The Effect of a Foveated Field-of-view Restrictor on VR Sickness

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ABSTRACT

Virtual reality sickness typically results from visual-vestibular conflict. Because self-motion from optical flow is driven most strongly by motion at the periphery of the retina, reducing the user's field-of-view (FOV) during locomotion has proven to be an effective strategy to minimize visual vestibular conflict and VR sickness. Current FOV restrictor implementations reduce the user's FOV by rendering a restrictor whose center is fixed at the center of the head mounted display (HMD), which is effective when the user's eye gaze is aligned with head gaze. However, during eccentric eye gaze, users may look at the FOV restrictor itself, exposing them to peripheral optical flow which could lead to increased VR sickness. To address these limitations, we develop a foveated FOV restrictor and we explore the effect of dynamically moving the center of the FOV restrictor according to the user's eye gaze position. We conducted a user study (n=22) where each participant uses a foveated FOV restrictor and a head-fixed FOV restrictor while navigating a virtual environment. We found no statistically significant difference in VR sickness measures or noticeability between both restrictors. However, there was a significant difference in eye gaze behavior, as measured by eye gaze dispersion, with the foveated FOV restrictor allowing participants to have a wider visual scan area compared to the head-fixed FOV restrictor, which confined their eye gaze to the center of the FOV.

Keywords: Virtual Reality, VR Sickness, Field-of-view Manipulation, Eye Tracking

Index Terms: Human-centered computing—Virtual Reality—;—

1 INTRODUCTION

Virtual Reality (VR) has finally emerged from research labs into consumers' hands. In less than a decade, consumer VR headsets have significantly advanced in terms of tracking, latency, refresh rate, resolution and optics. However, VR sickness is still preventing many people from using VR. VR sickness is considered a type of motion sickness that is specific to the domain of VR [30] and may involve various symptoms including nausea, pallor, sweating, stomach awareness, increased heart rate, drowsiness, disorientation, and general discomfort [21]. Up to 67% of adults may experience mild to severe symptoms [13], but there is growing evidence that women are more likely to experience VR sickness than men [19, 32].

Though various theories have been postulated that aim to explain VR sickness (see related work), the most likely trigger of VR sickness is generally considered to be vection, i.e., the visually-induced illusion of self-motion [10]. Self-motion perception involves inputs from the visual and vestibular systems and usually these inputs are in agreement. When walking around in VR with the viewpoint updated using positional tracking, users generally don't experience VR sickness because vestibular and proprioceptive afferents from walking are generated that match the perceived optical flow. VR sickness typically occurs when there is visual self motion, but no real physical movement which leads to sensory conflict [35]. This can happen when users try to navigate VR using a game controller with steering and rate control activated using a thumbstick. Teleportation avoids optical flow generation as it instantly translates the user's viewpoint and thus avoids sensory conflicts. Despite its wide usage, teleportation is considered to offer a low presence [12] while the absence of optical flow can lead to spatial disorientation [8]. For multiplayer games, discontinuous avatar representations present a challenge for gameplay design as it is impossible to follow or chase other players [20].

Figure 1: FOV restriction during locomotion is a widely used strategy to mitigate visual-vestibular conflict and VR sickness. A limitation of existing implementations is that they use a viewport fixed restrictor (left). In this paper we explore the effectiveness of a foveated restrictor (right) that moves with the user's eye gaze.

To be able to still use a controller for navigation, a widely used solution to reduce vection-induced VR sickness is to reduce the field-of-view (FOV) during locomotion. Because motion from optical flow is primarily detected by the periphery of the retina [48], the idea is to block the peripheral stimulation by applying an opaque texture with a transparent circular hole to the center of the user's FOV within the HMD (see Figure 1:left). This strategy is also known as tunneling as it gives users the impression that they are traveling through a tunnel. Restrictors can be implemented fairly non-intrusively with users barely observing their presence [17]. Various studies have found FOV restriction to be effective in reducing vection, visual-vestibular conflict and resulting VR sickness [11,17,23,28,40]. FOV restriction is already widely used in popular VR experiences and is recommended by Google's and Oculus' VR design guidelines [4,5].

Eye tracking isn't widely available on consumer VR headsets, therefore existing FOV restrictor implementations use a fixed restrictor where the effect is applied to the center of the head-fixed FOV which is only updated by the user's head gaze. Peripheral motion stimulation is most optimally blocked when the head and eye gaze align, i.e, when the user is looking at the center of the HMD. However, this may not always be the case; for example, the user's eye gaze may shift to eccentric targets in the visible field that are

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2642-5254/20/$31.00 ©2020 IEEE
DOI 10.1109/VR46266.2020.00087

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blocked by the restrictor.

In this example, the effectiveness of a FOV restrictor is impeded because the user's peripheral vision is not fully blocked by the restrictor exposing it to optical flow, which could increase VR sickness. Because the restrictor is head-fixed, the user's gaze is confined to a very small region because there is nothing to see where the restrictor is applied. This head-fixed FOV restrictor is a somewhat unnatural implementation that does not appropriately leverage known properties of the human visual system. Namely foveal vision offers high resolution centrally, with resolution that drops toward the periphery.

