Field-of-View Restriction to Reduce VR Sickness Does Not Impede Spatial Learning in Women

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Women are more likely to experience virtual reality (VR) sickness than men, which could pose a major challenge to the mass market success of VR. Because VR sickness often results from a visual-vestibular conflict, an effective strategy to mitigate conflict is to restrict the user's field-of-view (FOV) during locomotion. Sex differences in spatial cognition have been well researched, with several studies reporting that men exhibit better spatial navigation performance in desktop three-dimensional environments than women. However, additional research suggests that this sex difference can be mitigated by providing a larger FOV as this increases the availability of landmarks, which women tend to rely on more than men. Though FOV restriction is already a widely used strategy for VR headsets to minimize VR sickness, it is currently not well understood if it impedes spatial learning in women due to decreased availability of landmarks. Our study (n = 28, 14 men and 14 women) found that a dynamic FOV restrictor was equally effective in reducing VR sickness in both sexes, and no sex differences in VR sickness incidence were found. Our study did find a sex difference in spatial learning ability, but an FOV restrictor did not impede spatial learning in either sex.

CCS Concepts: • **Human-centered computing → Virtual reality**;

Additional Key Words and Phrases: Virtual reality, VR sickness, virtual locomotion, field-of-view manipulation

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1 INTRODUCTION

Virtual reality (VR) has enjoyed significant popularity in recent years and has finally emerged from research labs into consumer's hands. Though consumer VR headsets have significantly advanced in terms of tracking, latency, refresh rate, resolution, and optics, VR sickness is still considered a major barrier to the mass market success of VR. VR sickness is a type of motion sickness specific to the domain of VR [45] and may involve a suite of symptoms including nausea, pallor, sweating, stomach awareness, increased heart rate, drowsiness, disorientation, and general discomfort [34]. There is substantial evidence that women are more susceptible than

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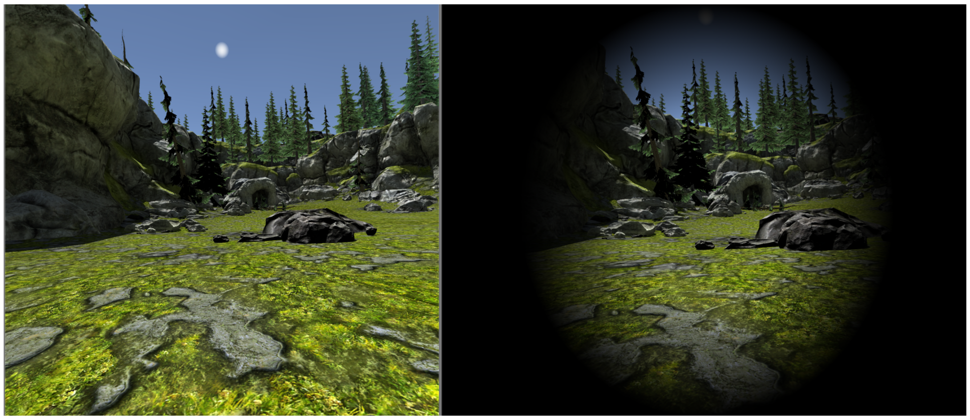

Fig. 1. Self-motion from optical flow is driven strongly by motion at the periphery of the retina. Blocking peripheral motion by reducing the field-of-view during locomotion (right image) mitigates sensitivity to visual-vestibular conflict and VR sickness.

men to sickness caused by simulators [24, 25, 28, 54] and virtual reality [49], which might have contributed to a low adoption rate (<5%) of VR technology among women [78].

A likely trigger of VR sickness is vection, i.e., the visually induced illusion of self-motion [37]. Self-motion perception combines visual, vestibular, and proprioceptive afferents, and these systems are usually in agreement. When using real walking using positional tracking, users generally experience no VR sickness as vestibular and proprioceptive signals are generated that match the presented optical flow [42]. However, when navigating VR using a game controller, the absence of any real physical movement in spite of visual self-motion leads to a sensory conflict [56], which can induce VR sickness [37].

Self-motion from optical flow is driven strongly by motion at the periphery of the retina [80]. An effective strategy for reducing VR sickness is to reduce the user's **field-of-view (FOV)** during locomotion (see Figure 1) as this reduces stimulation of the periphery by visual motion [41, 65]. However, related studies found that applying an FOV restrictor on desktop three-dimensional (3D) environments impedes spatial navigation performance [39, 50, 57], and this effect was significant for women [14].

Spatial learning is the process of encoding spatial information about an environment to enable efficient navigation and to develop a mental representation of this environment. Sex differences in spatial learning have been well documented [79]. Although the biological factors that cause this difference remain unclear, men and women employ different strategies in spatial learning, e.g., men rely primarily on geometric information (e.g., turns and distance travelled) while women rely primarily on landmarks (e.g., salient objects seen along the path travelled) [64, 82]. Though men exhibit better spatial learning performance on certain tasks [15, 17], on desktop 3D environments this sex difference can be mitigated by providing women with a larger FOV, which is thought to work by increasing their ability to use landmarks [14, 71].

Sex differences should be considered in the design of interactive systems [4]. FOV restriction is already a widely used strategy [53], but we currently do not know whether it impedes spatial learning in women. Changes in availability of spatial learning cues might have significant implications for the general accessibility of VR. Our article aims to provide insight into this complex relationship.

