The Effect of Field-of-View Restriction on Sex Bias in VR Sickness and Spatial Navigation Performance

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ABSTRACT

Recent studies show that women are more susceptible to visually-induced VR sickness, which might explain the low adoption rate of VR technology among women. Reducing field-of-view (FOV) during locomotion is already a widely used strategy to reduce VR sickness as it blocks peripheral optical flow perception and mitigates visual/vestibular conflict. Prior studies show that men are more adept at 3D spatial navigation than women, though this sex bias can be minimized by providing women with a larger FOV. Our study provides insight into the relationship between sex and FOV restriction with respect to VR sickness and spatial navigation performance which seem to conflict. We find the use of an FOV restrictor to be effective in mitigating VR sickness in both sexes while we did not find a negative effect of FOV restriction on spatial navigation performance.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; • **Computing methodologies** → **Virtual reality**;

KEYWORDS

Virtual Reality, Field-of-view manipulation, virtual locomotion, VR Sickness, Sex differences, spatial navigation performance

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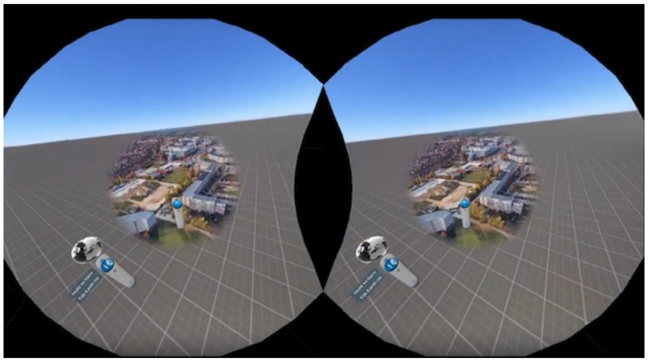

Figure 1: Popular VR apps like Google Earth reduce the field-of-view during locomotion (e.g., tunneling) to block peripheral motion perception as to mitigate visual-vestibular conflict and to reduce VR sickness. However, prior studies suggest that reducing the field-of-view can impede spatial navigation performance in women.

1 INTRODUCTION

Virtual Reality (VR) holds a significant promise to transform and define the way we interact with computers [67], but mass market adoption of VR is threatened by VR sickness [52]. VR sickness (also known as cybersickness or simulator sickness) may involve a suite of symptoms including nausea, pallor, sweating, stomach awareness, increased heart rate, drowsiness, disorientation, and general discomfort [37]. While up to 67% of adults may experience mild to severe symptoms [15], there is substantial evidence that women are more likely to experience VR sickness than men [25, 27, 30, 51, 55]. Games have been a significant driver of innovation in VR and though gaming demographics have shown a near sex parity for a decade (48% of gamers were women in 2014 [2]), a recent survey [3] of 2,500 HTC Vive owners (a popular consumer VR headset) revealed that fewer than 5% of them were women. This low adoption rate of VR technology among women suggests that VR is currently less accessible to women than it is to men [14], and sex differences in the incidence of VR sickness are likely contributing to this problem.

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Though there are various theories that aim to explain VR sickness, vection [44], i.e., the visually-induced illusion of self-motion, is currently considered the most likely trigger of VR sickness [11]. Self-motion typically involves inputs from the visual and vestibular systems and usually these inputs are in agreement. From a perceptual standpoint, natural walking in VR with the viewpoint updated by positional tracking should not generate VR sickness [46] because it generates vestibular and proprioceptive afferents (i.e., sensory signals) that match the perceived optical flow (i.e., full-field visual motion).

Unfortunately, the use of natural walking in VR is bounded by available positional tracking space, which in most consumer home environments is limited [23]. To navigate beyond the confines of limited available tracking space, users must switch from walking to using a controller-based artificial locomotion technique (ALT). Popular ALTs include target selection techniques, the most common of which is teleportation; or steering-based techniques (e.g., using a controller). The optical flow generated using steering-based locomotion generates vection, which in the absence of any vestibular/proprioceptive afferents confuses the senses and may lead to VR sickness [11]. Teleportation circumvents sensory conflict because it instantly translates the virtual viewpoint which avoids any optical flow generation. Though it is a standard ALT in many VR experiences, there are significant concerns with using teleportation such as low presence and disorientation [13, 34]. The discontinuous locomotion offered by teleportation is also a challenge for multiplayer games.

To reduce vection-induced VR sickness, various solutions have been proposed (see [19] for an overview). Motion from optical flow is primarily detected by the rods on the periphery of the retina [71]. Blocking the perception of peripheral motion by reducing the user's field-of-view (FOV) during locomotion [45, 64] is therefore considered an effective strategy to reduce VR sickness. FOV restriction -also known as "tunneling" -is already widely used in popular VR experiences like Google Earth VR and is recommended by both Google's [1] and Oculus' [4] VR design guidelines as a feasible strategy for reducing VR sickness.

However, these design guidelines seem to conflict directly with results from prior studies [17, 68] that found that women benefit from spatial navigation using a larger FOV. Sex differences in spatial cognition have been well documented [73]. Women navigate predominantly using landmarks where men rely mostly on geometric information, such as distance and vestibular cues [63]. These differences affect spatial navigation performance in real [18] and virtual 3D environments [20]. Studies have shown that men are more adept at 3D spatial navigation [18], but this sex bias can be reduced by providing women with a larger FOV –which improves their ability to perceive landmarks [17, 68]. Though prior studies used desktop environments, their findings seem relevant to VR given that the FOV of consumer VR headsets (up to 110°) is still well below the human binocular FOV (up to 190°) [31].