In this paper we evaluate a new type of FOV restrictor, one where the restrictor is gaze responsive. This foveated FOV restrictor assures that peripheral vision always remains blocked from any optical flow, which could lower VR sickness, and makes it impossible for a user to look at the restrictor itself, allowing users to visually explore a larger portion of the virtual environment during locomotion.

2 Related Work

VR sickness is still considered a major hurdle for the large scale adoption of VR. A number of theories have been proposed that aim to explain VR sickness-but these theories are neither exclusive nor exhaustive [24]. We discuss these as well as various solutions that have been proposed to mitigate VR sickness.

The eye movement theory suggests that rapid involuntary eye movements evoked by optical flow or visual patterns can innervate the vagal nerve and cause VR sickness [15]. This happens when an image moves contrary to the user's expectations and unnatural eye motions are required to keep the scene image stable on the retina. To judge space, positions, and orientations around them, a person must select a reference frame within which to make judgements. A rest-frame can be defined as a specific reference frame that the observer chooses and that appears to be stationary [36]. Many VR experiences are devoid of such a rest-frame, but involuntary eye movements can be reduced when a rest frame is added. For example: in a driving or flying simulator one can add a heads-up display (HUD). For other VR experiences a HUD might break presence, therefore a virtual nose [49], or an independent background [36] can be used.

The postural instability theory [38] links VR sickness to a disruption of posture stability caused by the motion patterns of the visual stimulus of the virtual experience [38]. Repeated exposure to VR would allow users to better control posture and balance and in due time VR sickness will dissipate.

The sensory conflict theory [37] attributes VR sickness to a conflict between the visual, vestibular, and proprioceptive senses. VR sickness results from a sensory disagreement between expected motion and motion that is actually experienced. An evolutionary explanation [43] as to why conflict leads to sickness is that the brain interprets sensory conflict as a sign of intoxication which then triggers nausea/vomiting/sweating as self-defense responses.

The sensory conflict theory is currently the most widely accepted VR sickness theory [22, 25]. Due to recent advances, tracking inaccuracy and rendering latency are no longer significant causes of visually induced VR sickness on consumer VR platforms -though these are still problematic on mobile VR platforms.

Sensory conflict can be reduced by avoiding optical flow generation, for example by using teleportation. Teleportation is a widely used alternative locomotion technique that allows users to safely navigate beyond the confines of available tracking space but it has issues with low presence [12] and spatial disorientation [8]. A controller is the defacto input technique for navigating 3D environments on desktop/console platforms but using a controller in VR is likely to cause VR sickness [44].

Several studies [26, 28, 40] suggest a positive relationship between FOV size and presence but that negative relationship to VR sickness exists, i.e. using a larger FOV increases presence but also increases VR sickness. Self-motion from optical flow is driven most strongly by motion at the periphery of the retina [45, 48]. Blocking peripheral motion stimulation by reducing the user's FOV (i.e. tunneling) during locomotion is an effective strategy to reduce VR sickness [11, 17, 23, 28, 40]. FOV restriction has been found to be equally effective for both men and women and does not impede path integration ability [7]. Other strategies to reduce optical flow generation include blurring non-salient virtual objects [33] and optical flow analysis to filter out content that increases optical flow [27]. Optical flow can also be minimized by dynamically controlling the travel velocity [18, 42]. FOV restriction seems to be the most widely implemented strategy to reduce VR sickness and can be found in many popular VR experiences (e.g., Google Earth VR). However, current implementations of FOV restriction do not take the user's eye gaze position into consideration, and could therefore be less effective when the user's eye gaze and head gaze are not aligned. An abandoned patent application exists [16] that describes a foveated FOV restrictor, but to date no studies have evaluated the effectiveness of such a restrictor, which is what our paper contributes.

3 Design of foveated FOV Restrictor

To implement a foveated FOV restrictor (FV) that responds to the user's eye gaze, we first implement a fixed FOV restrictor (FX) based on the strategy of Bolas et al [9], Fernandes, and Feiner [17] to dynamically manipulate the FOV in response to changes in the participant's linear and angular velocities in the virtual environment. After the fixed restrictor we implement a method to manipulate it's position in the VE based on the user's eye gaze position.

