Mitigation of Cybersickness in Immersive 360° Videos

Colin Groth* Jan-Philipp Tauscher * Nikkel Heesen* Steve Grogorick* Susana Castillo* Marcus Magnor*

Institut für Computergraphik
TU Braunschweig

Figure 1: We investigate the effectiveness of two visual techniques to mitigate cybersickness in virtual reality with pre-captured 360° videos. Here, we show exemplary frames of the videos used in our experiment.

Abstract

We investigate the mitigation of cybersickness (CS) in 360° videos, a phenomenon caused by the visually induced impression of ego-motion while being physically at rest. We evaluate the effectiveness of scene modulations to reduce motion in the peripheral visual field by deliberately blurring or opaque occluding eccentric view areas of up to ten degrees. Our results indicate that both methods effectively reduce CS in pre-recorded 360° video with the dynamic opaque occlusion method yielding best results.

Index Terms: Computing methodologies—Computer graphics—Graphics systems and interfaces—Virtual reality; Computing methodologies—Computer graphics—Graphics systems and interfaces—Perception; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—Empirical studies in HCI; Applied computing—Life and medical sciences—Consumer health

1 Introduction

Virtual reality (VR) has been around for a very long time and nowadays reaches a broader audience than ever before [53]. The technology is constantly improving and the industry is releasing an increasing number of games, videos and even movies for VR devices. This raises the bar for expectations and the acceptance of the general public. 360° videos in VR are a novel viewing experience that allows the spectator to be deeply immersed in the content. The viewers can turn their heads in arbitrary directions while a linear story unfolds around them. Similar to traditional linear video formats like TV shows or movies, the story takes place from the position of the camera but the viewers are in control of their own gaze. While a VR world gives the user the freedom of 6 DOF navigation, videos without depth information push them back into the passive consumer seat as they cannot walk around or modify objects. Still videos remain to be experienced in VR and therefore provide a *virtual reality experience* [62].

*e-mail:
{groth, tauscher, heesen, grogorick, castillo, magnor}@cg.cs.tu-bs.de

But any discomfort the user may experience while watching video in a VR device could potentially impact the spread of this technology. A major problem common to all types of immersive virtual experiences is cybersickness (CS) [29, 52]. This term describes any physical discomfort caused by visually perceived motion that does not correspond to what is actually experienced [25, 34]. CS describes an extensive collection of symptoms which include, in a low state, oculomotor conditions (e.g., blurry vision), headaches, and dry eyes. In severe cases, the user can even experience disorientation and nausea [27, 59]. One of the most accepted theories, the sensory conflict theory [51], establishes a mismatch in motion perception between the visual and vestibular system as its main cause [51]. This conflict can be triggered in both directions: the person moves while the scene in their field of view remains static, or when the impression of ego-motion is induced while in fact the individual remains stable [65]. Physical negative effects are not the only reason why reducing CS in VR experiences is critical. The occurrence of CS may raise ethical concerns by knowingly exposing participants to discomforting situations and can impact the validity of results from simulation-based studies (e.g. driving simulations [17]). Thus, there is a strong need to prevent CS.

Nowadays, the most common way to prevent CS is to directly avoid simulations that may cause it [10] but this limits the VR experiences that can be presented e.g. no camera motion would be possible in 360° videos.

Often, motion is central to videos but the user cannot influence the camera's trajectory. Therefore it is the focus of our current study to mitigate CS in this scenario.

Given that the motion of objects is primarily perceived through peripheral vision of the human eye [66], manipulating the peripheral area of a scene may reduce CS. In theory, as the foveal area is responsible for sharp central vision, this manipulation should remain unobtrusive. Eye-tracking technology is available for most modern VR hardware to follow the eye gaze and determine the foveal regions of the screen [23]. Previous studies already employed manipulation of the users' view but most of them are not gaze-contingent and therefore not subtle due to their static nature, or are not directly focused on the reduction of CS [38, 45, 46, 49, 67].

In this work, we investigate two visual techniques to gaze-contingently constrain the peripheral field of view (FOV) by applying *blur* and *opaque occlusion* to real-world 360° videos in VR. The FOV is dynamically modified to reduce the peripheral optical flow to which the human eye is most sensitive to. The level of peripheral reduction is determined either by translucent blur [38] or complete occlusion to establish a perceptual threshold. We compare both techniques and their effectiveness on CS. Mitigating CS in real-world videos is of major interest but only few studies have been conducted to prevent sickness in VR such videos. Therefore, our experiment uses real-world videos to investigate the effectiveness of these methods to be used in practice.

The experimental results confirm the effectiveness and unobtrusiveness of the proposed methods.

2 Previous Work

2.1 Theories on Cybersickness Occurrence

There are several theories on the cause of CS and it is still controversial as to which theory is most likely to apply [10].