Existing studies on the effectiveness of an FOV restrictor to reduce VR sickness [24, 45, 64] have not explored sex as a variable (i.e., not enrolled an equal number of women/men) nor evaluated the effect of this strategy on spatial navigation performance in women. Given that women were found to have significantly higher thresholds for motion perception [28] and fewer rods in their retinas to detect peripheral motion [7], one can question whether FOV restriction is an effective strategy for reducing VR sickness in women, given that they likely impede their spatial navigation performance [17, 68]. This paper makes the following contributions: (1) we investigate if FOV restriction impedes spatial navigation performance in women; and (2) we investigate whether an FOV restrictor is equally effective in reducing VR sickness symptoms in both sexes. Both contributions provide insight into how to make VR more accessible to women.

2 BACKGROUND

Motion sickness (MS) is experienced as a result of motion patterns of an organism that result in symptoms that include dizziness, cold sweating, headache, increased salivation, and nausea [38]. Visually induced motion sickness (VIMS) is a related phenomena that has induced symptoms similar to those of MS without being subject to physical motion [40]. VIMS is a common adverse effect that results from the exposure to computer simulations in general and VR experiences in particular. Several terms have been given to VIMS in the literature [38], the most common of which are: simulator sickness, cybersickness, and VR sickness. We choose to use the term "VR sickness" to refer to VIMS from this point forward. Several theories attempted to explain the cause of VR sickness. Some theories attribute VR sickness symptoms to a sensory conflict [58] while others believe that it is a result of a failure to maintain postural stability while being immersed in the virtual environment [60]. Other less prominent theories include the eye movement theory [22] and the poison theory [70]. None of these theories is complete, though the sensory conflict theory is the most accepted [38, 40]. Another body of research on VR sickness aimed to show the influence of individual differences on the susceptibility to VR sickness [29, 40, 43, 65]. Sex was among these investigated differences, with women being more susceptible to VR sickness [51, 58, 65]. Theories that attempt to explain such sex difference include the underreporting of VR sickness symptoms by men [9], hormonal differences [16], evolutionary differences [29], and wider field of view of women [40, 43].

VR Sickness restriction Mechanisms

Several medical and behavioral countermeasures to VR sickness have been proposed [38, 43]. Medical interventions suffer from adverse effects that limit their applicability [29]. Behavioral countermeasures, on the other hand, focus on mutating the course of interaction between the user and the virtual stimuli. Some of these countermeasures aim to modify the behavior of the user (e.g., by reducing head movements or by regulating breathing) to minimize the incidence of VR sickness while others manipulate the visual or vestibular stimuli without counting on the user's involvement for the countermeasure to work [38]. Relevant examples of the latter to this research are ones that involve manipulations of the visual stimulus such as the restriction of field of view [10, 12, 24, 39, 45], the use of independent virtual backgrounds and fixed reference frames [21, 57, 75], the dynamic control of travel velocity [26, 69], freezing head rotations [35], and non-salient objects blurring [54].

FOV Manipulation in Virtual Environments

Manipulation of FOV is the most relevant intervention to our study. Several studies investigated the effects of manipulation of both the horizontal display field of view, defined as the angle that extends from the eye to the left and right edges of the display, and the horizontal geometric field of view, defined as the angle that extends from the virtual camera to the left and right edges of the viewpoint frustum [12, 17]. Many of these studies revealed positive effects of FOV manipulation on VR sickness [12, 24, 39, 45, 64] and presence [41, 45, 64]. Other studies, on the other hand, showed the negative effect of FOV manipulation on task performance on virtual environments [53, 56, 74] and the magnitude of such effect was shown to be more significant on women [17, 68].

3 USER STUDY

The goal of this study is to examine the effect of dynamic FOV restriction on sex differences in VR sickness and spatial navigation performance in the context of a triangle completion task.

Participants

We recruited 30 participants, two women of whom exited during the first session due to severe discomfort[1], leaving us with 28 participants (14 women) whose data is used in this study. Participants age ranged from 18 to 33 years (average = 23.04, SD = 3.59). Participants were recruited by flyers and word-of-mouth and they were affiliated with the local higher education institutions. 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 1. All participants were compensated with a $15 Amazon gift card. The user study was approved by an IRB.

	1	2	3	4	5	
Never	▢	▨	▨	■	■	*Very frequently*

How frequently do you use VR?

Women	43% (6)	36% (5)	14% (2)	7% (1)	0% (0)
Men	7% (1)	21% (3)	21% (3)	36% (5)	14% (2)
Total	25% (7)	29% (8)	18% (5)	21% (6)	7% (2)

How frequently do you get motion or VR sick?