For both FOV restriction conditions (FX and FV), the FOV was decreased as the participant's speed or angular velocity increases. To restrict the FOV, we used a black texture with a fully transparent circular cut-off. The circular cut-off is defined by an inner and outer radius that together form an annulus. We call the region between these two radii the feathering region. In this region the opacity of the circular cut-off increases linearly from completely transparent to completely opaque. The inner radius of the circular cut-off is calculated using the following formula [2].

$$FOV_{r,t} = FOV_{r,t-1} \times [1 - (RF_{max} \times max(\frac{v_t}{v_{max}}, \frac{\omega_t}{\omega_{max}}))] \quad (1)$$

$FOV_{r,t-1}$ is the radius of the circular cut-off at time $t-1$. RF_{max} is the amount of restriction applied to $FOV_{r,t-1}$ at the maximum virtual speed. v_t and ω_t are the virtual linear and angular virtual speeds, respectively, at time t. v_{max} and ω_{max} are linear and angular virtual speeds, respectively, at which the maximum FOV restriction is applied. We set RF_{max} to 0.75 for both conditions, which is equivalent to a minimum FOV of 55° on the HTC Vive Pro Eye with a FOV of around 110°. We empirically found that this value is close to the max FOV restriction applied by popular VR experiences such as Google Earth VR [6]. We specifically chose this value as to be able to maximally suppress VR sickness. The outer radius is always set to be $RF_{max} + 0.1$, which indicates that the feathering region covers about 11° of the FOV on the HTC Vive Pro Eye. The value of v_{max} was set to 1.4 m/s, a value that matches the average preferred walking speed of humans [31]. We empirically found 180°/sec worked best as a maximum angular speed to ensure a frequent FOV restriction as a response to the dynamics of head movement. The FOV restriction was applied gradually over 0.15 seconds and the edges of the circular cut-off were feathered as these factors were found to make the restrictor less noticeable to the participants [17].

For the fixed FOV restrictor the center of the restrictor was always fixed at the center of the user's viewport, or at $(0,0)$ in normalized screen coordinates, where the lower left corner of the viewport is represented by (-1,-1) and the upper right corner is represented by (1,1). For the foveated FOV restrictor the center of the circular cut-off is moved in response to the user's eye gaze. The user's eye

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gaze position in normalized coordinates was used to move the center of the circular cut-off accordingly at every frame update. To ensure that the movements of the FOV restrictor are smooth and subtle to the user, the eye gaze positions are smoothed using Unity's smooth damp algorithm with a smooth-time parameter of 0.15 seconds. Eye gaze smoothing also helps us avoid jerky movement of the restrictor during blink events. Finally, to avoid blocking large parts of the VE by the foveated restrictor, we ensure that the center of the restrictor does not move beyond the central 20° of visual angle. We chose this value because it is the threshold for gaze shifts that do not involve head movements [34].

4 User Study

Based on the arguments presented in the introduction, our study aimed to investigate the following three research questions:

Research Questions

RQ_1: Will the foveated FOV restrictor reduce VR sickness more than a fixed FOV restrictor?

RQ_2: Will the foveated FOV restrictor allow for a more unrestricted view of the VE than the fixed FOV restrictor?

RQ_3: Will a foveated FOV restrictor be less noticeable to users than a fixed FOV restrictor?

Because there is some evidence that women are more likely to experience VR sickness [19, 32], as a secondary factor, we evaluate the effect of sex for each research question. In order to do achieve this we balance the sex of participants.

4.1 Equipment

We use an HTC Vive Pro Eye HMD with a diagonal FOV of 110°, refresh rate of 90Hz, a combined resolution of 2880×1600 pixels, six degrees of freedom (DoF) for position and orientation tracking, and adjustable interpupillary (IPD) and focal distances. The headset was powered by an AMD Ryzen 7 1700X Eight-Core processor with 16GB of memory and NVIDIA GeForce GTX 1080ti graphics card running Windows 10. We track eye gaze using the HTC Vive Pro Eye's integrated binocular eye trackers which are capable of dark pupil binocular eye tracking with an output frequency of 120 Hz. Eye tracking can be performed in a 110° field of view which is equal to the HMD's field of view. The eye trackers have an estimated accuracy of $0.5^\circ - 1.1^\circ$.

Participants provided input using an XBox controller that we preferred over the Vive's motion sensing controller because participants were likely to be more familiar with this controller and the profile of the thumb stick used for navigation provides better tactile feedback than the Vive's touchpad.

We use Unity3D engine version 2019.1.6 and the Unity3D VR plugin SteamVR version 1.7 to develop the application. HTC's Sranipal SDK version 1.1.0.1 [1] was used to read eye tracking data from the eye trackers. We used the tunneling effect implementation of SixWays [2] to dynamically manipulate the FOV as per the specifications mentioned in Section 3.

4.2 Virtual Environment

The VE used was adapted from the Windridge City environment asset [3] from the Unity Asset Store. The environment (Figure 2) consists of an urban setting surrounded by lush forests and winding dirt roads. A set of 105 waypoints, each represented by a blue glowing orb, with a surrounding particle effect animation, were added to guide the participant's movement in the VE. The average distance between successive waypoints was 30m. During the experiment only one way point is shown at a time starting with the first waypoint. A waypoint disappears as a participant approaches within 1.5m of the waypoint, and the next waypoint appears in the environment. Participants used the Xbox controller's thumbstick to navigate the VE at a speed that varied between 0 and 3 m/s. The same thumbstick was used for steering in a direction relative to the head's forward vector.