The most common reason for the cause of CS among the theories is a conflict between different modalities (vision vs. vestibular system) that are expected to be congruous as the foundation of the symptoms [50, 51, 61]. It is called the sensory conflict theory [51]. Reason and Brand describe sensory rearrangement as a core principle of this theory. Sensory rearrangement arises when the perception of one modality in a given situation does not match the perception of functionally related modalities. According to them, the vestibular system has to be involved in any sensory conflict causing CS. Golding et al. addresses this though and even states that any person with an intact vestibular system will experience CS at some degree when the simulation is inducing enough [20].

Their theory defines two categories for situations that are likely to cause CS: visual-inertial rearrangements (i.e. conflicts between modalities) and canal-otolith rearrangements (i.e. conflicts within the vestibular system) [51]. Furthermore, these categories can be divided into three subcategories each differing in what system sends contradict information (Type 1: both; Type 2 and 3: just one). From this follows, that CS is a visual-inertial rearrangement of type 2 with the visual system sending contradict information and the vestibular system remaining passive.

It was empirically proven that people can adapt to CS over multiple sessions [50]. Unfortunately, this adaption was not sufficiently explained by the sensory conflict theory. Therefore, Reason revised his work and published the neural mismatch theory [50]. This theory states that CS results from a mismatch between the perceived and expected perceptions in a given situation and not between the perceptions themselves. The name is derived from the mismatch in the brain between the neural activations from the perception and the stored neural connections from learned experiences. With the neural mismatch theory, the adaptation to CS can be sufficiently explained, as the mismatch signal is stored with repeated occurrence.

For Treisman [61] CS results from evolutionary reasons. In her toxin detector theory she argues that CS arises from problems with motor coordination caused by conflicts between the spatial orientation systems of the body. In her point of view CS is adaptive for the human in an evolutionary sense and the symptoms arising from CS are a warning sign of neurotoxin poisoning which is tried to be removed.

Riccio and Stoffregen [54] argued that sensory conflicts not only occur in situations that induce sickness but also in non-sickness-inducing situations. Therefore, the sensory conflict cannot be the only reason for CS. Furthermore, because the sensory conflict theory depends on expectations that cannot be measured, it cannot be falsified. They suggest that CS is rather based on prolonged postural instability causing the symptoms to occur. Nowadays, their postural instability theory is also one of the most respected theories for CS occurrence [54].

2.2 Cybersickness and 360° Videos

Real-world 360° videos in VR are of interest due to their sophisticated form of viewing a scene. This form of presentation is considered separately from computer-generated content as recorded content allows for pre-computation of properties like angular velocity and linear acceleration of the camera motion and use them without incurring any latency penalty. In contrast, computer-generated virtual worlds have no pre-defined camera trajectories and the camera's position in the world can only be considered at run-time. Still, the number of works addressing CS in 360° videos is small, especially when it comes to mitigate its occurrence.

The fact that 360° videos can actually provoke CS was demonstrated by former works [14, 30]. Elwardy et al. evaluated CS in 360° videos with an head-mounted display (HMD) [14]. Particular attention was paid to the influence of the level of experience with immersive media on CS. The results indicate that especially participants with a low level of VR experience suffered from CS in the 360° videos.

The high risk of CS of viewers exposed to 360° videos was also recognized by Kim et al. [30]. They proposed a neural network solution that predicts a sickness score for videos that are experienced in VR. Thus, they do not try to mitigate CS rather than warn about videos that are most likely to make users sick. Their experimental results reveal two things: 1) prediction correlates for the human perception exist and 2) 360° videos are very likely to cause CS in VR.

The video format (monoscopic, stereoscopic) and audio format (stereo, spatialized) was found to not influence the users' feeling of presence and CS for 360° videos [44]. In contrast, gender is an significant variable that should be considered for VR scenes that display 360° videos [44].

Bala et al. [3] started investigations on CS mitigation for real-world 360° videos. They used an independent background grid and a fixed FOV restriction as well as a combination of both to reduce CS in their experiment. Their results did not show any significant difference in CS which was according to their own statement due to the small number of participants [3]. In a later work with 360° videos they included more participants and only focused on the combined method (independent background grid and FOV restriction) and were able to show a decrease of CS [4].

2.3 Mitigation Techniques for Virtual Scenes

Given the ubiquity of CS, a lot of works study the mitigation of CS in user-controllable virtual environments like games that usually give the user 6 degrees of freedom (DOF) to explore the scene.

General concepts to reduce CS in immersive experiences include high frame-rate renderings, high quality tracking and reduced latency systems [9, 33, 57]. Since all these approaches require special hardware and setup, visual techniques that do not require this hardware are used increasingly.

Visual methods directly modify the user's perception of motion by reducing the optical flow of the rendering. This is typically done by reducing the users' FOV, either opaque [5, 16, 35, 36, 47, 56] or semi-transparent [6, 22, 38, 48, 49]. Also, methods that modify the FOV were found to be equally efficient for all genders and do not influence the spatial navigation performance [2].

Existing methods commonly employ fixed FOV restrictors that do not follow the eye movement and are centered on screen [5,36,48,56]. As these fixed restrictors are clearly visible, they may impact the quality of the VR experience [1].