Women	36% (5)	21% (3)	14% (2)	14% (2)	14% (2)
Men	43% (6)	43% (6)	7% (1)	7% (1)	0% (0)
Total	39% (11)	32% (9)	11% (3)	11% (3)	7% (2)

Table 1: 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).*

Experiment Design

Our study is a 2×2 mixed factorial design with sex as the between-subject factor and the FOV condition as the within-subject factor. The latter factor has two levels: no FOV restriction (RN) and dynamically changing FOV (RY). We inspect the effect of these factors on seven dependent variables: (1) the home position estimation error (HPE), (2) the Simulator Sickness Questionnaire [37] (SSQ) total severity score (TS), (3) the SSQ-Nausea score (N), (4) the SSQ-Oculomotor discomfort score (O), (5) the SSQ-Disorientation score (D), (6) the average discomfort score (ADS) [24], and (7) the ending discomfort score (EDS) [24]. To account for order effects, half of the participants started with the RN condition (Group A) while the remaining half started with the RY condition (Group B). 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.

FOV Test Conditions

In the RN condition, no FOV restriction was applied and participants were consequently exposed to the full visual field provided by the HMD's FOV. In the RY test condition, on the other hand, we followed the strategy of Bolas et al. [10] and Fernandes and Feiner [24] who proposed to manipulate

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[1] One of these women exited while experiencing the full FOV condition while the other was experiencing the dynamically changing FOV condition

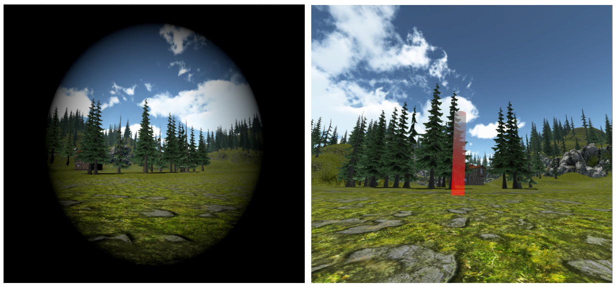

Figure 2: Left: the FOV restrictor we used in the RY condition at its maximum FOV restriction. Right: the waypoint used in the triangle completion task

the FOV as a function of the user's current state. We manipulated the FOV according to changes of the participant's linear and angular velocities [24]. In other words, the FOV was decreased as the participant's virtual speed (linear or angular) increases. To restrict the FOV, we used a black texture with a transparent circular cut-off, shown in Figure 2-left, whose radius ($FOV_{r,t}$) is controlled according to following equation[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. This is equivalent to a minimum FOV of 50° on the HTC Vive with a horizontal FOV of around 100°, which we empirically found close to the max FOV restriction applied by popular VR experiences such as Google Earth VR [5]. The value of v_{max} was set to 1.4 m/s, a value that matches the average preferred walking speed of humans [50]. 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 expected from our task. The FOV restriction was applied gradually over time and the edges of the circular cut-off were feathered as these factors were found to reduce participants' distraction [24].

Equipment

The artificial stimuli, both visual and aural, were delivered via the HTC Vive HMD with a diagonal FOV of 110°, refresh rate of 90Hz, a combined resolution of 2160×1200 pixels, six degrees of freedom (DoF) for position and orientation tracking, and adjustable interpupillary (IPD) and focal distances. The headset was powered with a 2.8GHz Intel Core i7 processor with 16GB of memory and NVIDIA GeForce GTX 1070 graphics card running Windows 10. 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 thumbstick used for navigation provides better tactile feedback than the Vive's touchpad. We used Unity3D engine and the SteamVR plugin to develop the artificial stimuli. We used the tunneling effect implementation of SixWays[3] to dynamically manipulate the FOV as per the specifications mentioned in Section 3. Participants' IPD was measured using the PD Meter app[4] that runs on Android.

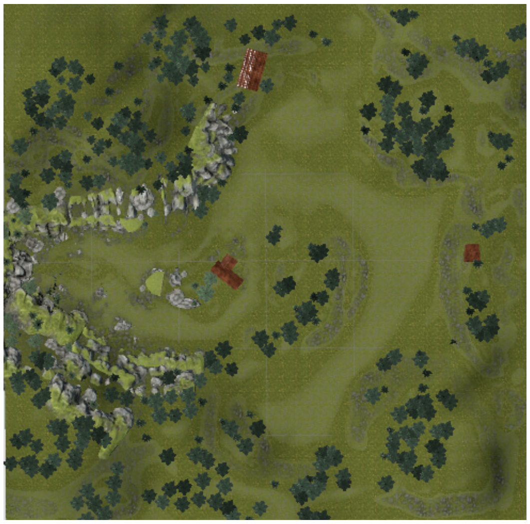

Figure 3: Top-down view of the virtual environment we used in the experiment sessions

Virtual Environment

For both experiment sessions, we adapted the Rocky Hills Environment - Light Pack asset[5] from the Unity Asset Store. We mapped the environment's measurement system from Unity units to Metric units such that three Unity units are equivalent to one meter. Such mapping was important for design decisions that involved knowledge about distance such as target travel distance for a given task and appropriate travel speed. The environment (Figure 3) is a 200m × 200m forest-like space that consists of trees, rocks and hills that can be used as subtle spatial cues. Three forest cabins were distributed over the hills of the environment to be used as salient landmarks during the task. Some parts of the terrain were made uneven in order to expose participants to optic

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[2] https://github.com/SixWays/UnityVrTunnelling

[3] https://github.com/SixWays/UnityVrTunnelling

[4] https://play.google.com/store/apps/details?id=techpositive.glassifyme&hl=en

[5] https://assetstore.unity.com/packages/3d/environments/landscapes/rocky-hills-environment-light-pack-89939

flow at the vertical axis. For the training session, we used the Mecanim Example Scene[6] from the Unity Asset Store. Five-meter high red posts (Figure 2-right) were used as waypoints, each representing a triangle vertex that participants navigate to, one after the other. Unity's UI panels, text, and sliders were used to communicate the task instructions and to collect the discomfort score from participants during trials. Participants used the controller's thumbstick to control the rate of travel at a speed that varied between 0 and 1.4 m/s. The same thumbstick was used for steering in a direction relative the head's forward vector.