2 BACKGROUND

VR sickness (also known as cybersickness or simulator sickness) is a type of motion sickness that is specific to the domain of VR [45]. There are several theories that aim to explain VR sickness, but these theories are neither exclusive nor exhaustive [37, 60]. The sensory conflict theory [59] attributes VR sickness to a conflict among the visual, vestibular, and proprioceptive senses. The postural instability theory [61] links VR sickness to a disruption of postural stability caused by the motion patterns of the visual stimulus of the virtual experience [61]. 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 [19]. The poison theory suggests VR sickness symptoms like nausea and vomiting are due to an incorrect application of a survival mechanism that becomes active when the body is poisoned [75]. The sensory conflict theory, however, seems to be the most widely accepted theory [35, 38].

Among individual traits that have been shown to increase the vulnerability to VR sickness [26, 38, 40, 67], sex is commonly reported, with the observation that women are more susceptible to VR sickness than men [49, 59, 67, 77]. Hormonal differences [12], physiological differences [26], under-reporting of sickness symptoms by men [6], and differences in FOV [38, 40] have all been proposed as explanations of this sex disparity in the incidence of VR sickness.

An improperly calibrated **interpupillary distance (IPD)** on a VR headset could lead to eye strain, which is a symptom of VR sickness as measured by the widely used Simulation Sickness Questionnaire's oculomotor discomfort score [34]. U.S. women have an IPD range of [52–76 mm] [27] while popular VR headsets support a minimum IPD range of [58–60] mm. It has been shown that improperly calibrated IPDs could be a reason why women tend to become VR sick more than men [66].

Various methods have been proposed to reduce the incidence of VR sickness. Due to recent advances, tracking inaccuracy and rendering latency are no longer significant causes of VR sickness on consumer VR platforms—though these are still problematic on mobile VR platforms. Real walking using positional tracking generally does not cause VR sickness, but its use is bounded by available tracking space.

To travel larger distances, users must rely on **artificial locomotion technique (ALT)**. Examples include partial gait techniques like walking-in-place [74], arm-swinging [46], or gait negation techniques like omnidirectional treadmills [16] or low friction surfaces [70]. See Reference [2] for an extensive survey of ALTs. Teleportation is a widely used ALT that 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 [9] and spatial disorientation [5, 11, 32]. For multiplayer games, having avatars being discontinuously represented when they teleport is an issue as it makes it difficult to follow or chase other players [29].

VR sickness can also be reduced by drugs [40], but effectiveness is limited due to adverse side effects [26]. An alternative is to use behavioral interventions that either regulate the user's behavior (e.g., head movements or breathing) or manipulate the visual stimuli [35]. There is some evidence that balance training can prevent motion sickness symptoms [63]. Manipulation of the visual stimuli has been achieved by controlling the FOV [7, 8, 22, 36, 41], using independent backgrounds and rest frames [18, 58], dynamically controlling travel velocity [72], freezing the virtual viewpoint rotations [33], and blurring non-salient virtual objects [51].

The effect of FOV on participants' performance and quality of user experience in VR has been the focus of several studies. Reducing the FOV was shown as an effective intervention to reduce the incidence of VR sickness [8, 36, 41, 65]. Dynamic FOV restriction [22] applies an FOV restrictor as a function of the users linear and angular velocities [22], which allows users to experience the full FOV when there is no optical flow. Other studies showed that larger FOV can increase the sense of presence [39, 41, 65]. However, on desktop 3D environments, FOV restriction was shown to impede spatial learning performance [50, 57, 81] with a greater negative impact on women [14, 71]. Even though prior studies used desktop environments, their findings are highly 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°) [30].

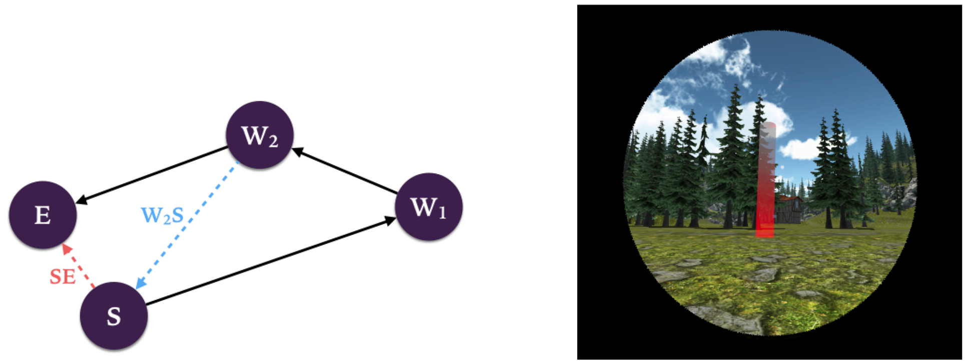

Fig. 2. Left: The triangle completion task. S = starting position, E = estimated position, W_1 = first waypoint, W_2 = second waypoint, $\vec{W_2S}$ = the vector from the second waypoint to the starting position, and $\vec{SE}$ = the vector from the starting position to the estimated position, which indicates the error of the path integration. Right: FOV restrictor showing the waypoint users must navigate to.

2.1 Prior Work

In closely related earlier work [1], we investigated whether dynamic FOV restriction affects path integration ability differently in women versus men. Path integration is one component of spatial navigation and refers to the process of integrating self-motion (using inertial/visual/auditory cues) over time to obtain an estimate of one's current position relative to a starting point [43]. Participants performed a triangle completion task [44], which is a standardized navigation task for assessing path integration ability. This task required participants to travel from a starting position to two consecutive waypoints (see Figure 2) 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 (S)** and **confirm their location (E)**. The distance between (S) and (E) is an indication of the path integration error. Similar to prior FOV studies [7, 8, 22, 36, 41], participants used a controller for navigation as this is most likely to induce VR sickness. We recruited 28 participants (14 females) in our study and found that a dynamic FOV restrictor was effective in reducing VR sickness in both sexes, as measured using the **simulator sickness questionnaire (SSQ)**. Contrary to our expectations, FOV restriction did not impede path integration ability in men or women.