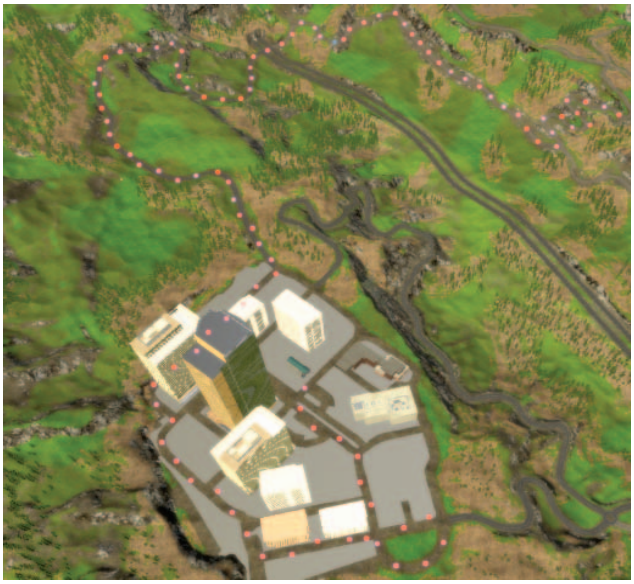

Figure 2: Birdseye view of the virtual environment we used in the experiment sessions, with red dots representing waypoint positions.

4.3 Measurements

Measurements were collected through our custom virtual environment (VE) and various questionnaires. To investigate $\mathbf{RQ}_1$, we use the popular simulator sickness questionnaire (SSQ) [21] along with the self-reported discomfort scores in order to measure VR sickness. The discomfort score was collected through the VE by prompting the user to select a score after every five waypoints. This mechanism was pioneered by Fernandes and Feiner [17] and allows a sampling of a VR sickness score during the trial. The discomfort scores were averaged for each participant per FOV condition to obtain an average discomfort score (ADS), and an ending discomfort score was calculated by using the last discomfort score for each participant per condition. The SSQ scores were collected with post-exposure questionnaires using Google forms. Data collected from the SSQ are used to calculate four associated scores, namely: Total Severity, Oculomotor, Nausea, and Disorientation scores. These scores were calculated as per the conversion formulas by Kennedy et al. [21].

To be able to investigate $\mathbf{RQ}_2$, we measure eye gaze dispersion; a popular method in eye tracking research [29] to measure gaze behaviour and visual attention. The eye gaze data were used to compute participants' gaze dispersion to establish how visual attention was distributed during each of the two FOV restriction conditions [47]. Gaze dispersion is measured as the standard deviation of participant's gaze positions, and is measured separately for the horizontal (yaw) and vertical (pitch) gaze position components. Furthermore, we combine the two components into a single measure of relative distance using the Pythagorean theorem ($x^2 + y^2 = c^2$) [46]. In our study, since we are only concerned with the user's eye movements relative to the viewport, we measure eye tracking data in normalized viewport coordinates. These coordinates consist of (x, y) pairs, where the lower left corner of the viewport is represented by (-1,-1), the center is represented by (0,0), and the upper right corner is represented by (1,1). Thus, the vertical and horizontal coordinates of the eye gaze position are defined with respect to the position of the VR HMD.

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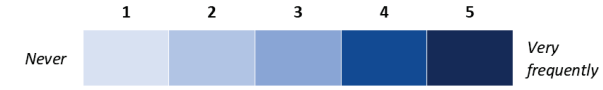

How frequently do you use VR?

Women	27.3% (3)	36.4% (4)	18.1% (2)	9.1% (1)	9.1% (1)
Men	36.4% (4)	36.4% (4)	18.1% (2)	0.0% (0)	9.1% (1)
Total	31.8% (7)	36.4% (8)	18.2% (4)	4.5% (1)	9.1% (2)

How frequently do you get motion or VR sick?

Women	18.1% (2)	54.6% (6)	0.0% (0)	27.3% (3)	0.0% (0)
Men	72.8% (8)	18.1% (2)	9.1% (1)	0.0% (0)	0.0% (0)
Total	45.5% (10)	36.4% (8)	4.5% (1)	13.6% (3)	0.0% (0)

Figure 3: Summary of participants ratings of their frequency of using VR and their tendency of getting motion or VR sick on a scale of 1 (never) to 5 (very frequently). The results are reported in the form of *percentage (count)*.

To investigate $\mathbf{RQ}_3$, after completing each session, participants also completed a participant observation questionnaire to assess whether the participants noticed the FOV restrictors during the experiment sessions. This questionnaire was adopted from [17] who adopted it from [41]. The participant observation questionnaire included two questions (bold) that relate to the FOV restrictors and the rest of the questions were distractor questions. Participants were asked to rate the following seven questions on a scale of 1 - 7, where 1 was "Did not notice or did not happen" and 7 was "Very obvious":

1. I saw the VE get smaller or larger.
2. I saw the VE flicker.
3. **I saw the VE get brighter or dimmer.**
4. I saw that something in the VE had changed color.
5. **I felt like my field of view was changing in size.**
6. I felt like I was getting bigger or smaller.
7. I saw that something in the VE had changed size.