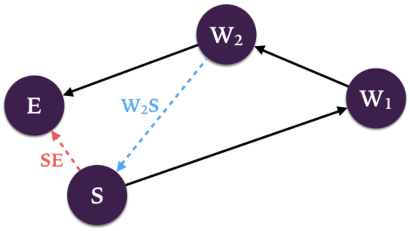

Figure 4: The triangle completion task we use in this study. S = starting position, E = estimated position, W_1 = first waypoint, W_2 = second waypoint, $\vec{W_2S}$ = the vector from the second waypoint to the starting position, and $\vec{SE}$ = the vector from the starting position to the estimated position

Task

Humans use several fundamental skills to achieve effective navigation such as spatial updating, spatial cognitive mapping, and constrained route planning [61]. In this study, we examine the effect of FOV restriction on participants' spatial updating abilities.

Spatial updating can be achieved through (1) path integration, where users update their current position based on an estimate of the direction and distance travelled obtained from visual, vestibular and proprioceptive senses [71]; and (2) landmark navigation, where users update their current position when a known landmark is identified [47]. Humans use the information collected from path integration and landmark navigation to form a survey representation that captures the distances and directions of the traversed trajectory to help them plan future navigation tasks [48]. To examine the quality of participants' survey knowledge, we used a "triangle completion" task that was described in early work on spatial navigation [48] and that has been used for assessing spatial navigation performance in VR [34]. This task required participants to travel from a starting position to two consecutive waypoints (Figure 4) shown one after the other, which are non collinear with the starting position and which form two adjacent legs of a triangle. After arriving at the second waypoint, participants were then asked to navigate back to the starting position and confirm their selection using the controller's (A) button. Being able to navigate back to each starting location relies on a combination of path integration and landmark based navigation. Participants' ability to navigate back to the starting position requires them to compute a new trajectory; an ability that is contingent on the quality of their survey representation [48]. As the focus of our study is to examine the effect FOV restriction (a visual manipulation intervention) on forming an effective survey representation, we aimed to limit the spatial updating cues to optical flow and minimize the interference from proprioceptive and vestibular cues. We achieved this by having participants navigate the virtual environment using joystick-control locomotion.

Similar to Loomis et al. [48], a total of 27 triangles were produced as a result of varying the distance of the first two triangle legs (A and B, respectively) and the turning angle α that corresponds to 180° minus the angle between the two legs. Leg A was one of three values (10, 15, or 20m) as well as Leg B (8, 12, 18m) and α (60, 90 or 120°). These distances and angles were selected such that the total exposure time after completing the 27 triangles is 25 minutes per session. To minimize learning effect, we varied the starting position of participants. The triangles were distributed over three selected zones and the starting vertex was varied across triangles that belong to the same zone. The order of the produced triangles was randomized to minimize the chance of having two consecutive triangles that have the same zone and starting vertex. Two sequences of triangles were produced for each experiment session.

Procedure

The experiment was conducted in a room that is free of noises and physical obstacles. Participants were greeted and seated to be given a short presentation at which the experimenter explained the goal the study, the sequence of the experiment, the risks involved, the collected data, and the details of the training and experiment sessions. Participants were then asked to fill the first SSQ [37] to provide a baseline input of their relevant symptoms. The participants' IPD was then measured and the measurement was used to set the IPD of the VR headset accordingly. If a participant's measured IPD was lower than the headset's minimum (60.8mm for the Vive), the headset's IPD was set to its minimum. Participants were then asked to stand at a marked position in the tracking space and were assisted to wear the VR headset and hold the controller so that they could start the training session. We chose to have participants standing in order to rotate with their body. Standing and rotating in place do generate some vestibular and proprioceptive cues. While the magnitude of these cues

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[6] https://assetstore.unity.com/packages/essentials/tutorial-projects/mecanim-example-scenes-5328

while standing and rotating in place is significantly lower than that of walking, these cues might interfere with the goal of our study that aims to limit spatial updating cues to optical flow. However, we made this choice since viewpoint rotation using a controller was found to cause unnecessary discomfort [24], aside from being uncommon to rotate with a controller in common VR experiences. The goal of the training session was to familiarize the participants with the controls needed to provide input and to give them an opportunity to practice the experiment task. To satisfy the former goal, participants were asked to move in each of the four directions (right, left, forward, and backward) one after the other and move the slider all the way to the right and then all the way to the left. They were then asked to complete three triangle completion tasks after which the training session concludes. To give participants a sense of their performance during the training session only, an arrow was shown at the actual starting position after they provided their estimation.