2.2 Study Overview

A limitation of our earlier study was that path integration is considered to be only one component of spatial navigation, which also involves skills like spatial learning, spatial memory, and constrained route planning [62]. For spatial navigation, women reportedly rely more on landmarks to cognitively map spaces [64, 82]. Applying an FOV restrictor can block peripheral landmarks that might impede spatial learning to a larger extent than path integration ability. In this article, we specifically explore spatial learning and how it is affected by FOV restriction using a virtual **Morris Water Maze (MWM)** [3] given that no studies have investigated this yet.

3 METHODS

3.1 Participants

We recruited 31 participants, with normal or corrected to normal vision, but three women exited the study due to severe discomfort. This resulted in a final sample of 28 participants (14 women) who completed the study (minimum: 18, maximum: 42, mean age: 22.96, SD: 5.41) and whose data were considered in our analysis. We balanced the sex of participants to assess the role of sex in spatial learning and VR sickness incidence. We asked

	1	2	3	4	5	
Never						*Very frequently*

How frequently do you use VR?

	1	2	3	4	5
Women	35.7% (5)	42.8% (6)	14.3% (2)	7.2% (1)	0.0% (0)
Men	42.8% (6)	28.5% (4)	7.2% (1)	7.2% (1)	14.3% (2)
Total	39.3% (11)	35.6% (10)	10.7% (3)	7.1% (2)	7.1% (2)

How frequently do you get motion or VR sick?

	1	2	3	4	5
Women	50.0% (7)	21.4% (3)	7.2% (1)	21.4% (3)	0.0% (0)
Men	50.0% (7)	42.8% (6)	7.2% (1)	0.0% (0)	0.0% (0)
Total	50.0% (14)	32.1% (9)	7.2% (2)	10.7% (3)	0.0% (0)

Fig. 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)*.

participants to rate their frequency of using VR on a scale of 1 (rarely) to 5 (very frequently) as well as their frequency of getting motion or VR sick, and the results, broken down by sex, are listed in Figure 3. Participants were recruited at the University of Nevada through flyers and word of mouth. Each participant was given a $15 Amazon gift card as compensation for their participation. This study was approved by the University of Nevada's Institutional Review Board.

A power analysis, with power set at 0.8, α set at 0.05, and estimated effect size set at 0.28, indicated that 28 participants would be required to have adequate power. The effect size was estimated based on effect sizes found in other similar virtual reality studies and in our closely related previous work [1, 22]. Power analysis was performed with G*Power 3 [20].

3.2 Materials

3.2.1 Equipment. We used the HTC Vive as the VR headset in this study, which has a 110° diagonal FOV, 90-Hz refresh rate, 2,160×1,200 pixels of combined resolution, adjustable interpupillary distances, and six-degrees-of-freedom tracking for position and orientation, respectively. The headset was powered by a computer having a 3.4-GHz AMD Ryzen 7 eight-core processor with 16-GB memory and NVIDIA GeForce GTX 1080 Ti graphics card running Windows 10. We were able to achieve a frame rate close to 90 fps for our MWM simulation. An Xbox 360 controller was used for omni-directional locomotion using the left thumb-stick and for selection participants used the A button. This controller was more familiar to participants and more suitable for our study than the Vive track-pad as the thumb-stick offers better haptic feedback and granularity of control.

3.2.2 Tasks.

Virtual Morris Water Maze Task. First introduced by Richard Morris in 1981 [48], the MWM task has been one of the gold standards in behavioral neuroscience to evaluate spatial learning and memory in rodents [3]. Studies on human spatial learning and memory have used a virtual version of the MWM [3]. Briefly, the task tests the quality of the subject's spatial learning through their ability to remember the location of a hidden object in reference to distal cues that are not co-located with the hidden object [48]. This task can be used to investigate which mechanism is more dominant during spatial navigation, path integration or landmark based navigation [43]. Previous work has reported sex differences in performance of the MWM task with men relying more on path integration and women relying more on landmark-based navigation [64, 82]. We believe findings achieved using the MWM task generalize to navigating any virtual environment as this typically relies on a combination of path integration and landmark based navigation.

For locomotion input we used a controller, because previous studies that have evaluated the effectiveness of FOV restriction also used a controller and found this to induce VR sickness [8, 22, 36, 41, 65]. In each trial, participants started from a starting position at the edge of the pool while facing the wall (see Figure 3). Participants were then asked to move around in the pool to find a hidden platform under the water surface within 1 minute. The platform was found when participants crossed its location under the water surface. This was indicated to the participant using sound feedback and by the platform raising up, which elevated their viewpoint. If the platform was not found within 1 minute, then participants heard a different feedback sound and the platform was made visible. When that happened, participants were asked to move towards the platform until they reached it. Participants then continued on to the next trial after 5 s.

To assess spatial learning over time, participants were asked to locate the hidden platform over several trials grouped in blocks. Within a block of trials, the location of the platform was fixed but the starting point changed on each trial. In blocks that followed, the location of the platform, the sequence of starting positions, and the landmarks were changed. Participants went through 6 blocks of 6 trials each for every FOV condition. Starting positions were separated by 30° and a random sequence of starting positions was created for each block of trials.

