were exposed to different scene complexity levels, we observed significant correlations with the blink counts recorded in sessions 1 and 2 and the mean fixation durations in session 1. When participants experienced different stereoscopic rendering parameters, their immediate discomfort scores significantly correlated with the saccade counts of sessions 1 and 2 and the blink counts recorded in sessions 2 and 3. While the discomfort experienced with the speed levels showed significant

Table 3: Pearson correlation coefficients (r) between immediate discomfort scores and eye-activity features. The discomfort scores are analyzed as separated by session and factor type. Results that are statistically significant are given in bold.

	Session 1			Session 2			Session 3		
Feature	Complexity	Speed	Stereo	Complexity	Speed	Stereo	Complexity	Speed	Stereo
Fixation Count	−0.016	−0.075	−0.006	0.009	**−0.232*****	0.067	0.016	**−0.150****	0.005
Saccade Count	0.119	**−0.159****	**0.271*****	0.086	**−0.281*****	**0.143****	0.098	**−0.268*****	−0.055
Blink Count	**0.223*****	0.025	0.043	**0.248*****	**0.131***	**0.138***	0.098	**0.241*****	**0.167****
Mean Fixation Duration	**0.151***	−0.081	0.107	0.114	**−0.195*****	0.039	0.070	**−0.122***	−0.100
Change in Pupil Size	0.000	0.059	−0.107	**0.151***	**0.152****	−0.043	**0.157***	**0.287*****	0.084

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

negative correlation with saccade counts only for the first session, significant correlations were observed with all eye-activity features in the following sessions. The r values of the correlation analysis are given in Table 3 with their significance levels marked.

4.3. Eye-activity features are linked to persistent cybersickness (H3)

With this correlation analysis, we are interested in the relationship between the eye-activity features and the SSQ results, which represent the persistent discomfort felt at the end of a session rather than the immediate discomfort felt during a given level of a session. For this, Pearson correlation was applied between the averages of the eye-activity features over the sessions and the differences between the pre- and post- session SSQ responses. Blink count, change in pupil size and saccade count are not found to be significantly correlated with the SSQ scores. Mean fixation duration is found to be weakly correlated with changes in nausea scores. In addition, fixation count is found to have weak but statistically significant negative correlations with changes in the disorientation and oculomotor subscores, as well as the total SSQ scores. The complete set of results are given in Table 4.

4.4. Eye-activity features show different responses to cybersickness in different sessions (H4)

As further sessions mean more time spent in the VE, eye-activity responses to cybersickness from different session can be compared to assess for significant differences. For this, individual analysis of variance (ANOVA) tests were conducted using only the trials where participants reported immediate discomfort. The blink, saccade and fixation counts showed significant changes across different sessions while the other eye features showed no such

Table 4: Pearson correlation coefficients (r) between the changes in SSQ scores and eye-activity features. Statistically significant correllations are shown in bold.

	Blink Count	Fixation Count	Saccade Count	Mean Fixation Duration	Pupil Size Change
SSQ-N	0.108	−0.174	0.036	**0.266****	−0.011
SSQ-O	0.130	**−0.220***	−0.086	0.137	0.157
SSQ-D	0.066	**−0.229***	−0.104	0.025	0.101
SSQ-T	0.125	**−0.248***	0.066	0.170	0.110

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

change. Corresponding statistics and the significance values are given in Table 5.

Table 5: Statistics of eye-activity features in trials where immediate discomfort is reported and the corresponding ANOVA analysis results per session. ANOVA results with p values less than 0.05 were considered statistically significant and shown in bold.

	Session 1 M ± SD	Session 2 M ± SD	Session 3 M ± SD	Significance
Blink Count	1.71 ± 2.22	2.19 ± 2.53	2.40 ± 2.76	$\mathbf{F_{2,1284} = 8.345}$ $\mathbf{p < 0.001}$
Pupil Size Change (%)	-19.48 ± 10.38	-19.25 ± 10.09	-18.65 ± 10.43	$F_{2,1284} = 0.788$ $p = 0.455$
Saccade Count	17.67 ± 10.49	16.63 ± 10.54	16.14 ± 10.14	$\mathbf{F_{2,1284} = 3.194}$ $\mathbf{p = 0.041}$
Fixation Count	14.24 ± 3.54	13.54 ± 3.92	13.89 ± 4.05	$\mathbf{F_{2,1284} = 3.914}$ $\mathbf{p = 0.020}$
Mean Fixation Duration (msec)	432.13 ± 126.71	437.79 ± 153.56	436.33 ± 157.45	$F_{2,1284} = 0.224$ $p = 0.799$

4.5. Eye-activity features show different responses to cybersickness invoked by different factors (H5)

ANOVA tests using only the trials where immediate discomfort was reported were also conducted to investigate which eye-activity features exhibited significant differences between the factors. Significant differences were observed for all eye-activity features between different factors. Corresponding statistics and the significance values are provided in Table 6.