Participants then took part in two experiment sessions; one for each condition. Group A participants started with the RN condition while Group B participants started with the RY condition. In each session, participants performed a total of 27 trials, each involving one triangle completion task. After each trial, participants were prompted with a slider [24] to provide their level of discomfort from 1 to 10, with level 10 signifying the highest level of discomfort [59]. Similar to Fernandes and Feiner [24], participants were told that when a value of 10 is selected, the experiment will be terminated, but they were assured that they will be fully compensated anyway. Participants were encouraged to strike a balance between time and accuracy. After each session, participants were asked to fill a post-exposure SSQ. A mandatory ten-minute break was given to each participant after the first session.

Upon the completion of both sessions, participants were asked to fill a post-experiment questionnaire at which they provided their demographic information that included sex, age, frequency of exposure to VR (five-point Likert scale), and tendency of being motion and/or VR sick (five-point Likert scale). The total duration of the study took approximately one hour and a half.

Measurements

In order to calculate HPE, we use the following formula [34]:

$$HPE = \frac{|\vec{SE}|}{|\vec{W_2S}|} \tag{2}$$

where $|\vec{SE}|$ is the magnitude of a 2D vector whose initial and terminal points are the horizontal plane coordinates of the starting and estimated positions, respectively, and $|\vec{W_2S}|$ is the magnitude of a 2D vector whose initial and terminal points are horizontal plane coordinates of the second waypoint and the starting position, respectively (see Figure 4). We use the vector $|\vec{SE}|$ as it captures errors in both heading and distance while we use the vector $|\vec{W_2S}|$ to normalize the differences across triangle designs. We also collected the 2D trajectory at the horizontal plane produced by each triangle completion task for all participants for further analysis, if needed. We use the data collected from the SSQs along with the self-reported discomfort scores in order to measure VR sickness. Data collected from the SSQ is used to calculate four associated scores, namely: TS, O, and N, and D scores. These scores were calculated as per the conversion formulas by Kennedy et al. [37]. The calculated scores of the baseline SSQ were subtracted from those of the first post-exposure SSQ to obtain the latter's relative SSQ scores. Similarly, the calculated scores of the first post-exposure SSQ were subtracted from those of the second post-exposure SSQ to obtain the latter's relative SSQ scores. We averaged the discomfort scores for each participant per FOV condition to calculate ADS and we used the last discomfort score for each participant per FOV condition to calculate EDS.

4 RESULTS

Table 2 shows the mean and the standard deviation of the HPE, ADS, EDS, and SSQ results. We analyze the results in the remainder of this section.

Spatial Navigation Performance

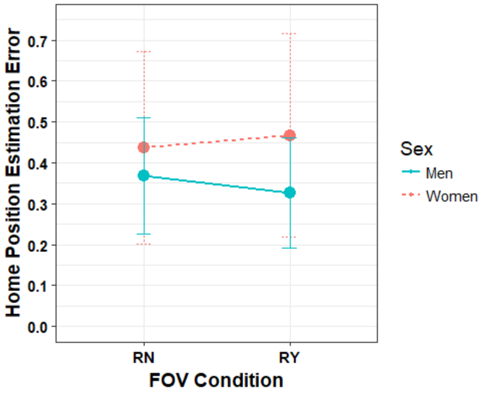

Figure 5: Spatial navigation performance measured in HPE. Results are aggregated per sex and FOV condition. RN = No FOV restriction; RY = Dynamically changing FOV. Error bars represent the standard deviation.

The HPE was used as a measure of spatial navigation performance of the 28 participants in this study. Figure 5 shows a summary of the results. A 2-way mixed-model ANOVA did not find an interaction between sex and FOV

Condition	No restrictor (RN)			FOV restrictor (RY)		
Sex	**Women**	**Men**	**Total**	**Women**	**Men**	**Total**
Spatial Navigation Performance						
HPE	0.44 (0.2)	0.37 (0.1)	0.40 (0.2)	0.47 (0.3)	0.33 (0.1)	0.40 (0.2)
Discomfort Scores						
ADS	1.93 (1.6)	1.36 (1.4)	1.64 (1.5)	1.11 (1.1)	0.85 (1.1)	0.98 (1.1)
EDS	3.07 (2.1)	2.64 (2.8)	2.86 (2.4)	2.36 (2.8)	1.29 (1.4)	1.82 (2.1)
Simulator Sickness Questionnaire (Relative)						
SSQ-TS	32.32 (32.9)	28.85 (29.6)	30.59 (30.7)	3.74 (39.2)	15.49 (27.1)	9.62 (33.6)
SSQ-D	31.82 (42.4)	37.78 (43.8)	34.80 (42.4)	8.94 (48.7)	12.92 (33.0)	10.94 (40.9)
SSQ-N	29.98 (38.3)	24.53 (24.5)	27.26 (31.7)	3.41 (40.2)	11.58 (28.3)	7.50 (34.4)
SSQ-O	24.36 (17.6)	18.41 (21.6)	21.39 (19.6)	0 (26.7)	15.16 (18.6)	7.58 (23.6)
Simulator Sickness Questionnaire (Absolute)						
SSQ-TS	52.89 (34.0)	49.69 (46.6)	51.29 (40.0)	41.14 (25.9)	29.92 (19.8)	35.53 (23.4)
SSQ-D	56.67 (38.8)	56.67 (58.4)	56.67 (48.7)	44.74 (29.5)	28.83 (27.6)	36.79 (29.2)
SSQ-N	42.25 (39.4)	42.25 (42.1)	42.25 (40.0)	34.75 (34.0)	26.58 (21.9)	30.66 (28.4)
SSQ-O	42.77 (23.9)	36.28 (33.1)	39.52 (28.5)	31.40 (15.1)	23.82 (16.8)	27.61 (16.1)

Table 2: Quantitative measures of the spatial navigation performance, discomfort scores, and relative Simulator Sickness Questionnaire in terms of *mean (standard deviation)*. For the sake of completeness, we also include the absolute Simulator Sickness Questionnaire results.