Object Placement Task. For navigation, humans generally rely on a combination of two distinct strategies defined by the spatial memory process they rely on, e.g., allocentric and egocentric navigation [10]. Where egocentric navigation relies on learned associations between the observer and landmarks (self-referenced), allocentric navigation relies more on a cognitive map of the environment (world-referenced). Because our assumption is that an FOV restrictor may impede the observation of landmarks, this would primarily affect allocentric learning. To evaluate this, we used an additional task where we tested participants' ability to estimate the location of the platform using an object placement task. This task was modeled after the **relative vector discrimination (RVD)** task proposed by Starrett and Ekstrom [69]. Spatial memory is never purely egocentric or allocentric [21] and the RVD task was designed in such a way that the optimal solution relies on allocentric information. With the RVD task, after finding the platform, participants were presented with a bird's-eye view of the arena and had to place a platform in the remembered location.

3.2.3 Virtual Environment. We modeled our virtual MWM exactly after the one used in Reference [3]. The virtual environment consists of a 42-m-wide circular pool filled with opaque water below which is a hidden 2m × 2m × 2m cubic platform. When made visible, the platform is elevated 1 m above the water surface. The pool is positioned at the center of an open-roof 75-m-wide circular arena with a wall that is 8 m high. Placed on the wall of the arena are four 2D images distributed evenly. Each of these images act as a distal cue that participants can use to remember the position of the platform. Distances were mapped such that 1 Unity unit equals 1 m. Participants experienced the environment at a first-person-view and achieved navigation using the thumb-stick of the Xbox 360 controller at a speed that varied between 0 and 4.2 m/s. Omni-directional steering was achieved using the same thumb-stick at a direction relevant to the virtual viewpoint's forward vector. Participants always started the virtual experience from a point at the edge of the pool. To ensure that participants always stay in the pool, the water surface was made 1 m below the pool wall. We used Blender to design the virtual environment that was imported to Unity3D, the virtual world generator used to run the study. We used the FOV restrictor developed by SixWays [73] and configured it as explained in the previous section. Our implmentation of the virtual MWM and the FOV restrictor can be found on Github.[1] Figures 4 and 5 show third-person and first-person views of the virtual environment, respectively.

[1] https://github.com/isayasMatter/virtual-morris-water-maze.

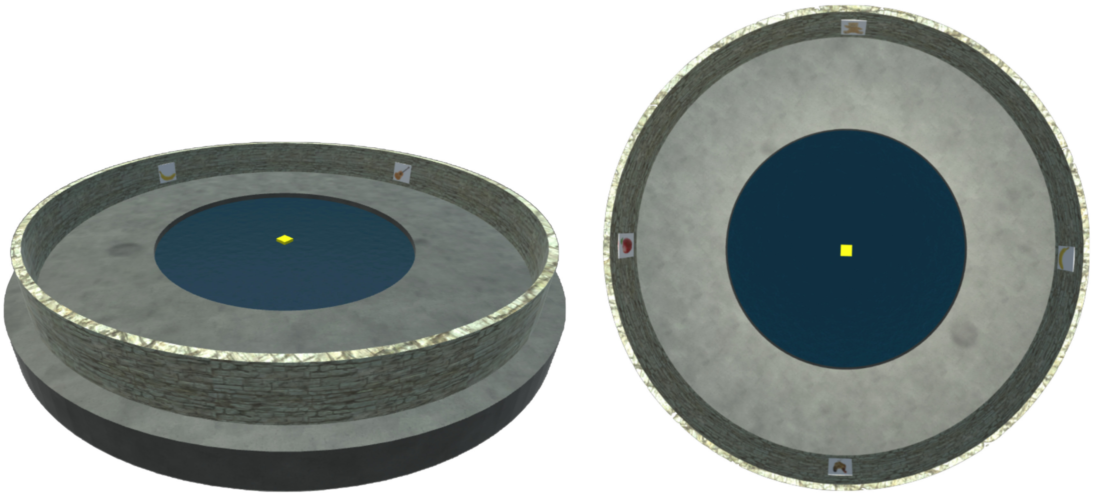

Fig. 4. Left: Depiction of the Virtual MWM we used in this study with one location of the platform location shown in yellow and landmarks on the walls. Right: Third-person view of the water maze used in the object placement task.

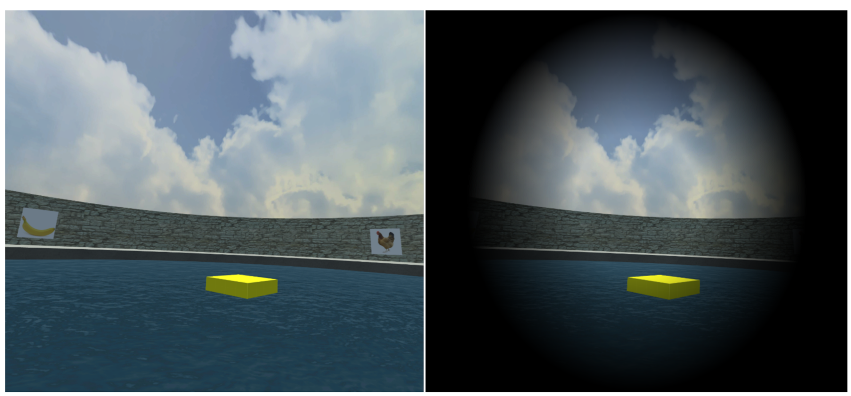

Fig. 5. Visual conditions used in the study. Left: Morris Water Maze with no restrictor. Right: Water maze shown using an FOV restrictor.