Few previous studies use gaze-contingent restrictors to only manipulate the peripheral regions. A first approach is demonstrated by Adhanom et al. with an opaque FOV modulation and the use of eye tracking [1]. In their experiment the gaze-contingent FOV restrictor was compared against a fixed FOV restriction. The results state that although both method achieved comparable CS scores, the fixed restriction is not only obvious but influences the users' eye gaze behaviour. Conversely, the gaze-contingent modulation was unobtrusive and allows for a natural gaze behaviour of the user [1].

The potential of semi-transparent FOV modulations to mitigate CS is investigated by Hillaire et al., who investigated the performance of gamers in response to visual blur effects [22]. They show no performance degradation arise from blurring the periphery. The participants even reported an increase in realism with the active blur [22]. The recent work of Venkatakrishnan et al. [38] used a fixed semi-transparent central window to reduce CS in a explorable VR environment.

Other visual methods to reduce CS involve non-salient blurring of objects in the virtual environment [45,46], snapping of moving frames [15,68] and skipping or obscuring translational frames with virtual teleportation [42,68]. While these techniques promise to potentially minimise CS, they represent a compromise and are often connected to a negative user experience or feeling of presence [38, 42,68].

In this paper, we are the first to directly compare the effects of gaze-contingent peripheral blurring against gaze-contingent peripheral occlusion in the context of seated viewing of pre-recorded 360° videos involving complex camera movements.

3 Experimental Framework

We investigate the mitigation of CS in a VR experiment with different visual techniques. The techniques are designed to unobtrusively influence the performance of our participants as little as possible. For this, real-time eye tracking of the HMD and pre-recorded gyroscopic data of the camera is used to only manipulate the peripheral areas of the view. The effectiveness of the methods is validated using psychophysical and physiological measurements.

3.1 Stimuli Generation

3.1.1 Restrictor Design

The goal of our visual techniques is to efficiently mitigate CS and be as subtle as possible to the user. In our experiment, we gaze-contingently post-process the presented video in real-time by restricting its periphery during motion by either blurring or opaquely occluding the eccentric area before presenting it on the HMD. For both techniques the foveal region remains unchanged for a natural viewing experience. The two techniques are in the following referred to as *peripheral blurring* and *opaque occlusion*.

The restriction with peripheral blur is realised by a post-process spiral blur filtering technique inspired by the Unreal Engine. The applied filtering technique achieves a uniform blur with a maximum of 64 samples per pixel i.e. 8 distance steps x 8 radial samples. The blur intensity increases radially to the outside [38]. Thus, the farther away a point is from the foveal region the more it is blurred (cf. Fig. 2).

The opaque occlusion is implemented in a similar way but instead of blurring the peripheral region, it occludes it completely. Only the foveal region is visible the whole time. The intensity of the occluding gray does not change throughout the scene and was chosen to match the average color intensity of the videos.

The design of both restrictors is shown in Figure 2.

The diameter of the visual modification techniques changes with the camera motion in the scene but is always kept above a minimum size of 10° to prevent occlusion of the whole scene and be less obtrusive. According to previous research, users are not able to reliably differentiate between full resolution and foveated rendering when the high-resolution area is larger than 10° [67].

During the experimental session, we change the size of the circular restrictors based on the linear acceleration a and angular velocity ω of the camera in the scene. This movement data was recorded by the camera's built-in gyroscope along with the video. We link the

Figure 2: Video frame of the unmodified ground truth condition (GT), with applied peripheral blurring (Blur) and opaque occlusion (OCC) of the user's FOV.

restrictors' opening diameter to camera acceleration, because the human vestibular system also perceives motion through acceleration in three dimensions [7]. For rotational movements, the angular velocity is taken into account as it is processed similar to linear accelerations in the vestibular system [41]. The restrictor is absent, i.e. fully open, when the camera is not moving following the prevalent theories on CS occurrence [50,51,54]. The restrictor size r at time point t is calculated as in Equation 1. Here, r_d represents the full range of the restrictor: $r_d = r_{max} - r_{min}$.

$$r_t = r_{min} + r_d \left(1 - \left(\frac{|a_t|}{2a_{max}} + \frac{|\omega_t|}{2\omega_{max}}\right)\right) \tag{1}$$

The maximum linear acceleration a_{max} and angular velocity ω_{max} is fixed to the maximum values of the scene. The restrictor sizes are filtered frame-wise with an exponential moving average filter, with 10% influence of the new size and 90% of the former size, to reduce possible flickering noise.

3.1.2 Virtual Environment

The video content is produced to evoke a high level of CS by relying on well-known theories [50, 51, 54] and current research on the causes of CS [1,4,38].

We present multiple 360° videos in an HMD. Our pre-recorded 360° videos showed scenes from parkour running and sport climbing with free falls up to 5 meter. We recorded the videos in ego-perspective in collaboration with professional athletes (see Figure 1). Also, in contrast to controlled, artificially designed scenes, real-videos may often expose a higher visual complexity. We used real-world videos to account for this complexity to investigate the effectiveness of the visual techniques when applied in practice.