($F_{1,26} = 3.11, p = .09, \eta_p^2 = .11$). No significant effects of sex ($F_{1,26} = 2.13, p = .16, \eta_p^2 = .076$) or FOV ($F_{1,26} = 0.09, p = .77, \eta_p^2 = .004$) were found either. Spearman's rank correlation did not find a significant association between HPE and frequency of using VR ($r_s = -.20, p = .31$). The correlation between HPE and motion/VR sickness tendency, however, was significant ($r_s = .52$, $p < .05$), indicating a positive association between spatial error and motion/VR sickness history.

VR Sickness

VR sickness was measured in terms of the self-reported discomfort score, from which we measured ADS and EDS; and the SSQ questionnaire, from which we calculated the SSQ's TS, N, O and D scores. Using the EDS score, we found that 6 out of the 28 participants (4 men) were asymptomatic. Unlike other studies [24] that used the ADS as a criteria to determine which participants were asymptomatic, we use the EDS due to its significant positive correlation with the SSQ-TS results (EDS: $r_s = .52, p < .05$; ADS: $r_s = -.04, p = .77$) and because both EDS and SSQ results capture the participant's discomfort level at the end of a session. As visual acceleration can affect the incidence of VR sickness [42], we analyzed the amount of time at which participants were travelling at a fixed speed. Both men and women travelled at a fixed speed more than 87% of the time (women: 87.60%, men: 87.56%; $F_{1,22} = .001, p = .97, \eta_p^2 = 0$)[7]. We report the VR sickness results of our 28 participants as follows.

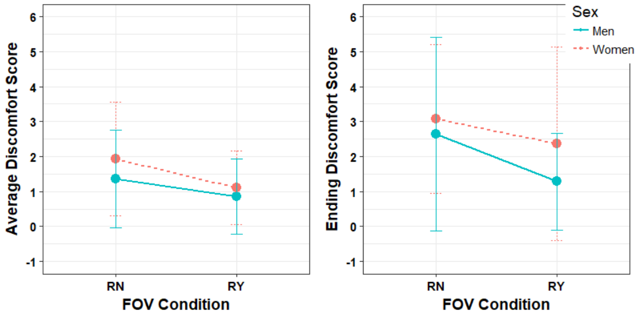

Figure 6: Average and ending levels of discomfort. Results are aggregated per sex and FOV condition. RN =No FOV restriction; RY = Dynamically changing FOV. Error bars represent the standard deviation.

Discomfort Score. A 2-way mixed-model ANOVA did not find an interaction effect between sex and FOV condition on both the ADS ($F_{1,26} = .5, p = .49, \eta_p^2 = .019$) and the EDS ($F_{1,26} = .70, p = .41, \eta_p^2 = .026$). While no significant difference between sexes was found with respect to both ADS ($F_{1,26} = .85, p = .37, \eta_p^2 = .032$) and EDS ($F_{1,26} = .90, p = .35, \eta_p^2 = .033$), FOV restriction resulted in significantly lower ADS ($F_{1,26} = 9.30, p < .05, \eta_p^2 = .26$) and EDS ($F_{1,26} = 7.23, p < .05, \eta_p^2 = .22$). Figure 6 summarizes the results of the average and ending discomfort scores. Spearman's rank correlation did not find a significant association between the reported frequency of using VR and neither ADS ($r_s = -.24, p = .22$) nor EDS ($r_s = -.25, p = .20$). Similarly, the reported tendency of motion/VR sickness was not found to be correlated with neither ADS ($r_s = .36, p = .061$) nor EDS ($r_s = .36, p = .059$).

Simulator Sickness Questionnaire Scores. A 2-way mixed-model ANOVA did not find an interaction effect between sex and FOV condition on all SSQ scores: TS ($F_{1,26} = .66, p =$

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[7] Due to a tracking error, we lost the speed data of the first 4 male participants, resulting in conducting this analysis using the speed data of the remaining 24 participants.