4.4 Experiment Design

A repeated measures mixed design was used for this study, with a within-participant factor of FOV condition (fixed FOV restriction (FX), foveated FOV restriction (FV)) and a between subjects factor of sex (men, women). We inspect the effect of these factors on the following dependent variables: (1) SSQ: total severity score, (2) SSQ: Nausea score, (3) SSQ: Oculomotor score, (4) SSQ: Disorientation score, (5) the average discomfort score (ADS) [17], (6) the ending discomfort score (EDS) [17], (7) the horizontal gaze dispersion score (8) the vertical gaze dispersion score and (9) the combined gaze dispersion score [47]. To account for order effects, half of the participants started with the FX condition (Group A) while the remaining half started with the FV condition (Group B). To minimize the transfer of VR sickness symptoms across sessions, each session was conducted on a separate day with at least 24 hours rest between sessions. To ensure that each group contained an equal number of men and women, we alternated the assignment of men and women across the two groups.

4.5 Procedure

When participants arrived for the first session they were given a short presentation explaining the goal of the study, the outline of the experiment, the risks involved, the data collected, and the details of the training and experiment sessions. The interpupillary distance (IPD) of the participants was measured and was used to set the IPD of the VR headset. Participants were then asked to stand in the middle of the tracking space and were assisted with putting on the VR headset and holding the controller so that they could start the training session.

The goal of the training session was to familiarize the participant with the controls used to provide input and the eye tracker's calibration procedure and to give them an opportunity to practice a short task that was similar to the experiment task. Before starting the training session, participants were asked to complete the eye tracker's calibration procedure. They were then asked to complete a task involving one block of five waypoints, after which they were asked to select a discomfort score from the discomfort score panel. The tunneling effect was not activated during the training session.

During the experiment sessions participants were instructed to follow a set of waypoints at their own pace. After every five waypoints, participants were asked to rate their level of discomfort and were shown a slider from which they had to select their level of discomfort from 0 to 10, with level 10 representing the highest level of discomfort. Participants were encouraged to look around and enjoy the environment around them. After completing each session participants were asked to fill out a SSQ [21] and a participant observation questionnaire to assess if they noticed the FOV restrictors [17] during the experiment sessions.

Finally, participants were asked to fill out a post-study questionnaire which was used to collect demographic information that included their age, sex, frequency of using VR (five-point Likert scale), and tendency of being motion and/or VR sick (five-point Likert scale). On average, the whole study took 1 hour to complete.

4.6 Participants

We recruited 25 participants, but three participants (1 man and 2 women) left due to severe VR sickness. 22 participants (11 males/11 females) attended and completed both sessions, and their data were used in the analysis. Participant ages ranged from 20 to 32 years (average = 23.73, SD = 3.9). Participants were recruited by flyers on a local campus. Participants were asked to rate their frequency of using VR and their tendency to get motion or VR sick on a scale of 1 (never) to 5 (very frequently). The results are summarized in Table 3. All participants were compensated with a $15 Amazon gift card. The user study was approved by an IRB.

	Fixed (FX) Restrictor			Foveated (FV) Restrictor		
	Total	**Women**	**Men**	**Total**	**Women**	**Men**
Discomfort Scores (Max 10)						
Average	0.62 (.7)	0.87 (.9)	0.38 (.5)	1.14 (1.5)	1.00 (.9)	1.27 (1.9)
Ending	1.23 (1.8)	1.27 (1.4)	1.18 (2.2)	1.64 (2.2)	1.36 (1.6)	1.91 (2.7)
Simulator Sickness Questionnaire						
Nausea	13.44 (16.0)	14.74 (19.7)	12.14 (12.1)	16.04 (20.9)	16.48 (22.6)	15.61 (20.1)
Oculomotor	14.82 (15.6)	19.98 (19.3)	9.65 (9.0)	21.36 (22.2)	21.36 (25.3)	21.36 (19.7)
Disorientation	18.35 (26.3)	22.78 (33.1)	13.92 (17.6)	28.47 (36.8)	34.17 (41.0)	22.78 (33.1)
Total	17.51 (19.5)	21.76 (25.3)	13.26 (10.9)	24.48 (27.6)	26.18 (31.0)	22.78 (25.1)
Gaze - dispersion						
Combined	.156 (.03)	.142 (.02)	.170 (.04)	.188 (.04)	.193 (.04)	.184 (.03)
Horizontal	.120 (.02)	.121 (.02)	.119 (.03)	.145 (.03)	.142 (0.03)	.148 (.03)
Vertical	.099 (.02)	.093 (.02)	.105 (.02)	.110 (.02)	.114 (0.02)	.107 (.02)

Table 1: Quantitative measures of the discomfort scores, simulator sickness questionnaire scores (Nausea, Oculomotor, Disorientation and Total) and gaze dispersion in terms of *mean (standard deviation)*.