Cinematic views like videos are known to cause CS and are therefore highlighted in VR interaction guidelines of leading game engines [63,64]. This sickness induction is supported by the fast movements and abrupt stops of the athletes according to the sensory conflict theory [51] and falls and swings supporting the postural instability theory [54]. Furthermore, some abrupt movements cannot always be anticipated and also increase CS according to the neural mismatch theory. This unpredictability occurs especially when the videos are watched for the first time and explains why we employ a counterbalanced experimental design to prevent adaptation to CS. In our experiment, participants had no control over the video except that they could change their viewing direction by head movement.

3.2 Measurements

The level of cybersickness one person is suffering from in a given experience can be measured by both subjective and objective measurements. Each of those methods are used in our experiment.

3.2.1 Subjective Measurement

A frequently used method to measure CS in virtual environments is the simulator sickness questionnaire (SSQ) [28]. It defines 16 sickness symptoms and derives from the more general pensacola motion sickness questionnaire (MSQ) [26]. The SSQ is known as an efficient and effective tool to self-assess the level of CS. In addition to the total sickness score, three clusters can be differentiated: nausea, oculomotorics and disorientation. We use the SSQ for subjective measurements of sickness values since simulator sickness evokes the same symptoms as CS experienced in VR [40]. Furthermore, it was used by multiple previous studies for 360°videos [14, 30, 37, 44].

The total sickness score as well as the corresponding subscores of the SSQ are calculated according to the original procedure of Kennedy et al. [28]. Participants filled the SSQ before and after the session. The final score is the difference of both questionnaires to measure relative changes.

3.2.2 Objective Measurement

Initially, the SSQ was designed with classical simulators in mind and could therefore raise the question of its validity for 360° videos. As a direct contrast to the self-reported SSQ, we also collect physiological data to objectively assess the level of experienced sickness.

Physiological measurements have been previously studied to identify CS in virtual environments [8, 11, 19, 32, 39, 60]. Multiple physiological symptoms appeared to be correlated with CS and its associated symptoms.

One indicator is the eye blink rate of a person as shown by Dennison et al. [8]. They state that the blink rate increases when participants start to feel sick. In this paper, we validate the use of blink rates for CS prediction for 360° videos. We further hypothesize eye gaze behaviour to be also expressed by angular saccade velocities. Gaze behaviour should not be impacted between sessions when the applied visual techniques are truly unobtrusive [55].

Furthermore, we measured the heart rate (HR) and electrodermal activity (EDA) of our participants as there physiological correlates were previously shown to be strong indicators of CS [8, 32, 60].

3.3 General Methods

In our experiment, we explored real-world video scenes with 3 DOF. We used a within-subjects design with three sessions per participant. Two of the sessions involved the visual techniques – peripheral blur and opaque occlusion – and the third was performed as control condition without visual post-processing. The sessions were counterbalanced and conducted with a two-day-break per participant.

3.3.1 Task

Before the main task, people stayed in the static virtual scene for one minute to obtain physiological baseline data to later control for individual differences and let participants get used to the VR environment.

The duration of the main task was 10 minutes for all sessions. The participants could voluntarily stop and leave the experiment in case of severe sickness symptoms. Participants watched several 360° videos of parkour running and sport climbing with free falling scenes as described in Section 3.1.2. The participants were instructed to remain still while watching the videos but were allowed to move their head to freely explore the scene. No input of the user other than the head rotation was required.

3.3.2 Apparatus

We used a commodity HTC Vive Pro Eye HMD with a FOV of 110° and a frame rate of 90 Hz. This HMD has a built-in eye tracking system that records gaze data with 120 Hz at an accuracy of 0.5°–1.1° [23].

The peripheral-physiological data was collected using a MindMedia Nexus-10 MK2 device with sensors placed on the left hand of the participants (cf. Fig. 3).

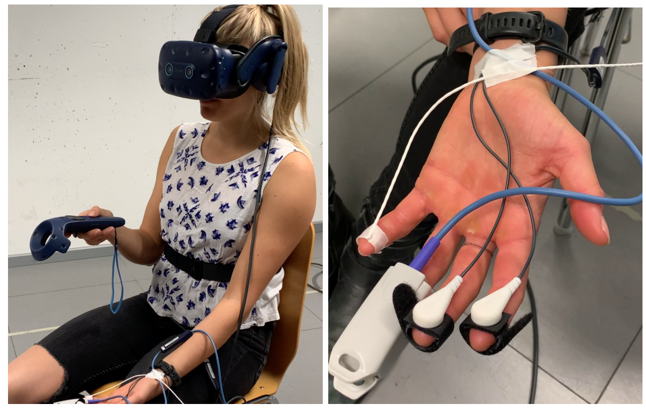

Figure 3: Participants always sat down during the experiment (left image). The physiological data was measured with a finger clip on the left hand (right image).