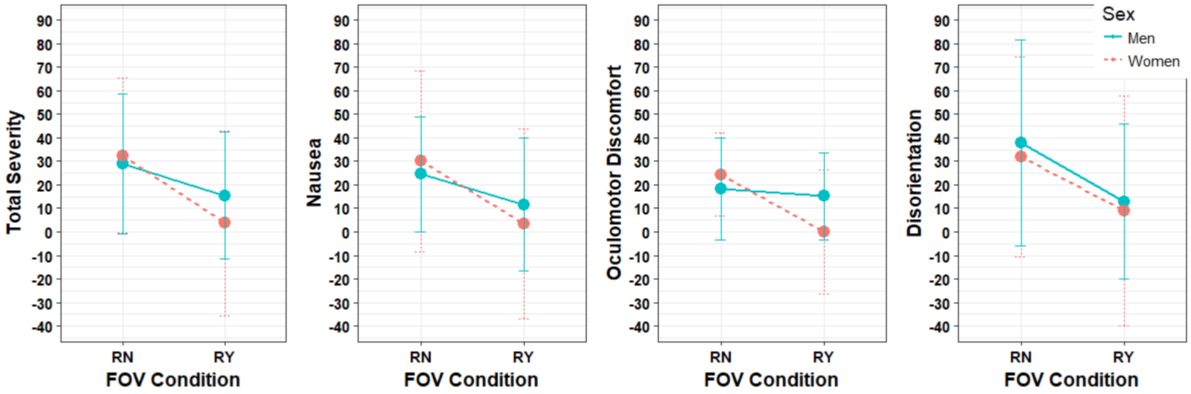

Figure 7: Relative Simulator Sickness Questionnaire results aggregated by sex and FOV condition. RN =No FOV restriction; RY = Dynamically changing FOV. Error bars represent the standard deviation.

$.42, \eta_p^2 = .025$), N ($F_{1,26} = .45, p = .51, \eta_p^2 = .017$), O ($F_{1,26} = 3.52, p = .072, \eta_p^2 = .12$), and D ($F_{1,26} = .006, p = .94, \eta_p^2 = 0$). No significant differences between men and women were found in any of the SSQ scores either: TS ($F_{1,26} = .27, p = .61, \eta_p^2 = .010$), N ($F_{1,26} = .032, p = .86, \eta_p^2 = .001$), O ($F_{1,26} = .64, p = .43, \eta_p^2 = .024$), and D ($F_{1,26} = .27, p = .61, \eta_p^2 = .010$). FOV restriction resulted in lower TS ($F_{1,26} = 5.04, p < .05, \eta_p^2 = .16$) and O ($F_{1,26} = 6.01, p < .05, \eta_p^2 = .19$) scores while no significance was found for the D ($F_{1,26} = 3.46, p = .074, \eta_p^2 = .12$) and N ($F_{1,26} = 3.80, p = .062, \eta_p^2 = .13$) scores. Spearman's rank correlation did not find a significant association between the reported frequency of using VR and any of the SSQ scores: TS ($r_s = -.26, p = .18$), N ($r_s = -.28$, $p = .15$), O ($r_s = -.23, p = .23$), D ($r_s = -.30, p = .12$). A significant positive correlation was found between the SSQ-TS score and the tendency of getting motion/VR sick ($r_s = .39, p < .05$) while no significant correlation between motion/VR sickness tendency and the rest of the SSQ scores was found: N ($r_s = .35, p = .066$), O ($r_s = .33, p = .081$), D ($r_s = .36, p = .060$). As shown in Figure 7, both sexes experienced an SSQ symptom profile [65, 66] of D > N > O in the RN condition. While women maintained the same profile in the RY condition, men's profile changed to O > D > N.

5 DISCUSSION AND FUTURE WORK

Unlike our expectation, no significant sex difference was found in spatial navigation performance, contradicting with previous studies that suggested otherwise [6, 8, 20, 62, 63]. The experimental conditions of these studies, however, were different, e.g., they used a virtual water maze task in desktop environments [8, 20, 63], a path following task in CAVE environment with children [6], or a search task with an HMD having 48° FOV [62]. Aside from using a different FOV that ranged between 50° to 100°, our study differs fundamentally from previous evaluations in terms of the target navigation skill. Our study aimed to focus on the evaluation of the spatial updating skill which relies on survey representation that is affected by both landmark-based navigation and path integration [48]. Since women heavily rely on landmarks for navigation while men navigate mostly using geometric information [63], we designed a virtual environment that contains both subtle and salient landmarks to give men and women a fair chance to form a quality survey representation. This might have resulted in finding no significant gender difference in spatial updating.

Regardless of sex, we did not find a significant effect of FOV restriction on spatial navigation performance. This is different from what was reported in earlier studies [53, 56, 74]. Some of these studies used desktop VR [53, 56]. To evaluate spatial navigation performance, some studies used a search task [53, 56] while others used an obstacle avoidance task [74]. This is different from our study at which we used an HMD and a triangle completion task. The restriction mechanism used in our study can be another contributing factor. Unlike previous studies that restricted FOV throughout the virtual experience, our restrictor only restricts FOV as a response to linear and angular speeds. This dynamic behavior of the restrictor might have given participants an opportunity to frequently gain a full view of the virtual environment while they were stationary, which might have caused them to perform efficiently in both FOV conditions.

Due to the physiology of women's eyes [7] along with their vision perception [28] as we explained earlier, we expected that FOV restriction would not be an effective intervention to reduce the VR sickness symptoms in women. However, FOV restriction was shown to be effective in mitigating VR sickness symptoms in both sexes as shown in the ADS, EDS, and SSQ results, agreeing with the results of previous studies [12, 24, 39, 45, 64]. Our analysis did not find a significant sex difference in any of the VR sickness measures. This seems surprising when compared with previous studies [51, 58, 65] that report on the higher susceptibility of women to VR sickness. This contradiction could be due to the nature of the virtual task, which was shown to have an effect on the incidence of VR sickness in general [49] and among sexes [51]. A recent study agrees with our findings [46]. Unlike our study, however, sex groups in the former study are unbalanced (64 men vs. 43 women).