Further, two-way multivariate analysis of variance (MANOVA) test showed statistically significant differences with discomfort for both different factor types and different sessions in the VE ($F_{2,1284} = 72.322$, $p < 0.001$ for different factors, $F_{2,1284} = 3.390$, $p < 0.001$ for time spent, $F_{4,1284} = 3.923$, $p < 0.001$ for interaction effect). This indicates a significant interaction between factor type and time spent in VE. That is, the effect of factor type changes as the sessions progress and vice versa.

The distributions of the eye-activity features extracted from the trials where immediate discomfort was reported are further illustrated using violin plots combined with box plots in Figure 9.

Table 6: Statistics of eye-activity features in trials where immediate discomfort is reported and the corresponding ANOVA analysis results per cybersickness factor. ANOVA results with p values less than 0.05 were considered statistically significant and shown in bold.

	Complexity M ± SD	Speed M ± SD	Stereo M ± SD	Significance
Blink Count	2.07 ± 2.74	1.88 ± 2.40	2.30 ± 2.52	$\mathbf{F_{2,1284} = 3.172}$ $\mathbf{p = 0.042}$
Pupil Size Change (%)	-20.68 ± 9.60	-14.19 ± 9.35	-21.24 ± 10.24	$\mathbf{F_{2,1284} = 66.444}$ $\mathbf{p < 0.001}$
Saccade Count	21.83 ± 9.12	6.87 ± 9.96	20.12 ± 8.55	$\mathbf{F_{2,1284} = 374.518}$ $\mathbf{p < 0.001}$
Fixation Count	14.82 ± 3.10	11.74 ± 3.01	14.70 ± 3.01	$\mathbf{F_{2,1284} = 91.649}$ $\mathbf{p < 0.001}$
Mean Fixation Duration (msec)	482.46 ± 157.65	378.51 ± 147.50	445.51 ± 129.75	$\mathbf{F_{2,1284} = 48.305}$ $\mathbf{p < 0.001}$

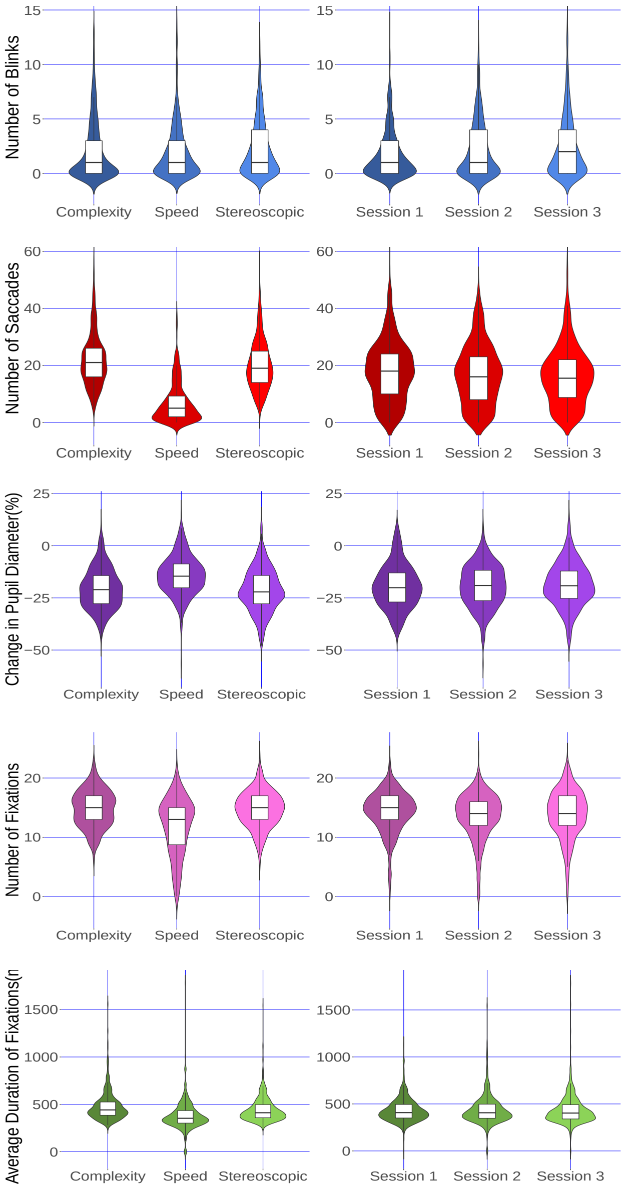


Figure 9: Combined violin and box plots of eye-activity features extracted from the trials where immediate discomfort was reported. The plots on the left side are separated by factor type and the plots on the right side are separated by session. Violin plots give density distributions for corresponding features. The lower and upper bound of the box plots represent the first and third quartile of the samples, respectively, while the one in the middle represents the median.