The 360° videos were recorded using an Insta360 Pro camera [24] with 6*k* resolution at 30 FPS. Gyroscopic data was recorded every 3ms. The 360° camera was mounted on a snowboard helmet to record the scenes since we required fast and flexible movements with hands-free control. In order to control the weight and increase wearing comfort, we added extra padding and stabilizers. The final apparatus can be seen in Figure 4.

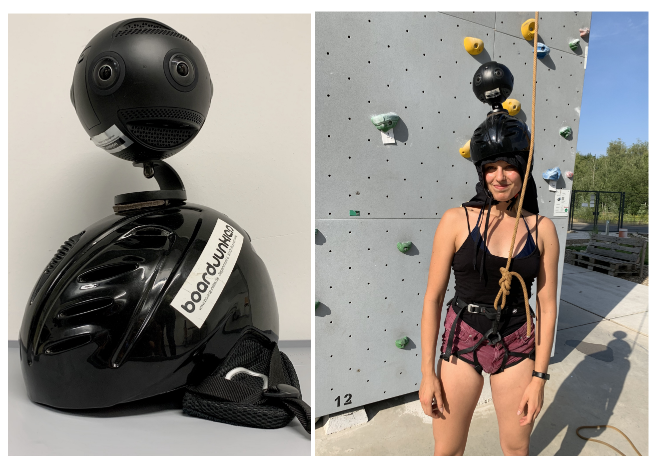

Figure 4: Helmet carrying the 360° camera to capture the recordings for the experiment.

3.3.3 Participants

A total of 23 participants were recruited for the experiment. 4 participants had to leave the experiment after the first session because of severe sickness symptoms and 19 subjects completed all three sessions (11 females, age range 20–32, mean age 25.68, SD 4.65). All participants were compensated with a payment of 25€. The experiment was approved by the corresponding ethics committee.

3.3.4 Procedure

Each of the three sessions of the experiment was conducted with a two-day-break and at least 48 hours between sessions to avoid any carry over effects, following the design of established studies [12, 13, 38]. Prior to the experiment, participants filled an informed consent form and a demographic questionnaire. The SSQ was filled before and after each session to capture the relative change in well-being. Before the main task was performed (cf. Section 3.3.1) the eye tracker was calibrated. During the entire experiment participants sat on a chair and were not allowed to stand up to not break the immersion, minimize the risk of accidents and not impair the physiological measurements.

4 Results

For the analysis of the experimental results we used factorial mixed repeated-measures ANOVAs with condition as within-subject and gender as between-subjects factor followed by pair-wise two-sided dependent t-tests for repeated measures with Bonferroni-correction.

According to previous research, gender has a strong influence on the susceptibility for CS [44]. Therefore, we additionally analyze men and women separately to investigate the influence of gender to mitigate CS.

Figure 5 illustrates the results of the SSQs and the average times for participants to end a session. The SSQ was analyzed for its total score and the three subscores of nausea, disorientation and oculomotor [28]. Based on the subjective self-assessments of the participants the results show the same trend for almost all analyses: the unmodified ground truth (GT) condition was perceived as the most sickness inducing while both modification techniques (blur and opaque occlusion) reduced the sickness score. For most observations, the average SSQ level for the session with dynamically occluded FOV (dark blue) was reported the least sickening (cf. Fig. 5).

The factorial mixed ANOVA shows a significant main effect on the SSQ total score (Fig. 5a) for condition ($F(2,34) = 4.261$, $p = 0.022$, $\eta^2 = 0.2$). No significant effect was found for gender, indicating that the methods work equally for both genders. Pair-wise dependent t-tests show a significant difference for females for the SSQ total score when peripheral blurring is applied ($T = 2.84$, $p = 0.0174$) as compared to the control condition (GT). For males there is no such difference. Also for the nausea subscale of the SSQ (Fig. 5b) a significant main effect for condition is present ($F(2,34) = 4.121$, $p = 0.025$, $\eta^2 = 0.2$). From the pair-wise t-tests for the females a significant effect is present for both blur ($F = 2.43$, $p = 0.0352$) and opaque occlusion ($F = 2.97$, $p = 0.0141$) when compared to the unmodified view. There is no significant effect for males. For the disorientation SSQ subscore (Fig. 5c) of all participants a significant effect is present for condition ($F(2,34) = 3.282$, $p = 0.05$, $\eta^2 = 0.16$) but not for gender. The pair-wise t-tests show a difference between GT and opaque occlusion for females ($T = 2.27$, $p = 0.0466$). For males this effect is absent. The oculomotor effects (Fig. 5d) only demonstrate a minor effect for condition when all participants are considered ($F(2,34) = 2.924$, $p = 0.067$, $\eta^2 = 0.15$). However, for the women the pair-wise t-tests shows a significance for GT compared to a opaque occluded view ($T = 2.37, p = 0.0391$). For the duration participants spent in the virtual scene before they chose to quit the experiment (Fig. 5e), we can see significant main effects for condition ($F(2,18) = 11.04$, $p = 0.00074$, $\eta^2 = 0.55$) and gender ($F(1,9) = 10.04$, $p < 0.011$, $\eta^2 = 0.53$). The pair-wise t-tests confirm this outcome and also reveal a significance for both mitigation techniques (Blur: $T = -3.05$, $p = 0.0123$; OCC: $T = -3.83$, $p = 0.0033$) for all participants. For only the female participants the effect is present for opaque occlusion against the unmodified GT condition ($T = -2.75$, $p = 0.0332$). Although the average session time also increased for men, the t-test did not reveal any significance, which may be due to the low number of male participants considered here ($N = 4$).