3.3 Design

We used a 2×2 mixed factorial design in which sex and FOV condition were the independent variables. Sex was the between-subjects variable with two levels: Men and Women. FOV condition, the within-subjects variable, also had two levels: no FOV restriction (RN) and dynamically changing FOV (RY). We use a dynamic FOV restriction [23] as unlike a static FOV restrictor this allows users to experience the full FOV while they are stationary. We considered eight dependent variables in this study. Four of these measured spatial learning: learning rate, distance traveled, placement error, and placement latency. The remaining four were the SSQ [34] scales: **Total Severity (TS)**, **Nausea (N)**, **Oculomotor Discomfort (O)**, and **Disorientation (D)**. Each participant experienced two sessions, one for each FOV condition. To minimize the transfer of VR sickness symptoms across sessions, each session was conducted on a separate day with at least 24 hours of rest between sessions. Most participants returned the next day but due to scheduling conflicts the maximum time one participant returned for the second session was 4 days.

Each session contained six blocks of trials with each block containing six platform search trials and one object placement task. The order of blocks was changed across sessions to minimize learning effects. Half of the participants started with the RN condition (Group A) while the other half started with the RY condition (Group B). We alternated the assignment of men and women to each group to ensure that both groups had an equal number of men and women.

Each participant experienced two FOV conditions in this study: the full FOV allowed by the VR headset (RN) and the dynamic FOV restriction (RY) (see Figure 5). Similarly to Fernandes and Feiner [22] and Bolas et al. [7], we dynamically manipulated the FOV as a function of the participant's linear and angular speeds using a black texture with a transparent circular cutoff (Figure 5). The restrictor narrowed down the FOV as a response to and increase in linear or angular movements by manipulating the radius of the circular cutoff according to the following formula [73]:

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

where $FOV_{r,t}$ and $FOV_{r,t-1}$ are the radii of the circular cutoff at times t and $t-1$, respectively. RF_{max} is the maximum restriction applied to $FOV_{r,t-1}$ at the peak linear or angular speeds. v_t and v_{max} are the current and maximum virtual linear speeds, respectively. ω_t and ω_{max} are the current and maximum virtual angular speeds, respectively. We empirically chose a value of 0.75 for RF_{max} to match the tunneling effect used in common VR experiences such as Google Earth VR. Through preliminary trials, we found the values 4.2 m/s and 180°/s suitable for v_{max} and ω_{max}, respectively. To make participants less distracted, the edges of the restrictor were feathered and FOV restriction was applied gradually over time.

3.4 Measurements

3.4.1 Virtual MWM Task. We measured participants' performance in the virtual MWM task in terms of learning rate and distance traveled. We quantify learning rate as the mean of slopes of the normalized search completion (t_n) times across blocks. For each search trial, we calculated t_n as follows:

$$t_n = \frac{t_c}{\vec{IP}}, \tag{2}$$

where t_c is the trial completion time and $\vec{IP}$ is the absolute distance between the starting position and the hidden platform position. We performed this normalization to factor out the time needed to travel directly to the platform from the search time. Because no place learning takes place during the first trial of a block, we excluded the first trial from the learning rate calculation. Because we are interested in the performance difference between the beginning and the end of a block, the slope was calculated from the second and last trials. A steep negative slope indicates learning. The distance traveled was measured as the mean distance traveled across all trials.

3.4.2 Object Placement Measures. We measured object placement performance in terms of placement error and placement time. The placement error was measured as the Euclidean distance between the estimated platform position and its actual position. The placement time was measured as the elapsed time from the start of the task until the participant presses the controller's A button.

3.4.3 Simulator Sickness Questionnaire Measures. We measured VR sickness symptoms through the SSQ and scored them according to the procedure prescribed by Kennedy and Lane [34] to obtain the weighted TS, N, D, and O scores.

3.5 Procedure

The study was conducted in a quiet space void of obstacles. On the first day, upon their arrival, participants were greeted and seated for an orientation at which participants were familiarized with the goal of the study,

Table 1. Quantitative Measures of Virtual MWM, Object Placement, and Simulator Sickness Questionnaire in Terms of *Mean (Standard Deviation)*

Condition	**No restrictor (RN)**			**FOV restrictor (RY)**		
Sex	**Women**	**Men**	**Total**	**Women**	**Men**	**Total**
Virtual MWM						
Learning rate	−.01 (.1)	−.03 (.1)	−.02 (.1)	−.01 (.1)	−.09 (.1)	−.05 (.1)
Distance	39.78 (8.0)	38.26 (8.6)	39.02 (8.2)	39.61 (6.2)	37.34 (8.4)	38.48 (7.4)
Object Placement						
Accuracy	3.04 (.9)	3.38 (1.4)	3.21 (1.2)	2.81 (1.0)	3.02 (1.3)	2.91 (1.2)
Time	8.84 (2.4)	10.53 (4.4)	9.69 (3.6)	9.36 (3.8)	10.92 (5.2)	10.14 (4.5)
Simulator Sickness Questionnaire						
SSQ Total Score	27.52 (27.9)	23.78 (28.7)	25.65 (27.6)	15.76 (18.2)	16.56 (17.8)	16.16 (17.6)
SSQ Disorientation	33.81 (41.1)	24.86 (37.9)	29.33 (39.1)	19.89 (27.14)	15.91 (26.1)	17.90 (26.2)
SSQ Nausea	25.21 (26.1)	22.49 (23.6)	23.85 (24.4)	12.95 (17.4)	14.31 (14.4)	13.63 (15.7)
SSQ Oculomotor	17.33 (18.7)	16.78 (22.7)	17.05 (20.4)	10.83 (11.4)	13.54 (16.3)	12.18 (13.9)

its duration, collected data, and tasks. The participants' IPD was then measured using a ruler and was used to calibrate the VR headset's IPD. We asked participants whether they could properly converge using this setting and if this was not the case, we let them adjust the IPD settings until they could. The IPD of the headset (HTC Vive) used in this study was limited to a value that varied between 60.9 and 75.4 mm. Accordingly, participants' measured IPD was rounded up or down to the limits of the headset's IPD when their IPD was outside the range of the headset's IPD. Participants were then asked to stand at the center of the tracking space to take part in the training session, whose goal was to familiarize participants with the controls, the virtual environment, and the tasks. The training session consisted of one block of three platform search trials followed by an object placement task. For training purposes, participants were informed that the platform shall be positioned at the center of the virtual pool for all three search trials. To familiarize participants with the unsuccessful search scenario, we asked participants not to move during the first training trial until the deadline has passed, which we set for 20 s only for the training session. While they were briefed about the platform search task, we pointed out to participants the location of the four landmarks that could be used to remember the location of the platform. Navigation generally relies on a combination of path integration and landmark navigation and we encouraged participants to use landmarks, since we anticipated this process to be affected by FOV restriction.