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5 RESULTS

Results regarding VR sickness and eye gaze behavior are shown in table 1 and we discuss each of these collected metrics in more detail in the following subsections.

5.1 VR Sickness

VR sickness was measured using the self-reported discomfort score, from which we calculated averaged discomfort scores (ADS) and ending discomfort scores (EDS), and using the simulator sickness questionnaire, from which we calculated the Nausea, Oculomotor, Disorientation and Total Scores.

5.1.1 Discomfort Scores

A Komogorov-Smirnov test found that our data were normally distributed. Using a 2-way mixed-model ANOVA, we did not find an interaction effect between sex and FOV condition in both the ADS ($F_{1,20} = .39, p = .54, \eta_p^2 = .002$) and the EDS ($F_{1,20} = .75, p = .41, \eta_p^2 = .007$). We found no significant difference between sexes with respect to both ADS ($F_{1,20} = .06, p = .82, \eta_p^2 = .002$) and EDS ($F_{1,20} = .08, p = .77, \eta_p^2 = .008$), and we did not find significant effect of FOV condition on ADS ($F_{1,20} = 1.71, p = .21, \eta_p^2 = .009$) and EDS ($F_{1,20} = 1.25, p = .28, \eta_p^2 = .01$).

5.1.2 Simulator Sickness Questionnaire Scores

Our data were normally distributed as tested using a Komogorov-Smirnov test. Using a 2-way mixed-model ANOVA, we did not find an interaction effect between sex and FOV condition on all SSQ scores: Total Score ($F_{1,20} = .27, p = .61, \eta_p^2 = .003$), Nausea ($F_{1,20} = .05, p = .83, \eta_p^2 = .001$), Oculomotor ($F_{1,20} = 1.67, p = .21, \eta_p^2 = .020$), and Disorientation ($F_{1,20} = .03, p = .86, \eta_p^2 = .001$). We found that FOV conditions did not result in significant difference in all SSQ scores: Total Score ($F_{1,20} = 2.03, p = .17, \eta_p^2 = .020$), Nausea ($F_{1,20} = .41, p = .530, \eta_p^2 = .005$), Oculomotor ($F_{1,20} = 2.68, p = .12, \eta_p^2 = .030$), and Disorientation ($F_{1,20} = 2.07, p = .17, \eta_p^2 = .030$). We did not find significant differences between men and women in any of the SSQ scores either: Total Score ($F_{1,20} = .43, p = .52, \eta_p^2 = .020$), Nausea ($F_{1,20} = .06, p = .81, \eta_p^2 = .002$), Oculomotor ($F_{1,20} = .52, p = .48, \eta_p^2 = .020$), and Disorientation ($F_{1,20} = .73, p = .40, \eta_p^2 = .030$).

5.2 Gaze Dispersion

A Komogorov-Smirnov test found that our data followed a normal distribution. Using a 2-way mixed-model ANOVA, we did not find an interaction effect between sex and FOV condition on all gaze dispersion measures: horizontal ($F_{1,20} = 1.91, p = .18, \eta_p^2 = .010$), vertical ($F_{1,20} = .33, p = .57, \eta_p^2 = .004$), and combined ($F_{1,20} = .20, p = .66, \eta_p^2 = .001$). However, we found a significant main effect of FOV restriction on gaze dispersion, with foveated FOV restriction resulting in significantly higher gaze dispersion on all measures: horizontal ($F_{1,26} = 51.04, p < .05, \eta_p^2 = .020$), vertical ($F_{1,26} = 8.84, p < .05, \eta_p^2 = .090$), and combined ($F_{1,26} = 34.51, p < .05, \eta_p^2 = .190$). Figure 4 clearly illustrates this significant difference in eye gaze dispersion using a heatmap for one participant. We did not find a significant difference between sexes with respect to all gaze dispersion measures: horizontal ($F_{1,20} = .004, p = .84, \eta_p^2 = .002$), vertical, ($F_{1,20} = 1.95, p = .18, \eta_p^2 = .070$), and combined ($F_{1,20} = .49, p = .49, \eta_p^2 = .020$). Looking at differences in gaze dispersion between FOV restrictors within each sex, our post hoc analysis using a Bonferroni correction found a statistically significant difference for women for combined ($p < .05$), horizontal ($p < .05$), and vertical ($p < .05$) gaze dispersion. For men, using the same test, we found a statistically significant difference for combined ($p < .05$) and horizontal ($p < .05$) measures, but not for vertical gaze dispersion ($p = .11$).