Visual acceleration input from the virtual experience can increase sensory mismatch between the visual and vestibular systems, which might lead to a greater incidence of VR sickness [42]. Both men and women travelled at a fixed speed more than 87% of the time. This low acceleration/deceleration rates might have contributed to masking potential sex differences in VR sickness.

Overall, although the results of this study did not support our hypotheses, they suggest a valuable implication: that FOV restriction seems to be an effective intervention in reducing the incidence of VR sickness without having a negative effect on spatial navigation performance in both sexes. However, we would like to reiterate that our study only tested participants' spatial updating skills through a triangle completion task. Follow-up studies are indeed needed to test the effect of FOV restriction of other navigation skills such as spatial mapping and constrained route planning [48].

Six participants (21% of the total) were asymptomatic and only two of whom were women. Most of those asymptomatic participants reported very frequent use of VR, which could explain why they showed no symptoms [40, 66]. Considering that typically 5% to 10% of the participants in early VR studies are asymptomatic [66], having 21% of our participants reporting no VR sickness symptoms is relatively high. The use of a state-of-the-art HMD and having participants use body input to rotate in VR could be contributing factors to alleviating VR symptoms [43] and hence increasing the number of asymptomatic participants.

Our correlation analysis did not find a significant association between prior VR exposure and VR sickness symptoms. This contradicts with previous studies which showed a positive effect of prior experience with VR on the severity of VR sickness symptoms [32, 33]. This contradiction may stem from how we quantified prior VR exposure compared to previous studies. As the effect of prior VR exposure was not central to our study, we simply asked participants to rate their frequency of using VR on a 5-point Likert scale. This is different from previous studies that designed their experiments around a controlled exposure procedure. The use of a state-of-the-art HMD might also have made the need for prior VR exposure to reduce VR sickness symptoms [40] less relevant, which might have led to the lack of correlation between prior VR experience and reported levels of discomfort in our study.

A significant positive association between motion/VR sickness history and VR sickness total severity was the only significant correlation that our analysis could find among the VR sickness measures we used in this study. This finding generally agrees with the findings by Stanney et al. [65] that showed a significant correlation between VR sickness symptoms severity, measured with the SSQ, and VR sickness history, measured with the Motion History Questionnaire (MHQ) [36]. Unlike their study, however, we did not find a significant correlation between the SSQ sub-scales (i.e., N, O and D scores) and the motion/VR sickness history. This difference might be due to our use of a 5-point Likert scale to measure motion/VR sickness history, which is fundamentally different from the MHQ.

The SSQ symptom profile was D > N > O for both sexes when no restriction was applied to the FOV. This is the same profile reported for men in a previous study [65], but the same study reported that women had a profile of D > O > N. While women's profile was not affected by FOV restriction, it was interesting to observe the change of men's SSQ symptom profile to O > D > N when the FOV was restricted. The notable difference between the two profiles seems to be related to Oculomotor discomfort. The cause of having Oculomotor discomfort higher in men than the other two SSQ scores when FOV was restricted is unknown to us. One future venue to explore that might help providing more explanation to this finding is the relationship between the differences in the visual system among men and women [72] and dynamic field of view restriction in virtual environments.

An improperly calibrated IPD on an HMD may lead to eye strain which is a symptom of VR sickness that is measured by the SSQ's oculomotor discomfort score. The measured IPD of most women participants in our study was below the Vive's minimum supported IPD of 60.8mm. As a result, we had to set the IPD of the headset to a value slightly higher than theirs. However, even with an improperly calibrated IPD, we did not observe any significant difference across sexes in oculomotor discomfort, which was also the least observed score in women according to their SSQ symptom profile in both FOV conditions.

A few limitations may have affected the results of our study. We asked participants to perform the study tasks while standing up in order to control their virtual rotation using body input due to the reported adverse effects of virtual rotation using a controller [24]. Most of today's VR experiences expect users to be standing up, especially the experiences offered by platforms that allow users to alternate between natural walking and artificial locomotion. However, having participants standing up for typically 25 minutes per session may have interfered with their perception of what accounts for discomfort, which may resulted in reporting fatigue due to prolonged standing as discomfort. Participants experienced both conditions one after the other, separated by 10 minutes. This may have affected their spatial navigation performance and reported discomfort at the second session. We mitigated this using counterbalancing as explained earlier in Section 3.

For future work, we would like to compare the effect of different FOV manipulations (e.g., independent rest frames [57] and non-salient objects blurring [54]) on sex differences. We also plan to study the effect of FOV restriction on sex differences in the context of spatial navigation tasks that differ from the one we used in this study. We also consider conducting follow-up studies with HMDs that has FOV closer to that of humans such as the 210°-FOV StarVR[8].

6 CONCLUSION

In this study, we investigated the effect of dynamically manipulating the FOV as a function of linear and angular speed on sex differences with respect to VR sickness and spatial navigation performance using consumer VR HMDs. The results showed that FOV restriction is effective in mitigating VR sickness symptoms in both sexes. We did not find, however, a significant effect of FOV restriction on the spatial navigation performance in women as well as men. As the focus of this paper was to study spatial navigation performance from spatial updating perspective, follow-up studies are needed to assess the effect of FOV restriction on other navigation skills; an endeavor that we aim to pursue in the near future. The contributions of our paper provides insight into how to make VR more accessible to women.

7 ACKNOWLEDGEMENTS

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