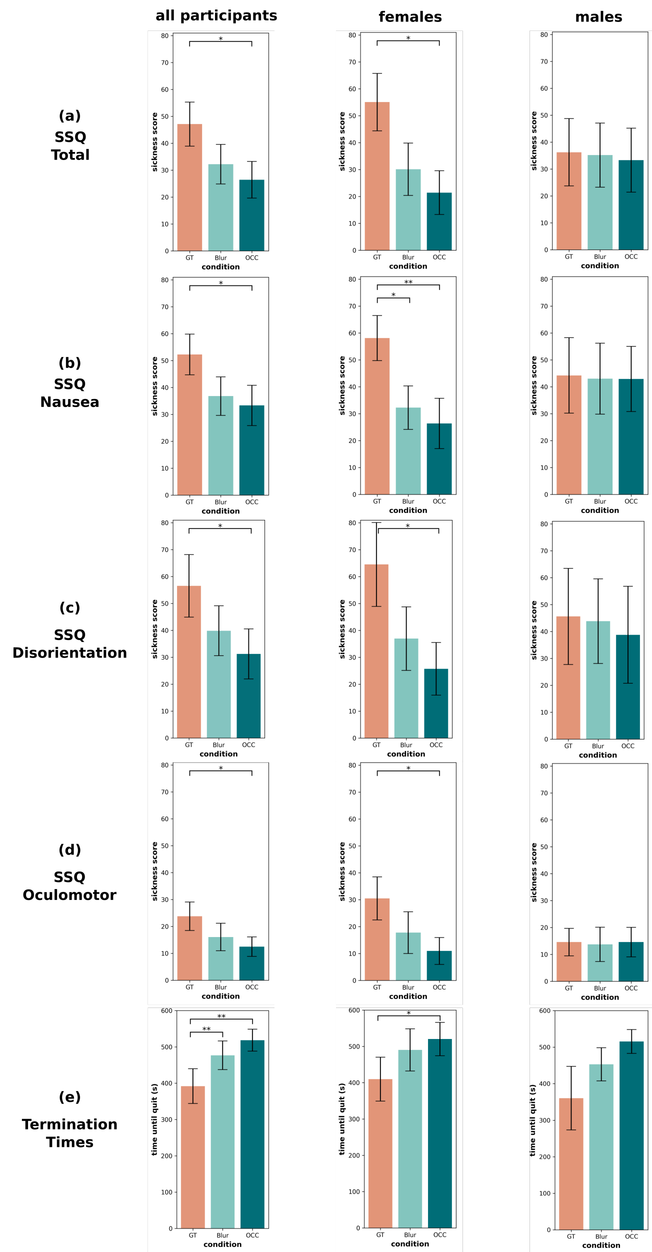

Figure 5: Averaged SSQ scores and termination times; error bars represent the SEM. **(a)** SSQ results for total score ($N_{all} = 19$, $N_f = 11$, $N_m = 8$). **(b-d)** SSQ results for each of the subscales. **(e)** Termination times for each session only considering participants that quit at least once prematurely. ($N_{all} = 11$, $N_f = 7$, $N_m = 4$). Significant results are denoted by '**' ($\mathbf{p \leq 0.016}$, Bonferroni-corrected for multiple comparisons) and '*' ($\mathbf{p \leq 0.05}$)

Overall 11 participants decided to terminate one or more of the sessions early because of severe sickness symptoms (57.9%). When the terminations are separated by condition, the participants felt the strongest urge to quit during the unmodified condition (GT = 47.3%, Blur = 36.8%, OCC = 31.5%), giving a first hint that the control condition (GT) was least pleasant to the participants. As expected, most experiment terminations occurred in the first session (S1 = 52.6%, S2 = 36.8%, S3 = 26.3%). Therefore, it is possible that familiarity with the scene increased after the first session and