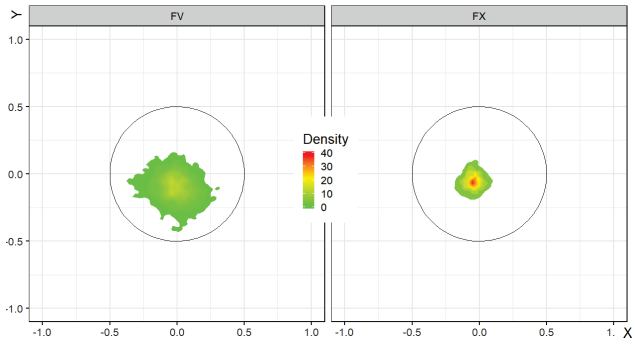

Figure 4: Example 2D density contour plot of eye gaze dispersion for one participant under both FOV conditions: FV (left) and FX (right). The plots illustrate the normalized full field of view of the viewport, and the black circle indicates the size of the restrictor at maximum restriction.

5.3 Participant Observation Questions

	Fixed (FX) Restrictor			Foveated (FV) Restrictor		
	Total	**Women**	**Men**	**Total**	**Women**	**Men**
Participant Observation Questionnaire						
VE smaller or larger	3.82 (2.5)	4.82 (2.3)	2.82 (2.4)	4.27 (2.4)	5.27 (2.1)	3.27 (2.4)
VE flicker	4.18 (2.1)	3.55 (2.3)	4.82 (1.7)	5.64 (2.0)	4.91 (2.3)	6.36 (1.3)
Brighter or dimmer	3.91 (2.3)	3.73 (2.3)	4.09 (2.4)	3.59 (2.3)	4.09 (2.4)	3.09 (2.2)
VE change color	3.18 (2.4)	3.64 (2.7)	2.73 (2.1)	2.64 (2.3)	2.91 (2.6)	2.36 (2.1)
FOV Change size	5.27 (2.3)	4.55 (2.3)	6.00 (2.2)	5.45 (2.2)	4.91 (2.7)	6.0 (1.6)
Me smaller/larger	1.55 (1.3)	1.18 (.4)	1.91 (1.8)	1.95 (1.5)	1.91 (2.0)	1.41 (1.6)
Size change in VE	1.55 (1.34)	1.18 (.4)	1.91 (1.8)	1.95 (1.5)	1.91 (1.6)	2.00 (1.41)

Table 2: Results from the participant observation questionnaire in terms of means and (stdev). Full content of the questions can be found in section 4.3.

Table 2 shows the detailed results from the participant observation questionnaire. For FV, the distractor questions' averages ranged from 1.95 to 5.64, which shows that some guessing occurred. Ratings for question 3: ("I saw the VE get brighter or dimmer") (M = 3.59, SD=2.3) and 5: ("I felt like my field of view was changing in size") (M=5.45, SD=2.2) were all within range of the distractor questions. For FX, some guesswork was involved given that the distractor questions ranged from 1.55 to 4.18. Ratings for question 3: (M = 4.00, SD=2.35) was within range of the distractor questions, but question 5:(M=5.45, SD=2.2) was outside this range.

We used a Wilcoxon Signed-rank test to check if the results for the two relevant questions were significantly different across restrictor types. However, we did not find a statistically significant difference for question 3 ($\boldsymbol{Z} = -0.968$, $p = .332$) or question 5 ($\boldsymbol{Z} = -.578$, $p = .562$). Looking at each sex, for question 3, we did not find a statistically significant difference between restrictors for women ($\boldsymbol{Z} = -.592$, $p > .05$) nor for men ($Z = -.919$, $p = .358$). Likewise, for question 5 we found no statistically significant difference between restrictors for women ($\boldsymbol{U} = 49.5$, $\boldsymbol{Z} = .689$, $p = .490$) nor for men ($\boldsymbol{U} = 53.5$, $\boldsymbol{Z} = -.427$, $p = .667$). Unlike our VR sickness analysis, we did not analyze for differences between sexes.

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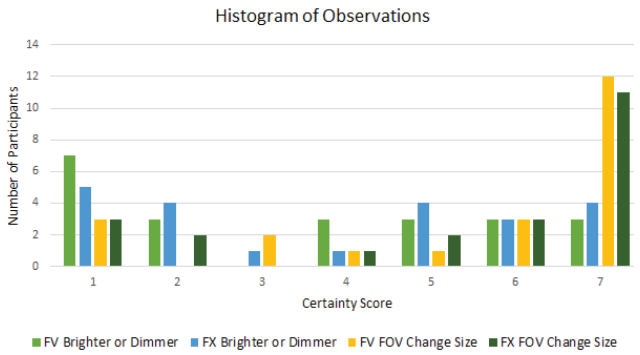

Figure 5: Histogram of responses to the participant observation questions relevant to FOV restrictors.