Table 7: Statistics from linear regression models that take factor parameters and eye-activity features as input and attempt to predict the immediate discomfort score separated by session. Adjusted R^2 metric, ranging from 0 to 1, describes how well the model predicts the output, while β is the standardized coefficient for the corresponding input. Inputs with p values less than 0.05 were considered statistically significant predictors of immediate discomfort and shown in bold.

	Session 1	Session 2	Session 3
Adjusted R^2	$R^2 = 0.212$	$R^2 = 0.263$	$R^2 = 0.366$
Blink Count	**$\beta = 0.104$** **$p < 0.001$**	**$\beta = 0.191$** **$p < 0.001$**	**$\beta = 0.164$** **$p < 0.001$**
Pupil Size Change	$\beta = 0.034$ $p = 0.304$	**$\beta = 0.077$** **$p = 0.010$**	**$\beta = 0.237$** **$p < 0.001$**
Saccade Count	**$\beta = 0.168$** **$p < 0.001$**	$\beta = -0.027$ $p = 0.537$	$\beta = -0.039$ $p = 0.332$
Fixation Count	$\beta = 0.069$ $p = 0.066$	**$\beta = 0.112$** **$p = 0.004$**	$\beta = 0.065$ $p = 0.058$
Mean Fixation Duration	$\beta = 0.048$ $p = 0.201$	$\beta = 0.051$ $p = 0.183$	$\beta = -0.006$ $p = 0.874$
Scene Complexity	**$\beta = 0.287$** **$p < 0.001$**	**$\beta = 0.410$** **$p < 0.001$**	**$\beta = 0.389$** **$p < 0.001$**
Navigation Speed	**$\beta = 0.394$** **$p < 0.001$**	**$\beta = 0.358$** **$p < 0.001$**	**$\beta = 0.306$** **$p < 0.001$**
Camera Interaxial-Distance	**$\beta = 0.361$** **$p < 0.001$**	**$\beta = 0.362$** **$p < 0.001$**	**$\beta = 0.557$** **$p < 0.001$**
Camera Zero-Parallax Distance	**$\beta = 0.092$** **$p = 0.009$**	**$\beta = 0.102$** **$p = 0.002$**	**$\beta = 0.078$** **$p = 0.013$**

4.6. Stimuli levels and eye-activity features are predictors of immediate cybersickness (H6)

To evaluate the predictive effect, a linear regression test was applied to the entire dataset. The trials were divided into three sessions, and all eye-activity features and factor parameters (navigation speed, scene complexity level, camera interaxial distance, and camera zero-parallax distance) were analyzed as potential predictors of immediate discomfort scores. The detailed results of the test are provided in Table 7. It was found that all factor parameters were significant predictors of discomfort in all sessions. Among the eye-activity features, blink count was a significant predictor in all sessions, while change in pupil size was identified as a significant predictor in the last two sessions. Saccade and fixation counts were significant predictors in sessions 1 and 2, respectively, while average fixation duration was not found to be a significant predictor in any session.

5. Discussion

To examine the accumulated discomfort associated with extended exposure to the simulated cybersickness factors, we used the differences in SSQ responses to assess changes in persistent symptoms across different VR sessions. Our analysis showed that the changes in SSQ subscales relating to nausea and oculomotor discomfort and the changes in overall cybersickness severity given by the total SSQ scale were significantly different across different sessions. Although the changes in disorientation subscale did not differ significantly, disorientation ratings showed large increases in all sessions, while nausea and oculomotor discomfort ratings showed large increases in later sessions. This implies that disorientation symptoms such as dizziness and vertigo may have been experienced earlier than the others. Overall, the results support hypothesis H1, which posited that the change in persistent cybersickness severity would be significantly different across sessions.