Participants were also encouraged to strike a balance between estimation time and accuracy while performing the placement task. Each participant performed six blocks, each consisting of six platform search trials and one placement task. Participants filled in a SSQ at the end of the session. On the second day, participants performed six experiment blocks, and then filled in another SSQ at the end of the trial. Participants then filled a post-study questionnaire at which they provided their age, sex, frequency of experiencing motion or VR sickness (five-point Likert scale), and their experience with VR (five-point Likert scale). On average, the duration of the study took approximately 1 hour divided between day one (≈40 minutes) and day two (≈20 minutes).

4 RESULTS

We report on the analysis of results of our 28 participants who fully completed our study. Table 1 gives a summary of the results in terms of means and standard deviations. For all our analyses, all our data were tested for normality using a Shapiro–Wilk test, and Levene's test for homogeneity of variances was used to test for homogeneity of variances amongst groups.

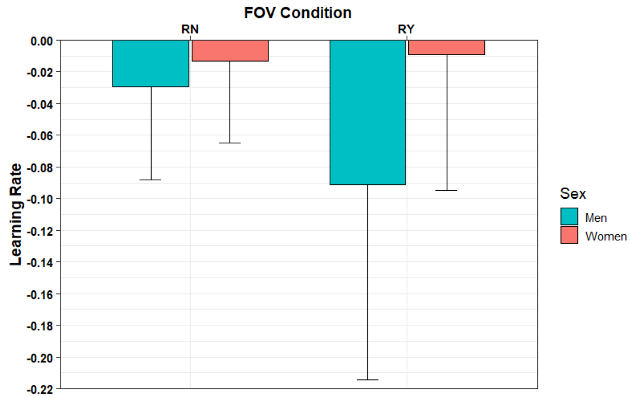

Fig. 6. Average learning rate shown in terms of the slope and summarized by sex and FOV condition. RN = No FOV restriction. RY = Dynamic FOV restriction. Error bars show standard deviation.

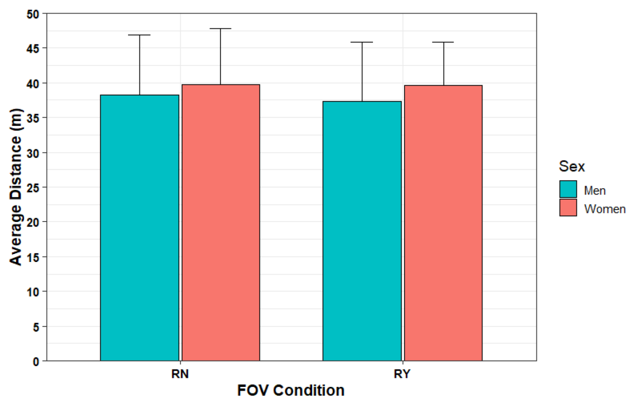

Fig. 7. Average distance traveled summarized by sex and FOV condition. RN = No FOV restriction. RY = Dynamic FOV restriction. Error bars show standard deviation.

4.1 Virtual Water Maze Task

Spatial performance in the virtual MWM task was measured in terms of learning rate and distance traveled. Figures 6 and 7 summarize the results. There was homogeneity of variances in our MWM task data, as assessed by Levene's test of homogeneity of variance ($p > .05$).

A two-way mixed ANOVA did not detect a significant interaction between sex and FOV condition ($F_{1,26} = 2.41, p = .13, \eta_p^2 = .085$) with respect to *learning rate*. No significant difference was found between FOV conditions ($F_{1,26} = 1.86, p = .19, \eta_p^2 = .067$) while women had significantly slower learning rate than men ($F_{1,26} = 4.21, p = .050, \eta_p^2 = .139$). This p-value was exactly 0.050 (truncated out to three decimal places) and is therefore considered significant given that p is significant for $p \leq \alpha$ [31].

A two-way mixed ANOVA did not find a significant interaction between sex and FOV condition ($F_{1,26} = .05, p = .83, \eta_p^2 = .002$) with respect to *distance traveled*. No significant main effect of sex ($F_{1,26} = .6, p = .45, \eta_p^2 = .023$) or FOV condition ($F_{1,26} = .10, p = .75, \eta_p^2 = .004$) was detected either.

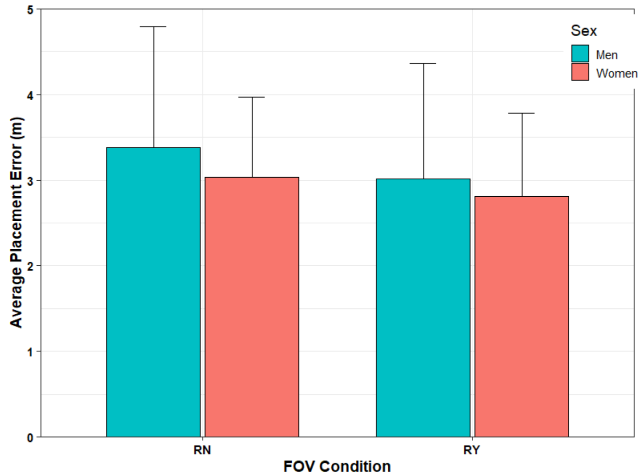

Fig. 8. Object placement accuracy in terms of placement error and summarized by sex and FOV condition. RN = No FOV restriction. RY = Dynamic FOV restriction. Error bars show standard deviation.