6 Discussion and Future Work

6.1 RQ_1: VR sickness

We did not find a statistically significant difference between the head-fixed and foveated restrictors for VR sickness as measured using discomfort scores and SSQ scores. In general the levels of observed VR sickness were very low with lower scores for the head-fixed restrictor (though this difference was not statistically significant). In addition to our sample size being on the low side, the amount of VR exposure in our experiment might not have been long enough to elicit a difference in VR sickness incidence between a foveated and a head-fixed FOV restrictor. This suggests that if restrictor type does influence VR sickness, the effect is likely to be very small. We did not detect a significant difference in VR sickness between sexes.

Though women are more likely to experience VR sickness [19,32] the FOV restrictors used were likely successful in suppressing a higher VR sickness incidence in women. A prior study [7] also found FOV restriction to be equally effective in men as in women. Because our study did not use a baseline for comparison, i.e., using no FOV restrictor, no hard claims can be made about the effectiveness of a foveated FOV restrictor to reduce VR sickness, though several studies [11, 17, 23, 28, 40] have found FOV restrictors to be effective in reducing VR sickness.

6.2 RQ_2: Gaze Behavior

We did detect a statistically significant difference in gaze dispersion between the foveated and the head-fixed FOV restrictor, which indicates that participants covered a larger visual scan area (see Figure 4). This result supports $\mathbf{RQ}_2$ and points out an important benefit of using a foveated FOV over a head-fixed FOV restrictor; users have more opportunity to look around (without having to change the orientation of their head). This might allow for taking in more details of the VE they are exploring, which could improve spatial navigation performance. Looking at sex, we noticed that the effect of FOV restriction on gaze dispersion was specially evident in women, where we found significant differences in gaze dispersion in the horizontal, vertical and combined measures. For men we did not detect any significant difference in the vertical gaze dispersion. This is an interesting finding which we speculate that it could be explained by the fact that women rely more on the perception of landmarks for spatial navigation while men rely more on vestibular/geometrical cues. [39].

6.3 RQ_3:Noticeability

We did not find statistically significant differences between FOV restrictor types for question 3 (VR getting brighter/dimmer) or question 5 (FOV increase). Compared with Fernandes and Feiner's study [17], which also used this questionnaire to assess noticeability of FOV restriction, we observed much higher values for these responses. We chose 55° as the minimum size of our restrictors to match those found in popular VR experiences like Google Earth VR. Though this size is highly effective in reducing VR sickness it also makes the restrictor quite noticeable to participants. In hindsight, we could have explored using a larger minimum FOV for our restrictor. This would likely have elicited lower scores for the two questions, and higher VR sickness scores. Regarding $\mathbf{RQ}_3$ we conclude that both FOV restrictors are noticeable but that there was no statistically significant difference between them. It is always possible to use a higher minimum FOV to reduce noticeability at the cost of an increase in VR sickness.

6.4 Study Limitations

In our study we did not assess how FOV restriction affects spatial navigation performance or presence though a foveated FOV restrictor could affect both. A prior study [7] already found that FOV restriction does not impede path integration which is a component of spatial navigation. The tradeoff between FOV and presence has been well established [26, 28, 40]. We did not assess presence due to a lack of testing a baseline (e.g., no FOV restrictor). Fernandes and Feiner's study [17] also found that when using a minimum FOV restrictor of 90° this will be barely noticeable to users and a high presence can be maintained.

Another limitation pertains to the low number of subjects in this study which might have impacted our findings. The study compared the effect of two FOV restrictors on VR sickness using a mixed-model design with 22 participants. However, considering that the incidence and severity of VR sickness varies greatly among individuals [14], this small number of participants might not have been sufficient to allow results to reach statistical significance. A larger number of participants would thus have increased the power of our study. Therefore, the findings of this study have to be seen in light of these limitations.

6.5 Future Work

In future work we aim to investigate optokinetic nystagmus (OKN), a type of eye movement that can be observed during locomotion. During OKN events, with their head remaining stationary, users smoothly track objects in the VE (the slow phase) until their eye position becomes too eccentric, then the eyes quickly move back to the center of their field of view (the fast phase). One study has suggested that OKN responses [15] are a possible cause of visually-induced motion sickness, but this issue has not been further investigated. Using a head-fixed FOV restrictor, OKN might not be observed as objects disappear in the restrictor fairly quickly. A foveated FOV restrictor would allow participants to follow an object all the way until it goes outside the FOV and thus might lead to higher frequency of OKN.

7 Conclusion

In this paper, we evaluate a foveated FOV restrictor which is different from current implementations as the restrictor is rendered around the user's eye gaze location. This implementation assures optimal blocking of peripheral optical flow, users cannot look at the restrictor itself and it allows users to see more of the VE during locomotion. We analyzed the effectiveness of the foveated FOV restrictor on VR sickness, gaze behavior and noticeability by comparing it to a head-fixed FOV restrictor. The results showed no significant difference in VR sickness or noticeability incidence between FOV restrictors, but we did find that participants had a wider gaze dispersion indicating wider visual scan area when using the foveated restrictor.

8 Acknowledgements

This work is supported by Mozilla, Google and NSF grant 1911041.

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