Evaluation of the immediate discomfort scores revealed multiple significant correlations with the eye-activity features scattered across the sessions. Fixation counts were observed to decrease with cybersickness related to navigation speed, similar to the results by Bahit et al. (2016), who reported a decrease in focus with high SSQ ratings in a driving simulator. However, during the navigation speed trials, saccade counts were reduced, indicating slower eye movements rather than rapid ones, when participants experienced cybersickness. Conversely, the analysis revealed positive correlation (increasing relationship) between immediate discomfort and saccade count when participants experienced VAC-related cybersickness, likely due to an inability to focus their gaze coherently, searching for objects that can be fused comfortably. These differing reactions in saccade counts suggest that VAC-related cybersickness and vection-related cybersickness can be distinguished using eye-activity features.

Similarly, mean fixation duration returned positive correlations with immediate discomfort during scene complexity trials while navigation speed trials returned negative correlations, indicating fixations with shorter duration. Increase in blink count was a persistent indicator of cybersickness across all factor types. This is consistent with Cebeci et al.'s (2019) findings that reported increased blink rates in users who returned higher ratings of nausea and oculomotor discomfort. Increased pupil size was associated with cybersickness due to movement speed, similar to the amount of fixations. We have observed the strongest reaction from the navigation speed related recordings, which showed correlations across all features. The analysis indicates that hypothesis H2 is confirmed only between saccade count and immediate discomfort for the navigation speed trials as no other eye-activity feature demonstrated a consistently significant link across all sessions. The analysis also hints that the blink count and change in pupil size can become more correlated with the cybersickness associated with the speed trials as participants spend more time in the VE.

However, correlation analysis with accumulated discomfort assessed via the SSQ ratings depicted a different picture by confirming hypothesis H3 for fixation count and mean fixation duration. Fixation count was found to correlate negatively with total SSQ and subscales of disorientation and oculomotor discomfort while mean fixation duration was found to correlate positively with nausea subscale. The contrast with the previous correlations on immediate discomfort imply that persistent cybersickness and immediate cybersickness from the simulated cybersickness factors can manifest differently in eye-activity features. The findings further suggest that the accumulated severity of cybersickness may be connected to fixation count and mean fixation duration.

The evaluation indicated both different sessions and different factors can evoke significantly different eye responses in case of cybersickness. Further examination of Figure 9 shows different eye-activity distributions related to speed trials in contrast to stereoscopic rendering and scene complexity trials when cybersickness is present. The finding is in line with the correlation analysis with immediate discomfort scores, where eye-activity features from the speed trials showed the highest correlations to immediate discomfort while the stereoscopic rendering and scene complexity trials displayed fewer. This distinction points out that eye-activity features can simplify the task of identifying the source of cybersickness once it is detected. Number of blinks, fixations and saccades were significant for both different factors and sessions. Cebeci et al. (2019) also reported significantly different saccade rates and fixation counts for environments differing in scene complexity and speed trials. Our results confirm hypothesis H4 for blink, saccade and fixation counts as they are significantly different in all sessions. Moreover, hypothesis H5 is confirmed for the whole set of eye-activity features we investigated as they all have significant differences for different factors.

Regression analysis identified that several eye-activity features and scene parameters can serve as significant predictors for immediate cybersickness. Stereoscopic rendering parameters were found to be significant predictors, especially the zero-parallax distance with the highest weight, suggesting the strongest effect. While we have manipulated the stereoscopic parameters from the default HMD values to induce visual discomfort with extreme disparities, they can be adjusted to improve the VR experience, as well. For instance, the system proposed by Avan et al. (2022) can automatically provide stereoscopic rendering parameters according to a sparsely pre-defined parameter set as the user navigates the virtual scene using a VR-HMD setup. The results indicate that their method is able to enhance the user experience in terms of overall perceived depth and picture quality while maintaining visual comfort on a par with the HMD's default settings. Navigation speed emerges as another significant predictor of immediate discomfort. However, the immediate discomfort curves across the simulated speed levels do not point to a critical value that could be regarded as a limit beyond which discomfort scores drastically increase. Same can be argued for scene complexity, which was also found to be a significant predictor in all sessions.

Number of blinks detected in a given stimulus interval (i.e., blink frequency) was also found to be a reliable predictor as it was significant in all three sessions. This suggests that blink frequency can be instrumental in predicting the existence of cybersickness, regardless of the time spent in VR. Several studies (Kim et al., 2005; Dennison et al., 2016) have demonstrated an increase in blink frequency with prolonged immersion in VR, highlighting the significance of this predictor and its increasing effect in further sessions. Change in pupil size was shown to be a significant predictor in sessions 2 and 3. The regression analysis designated saccade and fixation counts to be less reliable predictors, as they were significant only for a single session. Yet, saccade count was shown to have significant connections to navigation speed levels, which is compatible with Cebeci et al.'s (2019) findings that indicated significant correlations between SSQ subscores and saccade rate in a roller coaster scene. The adjusted R^2 values indicate that a linear regression model can explain some of the relationship between eye-activity features and cybersickness but not fully. This relationship is likely more complex than what a linear regression model might suggest, and could be further explored using a neural network. The resulting model partially supports hypothesis H6, as mean fixation duration was not found to be a significant predictor in any session.