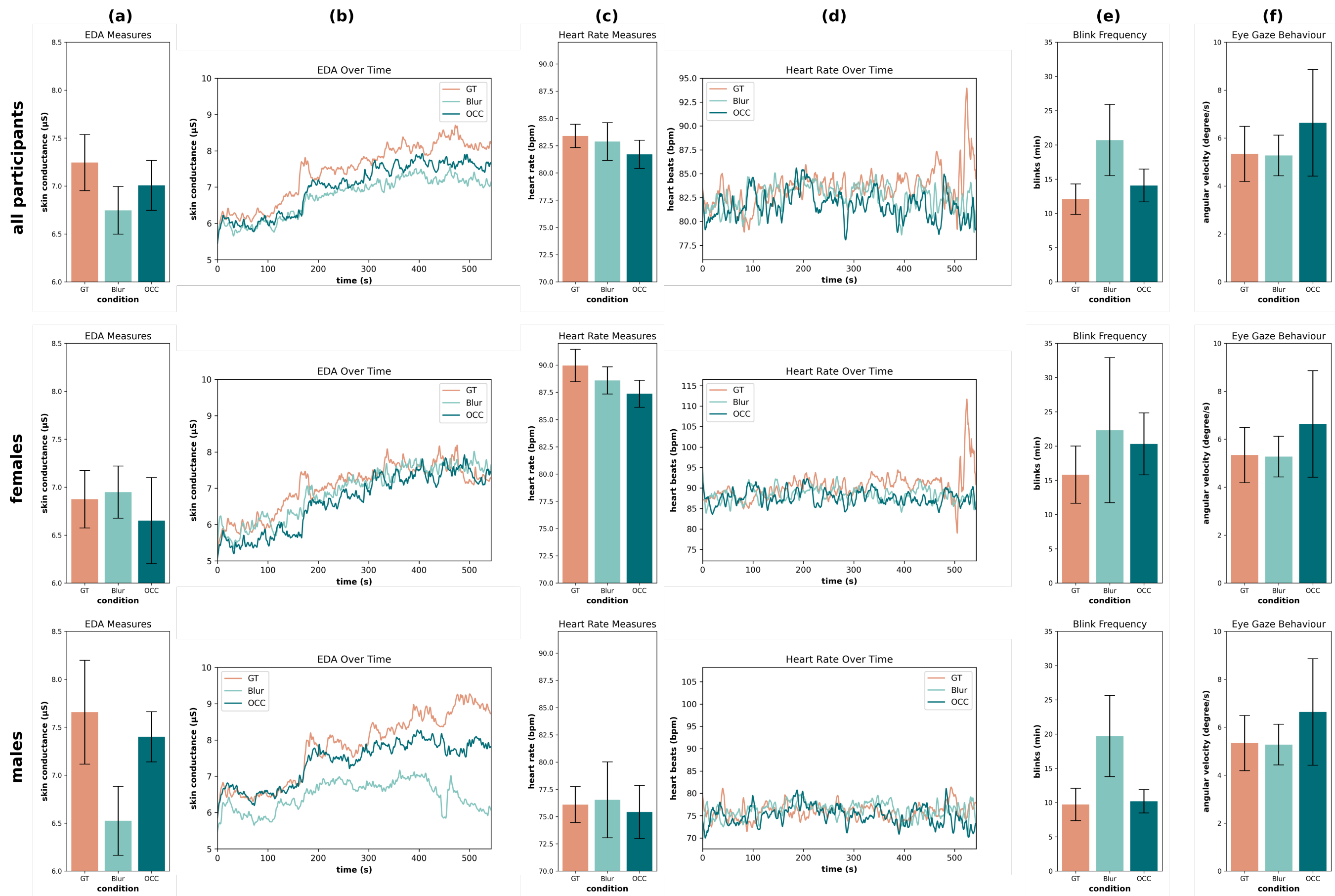

Figure 6: Physiological measurements ($N_{all} = 19$, $N_f = 11$, $N_m = 8$), error bars represent the SEM. **(a,c)** Baseline corrected EDA and HR averages. **(b,d)** The corresponding EDA and HR over time. Note, that the baseline-corrected values are raised by the constant of average heart rate of all sessions to make them more human readable. **(e,f)** Eye blink rates and eye gaze behaviour.

impacts the termination behaviour. The randomized order of the FOV modifications was used to prevent this effect.

Figure 6 shows the analysis results of the physiological measures. The average EDA and HR measurements over the time-course of the experiment are shown in Figure 6b/d. Additionally, for the eye tracking data, the blink rate per condition and the gaze behaviour by angular saccade velocities is plotted.

EDA and HR were baseline corrected per participant and session (Section 3.3.1). Although averaged physiological results do not indicate a clear trend for every condition, more pronounced changes are visible in the temporal evolution of the signal and indicate higher measures for GT. Note, that the results show a general increase of EDA for all conditions. This drift is not unusual for VR as the devices emit heat.

The blink frequency was highest when peripheral blur of the FOV was applied. For GT, the blink rates were the lowest. For the eye gaze behaviour we found no significant change.

5 Discussion

Our experiment investigates techniques that reduce the user's optical flow for 360° videos in VR. Modifying the FOV indicates a reduction of the CS level and, at the same time, increases the time participants are willing to spend in the VR scene, suggesting a more pleasant experience overall. Opaque occlusion of the peripheral regions with a dynamic radius was most effective to improve the SSQ score and the time spent in the VR environment. Blurring the peripheral area was also effective especially for the time until participants ended the experiment. The results suggest that the extent to which optical flow is reduced is related to the efficiency of the methods. Since the manipulation of the FOV with an opaque occlusion reduces optical flow the most, this technique indicated the highest efficiency in our experiment.