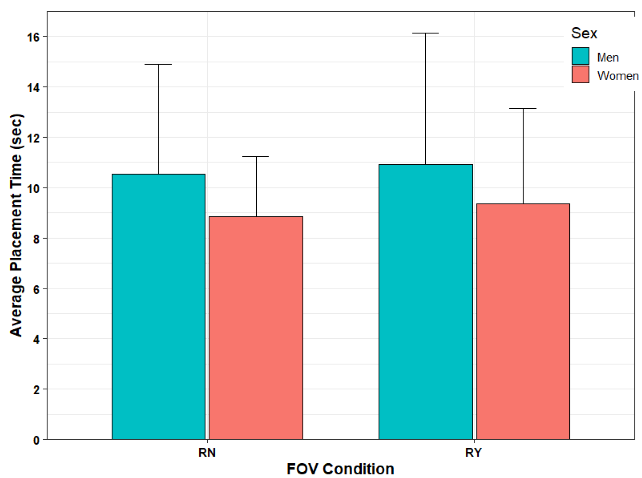

Fig. 9. Object placement time summarized by sex and FOV condition. RN = No FOV restriction. RY = Dynamic FOV restriction. Error bars show standard deviation.

4.2 Object Placement Task

We measured performance in the object placement task in terms of their estimation accuracy of the platform location and time delay to provide the estimation. Figures 8 and 9 summarize the results. A Levene's test of homogeneity of variance showed that there was homogeneity of variances ($p > .05$) across groups in our placement task data.

A two-way mixed ANOVA did not find a significant interaction effect between sex and FOV condition ($F_{1,26} = .13, p = .72, \eta_p^2 = .005$) with respect to *placement accuracy*. No significant effect of sex ($F_{1,26} = .47, p = .50, \eta_p^2 = .018$) or FOV condition ($F_{1,26} = 2.28, p = .14, \eta_p^2 = .081$) was found, either.

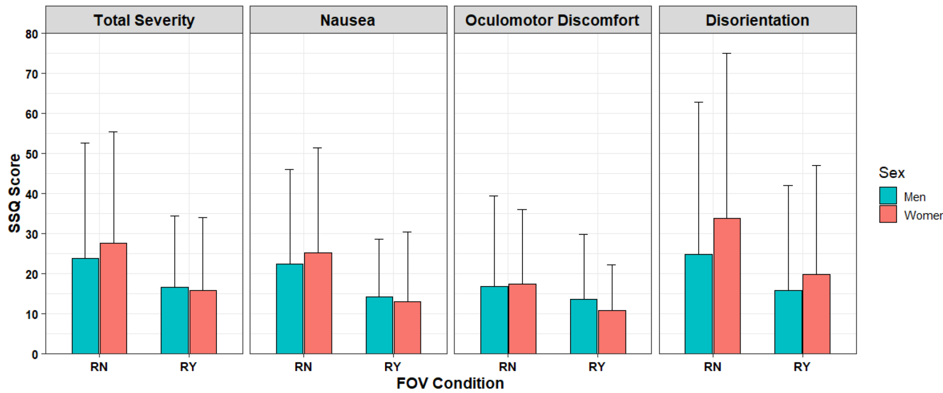

Fig. 10. The weighted total severity, nausea, oculomotor discomfort, and disorientation SSQ scores summarized by sex and FOV condition. RN = No FOV restriction. RY = Dynamic FOV restriction. Error bars show standard deviation.

A two-way mixed ANOVA did not find a significant interaction effect between sex or FOV condition ($F_{1,26} = .01, p = .92, \eta_p^2 = .000$) with respect to *placement time*. No significant effect of sex ($F_{1,26} = 1.33, p = .26, \eta_p^2 = .049$) or FOV condition ($F_{1,26} = .54, p = .47, \eta_p^2 = .020$) was found, either.

4.3 Simulator Sickness Questionnaire

Levene's test was conducted to assess the equality of variances in our SSQ data, and the test showed that there was homogeneity of variances ($p > .05$) across the groups. A two-way mixed ANOVA did not find an interaction effect between sex and FOV condition with respect to the TS ($F_{1,26} = .32, p = .58, \eta_p^2 = .012$), N ($F_{1,26} = .33, p = .57, \eta_p^2 = .013$), O ($F_{1,26} = .175, p = .68, \eta_p^2 = .007$), and D ($F_{1,26} = .213, p = .649, \eta_p^2 = .008$) scores. No significant main effect of sex was found on the TS ($F_{1,26} = .03, p = .86, \eta_p^2 = .001$), N ($F_{1,26} = .01, p = .92, \eta_p^2 = .000$), O ($F_{1,26} = .031, p = .86, \eta_p^2 = .001$), and D ($F_{1,26} = .31, p = .58, \eta_p^2 = .012$) scores. FOV restriction resulted in significantly lower TS ($F_{1,26} = 8.30, p = .008, \eta_p^2 = .242$), N ($F_{1,26} = 8.31, p = .008, \eta_p^2 = .242$), O ($F_{1,26} = 6.30, p = .019, \eta_p^2 = .195$) and D ($F_{1,26} = 4.50, p = .044, \eta_p^2 = .147$) scores. Figure 10 shows a summary of the results.