6. Limitations and Future Work

Each scene of the VE employed in this study was designed with the purpose of invoking discomfort due to a single cybersickness factor alone and studying it in isolation from the others. Similarly, the scenes were structured in abstract unrealistic layouts with the aim to minimize emotional and cognitive effects that are unrelated to that specific factor. Yet, these measures constitute an inherent limitation as the resulting scenes are quite unlike what users encounter in most VR applications. As a complementary to this work, these factors can be studied together in realistically designed VR scenes in future studies. Such realistic scenes would facilitate the study of aspects related to presence, as well.

The use of back-to-back sessions with three-minute breaks in between was a deliberate experimental design choice in order to evaluate time spent immersed in VR as a variable and account for accumulated cybersickness. However, the duration of the breaks between consecutive levels and scenes may be seen as somewhat limiting. In order to prevent contamination effects, participants were asked at the end of each designated break period if they were comfortable continuing the experiment. They were also instructed to resume the experiment by pressing a designated hand controller button only if they felt ready after any break following a level or scene. While such precautions have been utilized in previous cybersickness studies that employed multiple short-term stimuli in succession (Pöhlmann et al., 2021; Terenzi and Zaal, 2020; Pöhlmann et al., 2022), similar to our study, it should be noted that these measures may not have completely eliminated carryover effects.

Another noteworthy limitation is the sample demographics. Our sample is comprised of a fairly young (23.8 average) and mostly male (26 out of 33 total) group. They also showed somewhat low motion sickness susceptibility as reported by MSSQ and moderate video gaming habits. Should the future studies be carried out with larger samples that are more balanced in the demographics in question, they can convey a broader understanding of the nature of cybersickness in relation to the cybersickness factors under consideration.

7. Conclusions

In this study, we focused on investigating cybersickness experienced with VR-HMDs and addressed two primary research questions. Firstly, we aimed to assess the association between certain eye-activity features, including fixation count, saccade count, blink count, mean fixation duration, and pupil size change, with cybersickness in response to stimulus variations in key content factors of cybersickness, namely, navigation speed, scene complexity, and stereoscopic rendering parameters. Secondly, we aimed to investigate how the relationship between the aforementioned eye-activity features and cybersickness changes with the duration of exposure to VR. To achieve these objectives, we conducted a within-subject user study with 33 participants immersed in a VE through a VR-HMD. We collected their eye-activity data with corresponding self-reported discomfort measures while they experienced three different versions of the VE, each simulating one of the three content factors in varying degrees of severity. The experiment was conducted in three repeated sessions to account for the accumulation effects with increasing exposure duration. Additionally, we collected self-reported measures of discomfort using in-VR single-item queries and post-VR SSQs to account for both immediate and persistent cybersickness, respectively. The collected data and the code used to process the data are publicly available at the link provided below. Furthermore, we provide a supplemental video to illustrate the scenes used as stimuli in the study.

Our findings suggest that eye-activity can be instrumental in detecting cybersickness experienced with VR-HMDs, and may also be promising for determining the type of cybersickness, s.t., whether it stems from VAC, vection etc., as well. Eye-activity features are particularly relevant for speed-related stimuli that elicit vection, and further research in this area could be beneficial for creating more immersive movements in VEs while minimizing cybersickness. Blink frequency appears to be an especially important feature, as it was significant in both the correlation analysis with immediate discomfort scores and the regression analysis. The results also highlight the importance of carefully selected stereoscopic rendering parameters, as this factor was the most likely to cause discomfort, even though the effect also contributes to the feeling of depth. Methods offering optimized alternatives to the default stereoscopic parameters (Avan et al., 2022), can be key in improving the feeling of depth while maintaining visual comfort.

Declarations

Data Availability. The data collected with the user study is available at the paper website.

Code availability. The code used to process the data is available at the paper website.

Authors' contributions.

Alper Ozkan: Methodology, Investigation, Data Curation, Validation, Software, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Visualization

Ufuk Celikcan: Conceptualization, Methodology, Validation, Writing - Original Draft, Writing - Review & Editing, Supervision, Project administration, Funding acquisition

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Ethics approval. This study has been approved by Hacettepe University Ethics Board.

Consent to participate. Written informed consent was obtained from all individuals participated in this study.

Consent for publication. Participants consented to the publication of their collected data without identifying information.

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