We analysed the single subscores of the SSQ for a more in-depth understanding of the impact of the visual techniques. All subscales show the same trend as the total SSQ results with the highest sickness score for the GT condition and the lowest score for the opaque occlusion. In direct comparison, the oculomotor subscale exhibited the least effects. This low level of oculomotor effects may be explained by the fact that impairments like eye strain and blurred vision usually occur after prolonged VR sessions due to exposition to the display hardware. Here, the sessions had a maximum duration of 10 minutes. The subscales for disorientation and nausea are comparable, both with high values. Disorientation is a problem known to occur after VR sessions. In the case of nausea, on the other hand, some claim that it does not occur as severely in VR experiences [31]. The results of our experiment clearly state that nausea should be considered if 360° videos are experienced in VR.

The results of the physiological measurements show higher values for the GT condition for most of the time, especially for skin conductance (EDA) that varies with the activation of sweat glands of the hands. EDA can be considered as one of the most common observation channels of sympathetic nervous system activity, and manifests itself as a change in electrical properties of the skin. Other studies showed that the nervous system activity is related to CS [18, 60]. EDA as well as HR measures show more pronounced differences between conditions towards the end of session, indicating an increase of CS over the time-course of the experiment. Interestingly, the strong upward trend of EDA of male participants towards the end of the session for the GT condition suggests that severe sickness is experienced late in the session (Fig. 6b bottom).

For the results of the eye tracking data, no influence of the FOV modifications on the participants' saccadic length (eye gaze behaviour) is found (Fig. 6f), which confirms the subtleness of the investigated techniques [1]. This indicates that the participants did not feel restricted by the peripheral FOV modifications and looked around freely to the same extent in all scenes. The blink frequency was highest for the peripheral blur condition (Fig. 6e) and lowest for GT in contrast to previous work [8].

As previously discussed, the validity of the SSQ for 360° videos could be questioned as it was neither designed for such scenes nor validated for them. A direct comparison of the physiological data and our SSQ measures reinforces the validity of the SSQ to measure CS for 360° videos in VR.

Results from previous research indicates that CS disproportionately affects women [44]. In our experiment, the level of sickness participants experienced was likewise higher for women, at least for the unmodified GT scene. When the FOV modification comes into place, the level of CS is on the same level for both genders. Therefore, the investigated visual techniques seem to be more effective for female participants. This is the case for the total SSQ score as well as for all subscores. This is indeed an interesting finding as gender differences in the perception of VR have been pointed out in related research [21, 43, 44, 58]. Concerns have been raised about possible inequitable barriers when consuming immersive media. Reducing CS to an equal level could again democratize VR technology for all genders. The average SSQ score for female participants decreased by half (Blur: 45.4%, OCC: 61.1%) while, simultaneously, the time they spent in the scene increased (Blur: 20%, OCC: 27%). While men stayed longer in the scene when the visual modulations are applied (Blur: 27%, OCC: 43%), their SSQ scores did not significantly change across conditions. This may suggest that some male participants went up to their limit of tolerable sickness that simply occurred later with a restricted FOV. Furthermore, we can observe that women had a higher heart rate than men overall, with more than 10 bpm difference on average.

The cumulative video duration for the experimental task was ten minutes in total, which is probably shorter than a normal VR session. We chose this rather short time because our 360° videos represent a very challenging scenario with a high probability to cause CS. This strong scenario gives us a better control over the experimental variables. To ensure comparability this increases the likelihood for people to become sick at some point during the exposure time. The capability of our videos to cause CS during the chosen exposure time is further demonstrated by the number of participants leaving the experiment early (57.9%).

6 Conclusion

In this work we investigate the mitigation of cybersickness in 360° videos displayed in VR. By modifying the peripheral regions of the FOV with either blurring or opaque occlusion, we show that cybersickness is efficiently reduced, allowing VR users to have a more pleasant experience. The visual modulations were designed to be unobtrusive to the users by following the eye movements and only restricting non-central parts of the view.

For passively watched 360° videos with strong movements, opaque occlusion of the peripheral FOV is most recommended when both methods come into question.

Furthermore, our results indicate that the investigated techniques work especially well for women with a significant reduction of all sickness scores in our experiment. This is an important factor as VR technology raised the concern of gender bias and our investigated techniques may lead to a more general acceptance and stream-lined experience across all genders. Besides the total SSQ score, all subscales were also analyzed. We found that although all subscores were reduced with a modified FOV, 360° videos primarily caused nausea and disorientation. When videos that are shot along a moving camera trajectory are shown in a VR environment these factors should be considered.

The investigated methods were shown to be suitable for video scenarios with strong movements. In future work, we plan to focus on immersive videos with less strong movements and a longer exposure time. Furthermore, physiological measurements confirmed the SSQ as valid measurement for cybersickness in 360° videos. In the future we will therefore extend our work with more freedom for the user.

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