Seven participants (all women) had IPDs less than 60.9 mm, which is the minimum IPD of the VR headset we used in this study. We analysed the IPD results to check if improper IPD calibration due to the headset limitation could have led to eye strain that would, in turn, lead to oculomotor discomfort. We did not find, however, a significant difference between the Oculomotor Discomfort scores of the seven women in question and the rest of the participants ($t_{27} = -1.94, p = .062$).

5 DISCUSSION

5.1 Spatial Learning

Similarly to previous studies [3, 55] that explored sex differences using a virtual MWM task, our study found a significant sex difference in spatial learning, with women showing a significantly lower learning rate. This is quantified in terms of improvement in place learning over time, given fixed distal landmarks.

Also similar to these previous studies [3, 55], we did not observe any significant differences between men and women in the object placement task (i.e., spatial memory retrieval). Previous research suggests that having participants experience the object placement task from a third-person view makes performance depend more on allocentric information (e.g., landmarks) than the virtual MWM task [69]. The narrower sex difference in performance of the object placement task could be a consequence of women using landmark-based navigation more often than men do [64]. Participants took part in the object placement task after several repetitions of the virtual MWM task. This might have given participants enough time to learn the position of the platform by the time they started the object placement task, which might be another reason why no sex difference was found in the object placement task. This is in line with a previous study that suggests that environment familiarity through repetition can lead to reduced observations of sex differences in spatial abilities [52].

Our findings are important, because unlike earlier virtual MWM studies [3, 55] that used desktop 3D environments, our study used a VR headset, which offers a different spatial information fidelity profile than desktop VR [69]. Thus, our findings are applicable to today's consumer VR platforms.

5.2 FOV Restriction

Our analysis did not find a significant effect of FOV restriction on spatial learning. On the surface, this seems to contradict previous studies on desktop platforms that showed that restricting FOV impedes spatial navigation performance of both sexes in general [39, 50, 57] and of women in particular [14, 71]. There are, however, key differences in our study that might explain why we obtained different results. We used a VR headset that has an FOV of 110°. Participants in previous studies, however, experienced VR using a desktop monitor with significantly lower FOV. Moreover, the FOV was fixed throughout the experiment session in earlier studies. The restrictor that we used, however, only gets narrowed as a response to participants' linear or angular head movement, giving participants an opportunity to experience the full FOV provided by the headset while their head is stationary. However, when looking around to find the next waypoint, an FOV restrictor is applied based on angular head velocity. Our study investigated dynamic FOV restriction in comparison to the baseline condition of no FOV restriction, we believe future research should compare fixed vs. dynamic FOV restriction.

These two differences in the degree of FOV and the behavior of the FOV restrictor might have given both men and women a fair chance in performing equally across FOV conditions in our study.

5.3 VR Sickness

The use of a dynamic FOV restrictor was effective in reducing VR sickness for both sexes while it did not impede spatial learning. However, unlike previous studies [24, 25, 28, 49, 54, 67], we did not find a significantly greater report of VR sickness in women compared to men based on any of the SSQ scores. Besides issues regarding experimental conditions and hardware a possible reason for this could be due to the nature of the navigation task used in our study. Generally, VR experiences with involuntary movements are more likely to induce VR sickness than VR experiences where the user controls their movements [47, 68], though a recent study using a driving simulators found a contradictory result [76]. In our study, participants were standing up and could rotate their view with their head, which minimizes visual-vestibular conflict. Earlier studies that found sex differences used involuntary movements (i.e., roller coaster) or used fixed head positions with the viewpoint updated by a controller that could have exacerbated VR sickness incidence. An implication of this decision is providing participants with limited proprioceptive and vestibular input that might have reduced the magnitude of sensory conflict, which might have led to low VR sickness scores across sexes.

Of the 31 participants we recruited for this study, 3 participants exited due to severe discomfort on the first session. Two of these participants experienced VR with a full FOV, while the third experienced it with the FOV dynamically restricted. It is interesting to note that all of those who exited were women with very limited experience using VR. Two of these participants also reported having frequent occurrences of motion or VR sickness. Since frequent exposure to VR can reduce the symptoms of VR sickness and past experience with VR sickness [38, 67] can influence the incidence of VR sickness, these two factors might at least partially explain why these participants exited the study. Although our choice of number of participants matches previous similar studies [22], most of the effect sizes revealed a medium to large effect size [13]. A larger number of participants could increase the effect size and make our results and findings more certain. Therefore, as future work, we plan to expand the study by recruiting more participants.

Our results indicate that an FOV restrictor used with high-end consumer VR headsets seems to be effective for both sexes in reducing VR sickness without impeding spatial learning. Our results complement earlier findings on this relationship [1], but this prior study only evaluated path integration ability. Combining results from both studies provides strong evidence that FOV restrictors can be safely used to minimize VR sickness with no adverse side effects on spatial navigation performance.

6 CONCLUSION

FOV restriction is a widely used technique in VR to reduce visual-vestibular conflict and resulting VR sickness. However, prior studies on desktop environments suggest FOV restriction could have an adverse effect on spatial navigation and learning, especially in women. Using a virtual MWM, we studied the impact of dynamic FOV restriction on sex differences in spatial learning and VR sickness. Our results confirmed the existence of a sex difference in spatial learning. Nevertheless, our results suggest that FOV restriction is an effective solution to mitigate VR sickness in both sexes, and it does not impede spatial learning above and beyond pre-existing sex differences in spatial learning ability. We consider these outcomes to be valuable to VR interaction designers who aim to make their virtual experiences inclusive for women.

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