Estimation of Rotation Gain Thresholds Considering FOV, Gender, and Distractors

Niall L. Williams, Tabitha C. Peck, *Member, IEEE*

Fig. 1: Screen shot of the virtual forest scene with a distractor moving across the user's field of view (left) and a participant wearing the headset (right).

Abstract—Redirected walking techniques enable users to naturally locomote in virtual environments (VEs) that are larger than the tracked space. Redirected walking imperceptibly transforms the VE around the user with predefined estimated threshold gains. Previously estimated gains were evaluated with a 40° field of view (FOV), and have not been evaluated in the presence of a distractor—a moving object in the VE that may capture the user's attention. We conducted a 2 (FOV: 40°, 110°) × 2 (Gender: female, male) × 2 (Distractor: without, with) user study to estimate and compare thresholds for rotation gains. Significant differences in detection thresholds were found between FOVs, and significant differences were found between female and male gains with a 110° FOV. Males had significantly wider gains using a 110° FOV compared to a 40° FOV, and distractors affected females differently than males. Finally, strong correlations were found between simulator sickness scores and threshold gains.

Index Terms—Virtual reality, Locomotion, Perception, Detection thresholds, Distractors, Gender differences, Simulator sickness.

1 Introduction

Travel is essential for exploring virtual environments (VEs). Thus, it is important to provide virtual reality (VR) users with intuitive, easy-to-understand locomotion interfaces to enable natural and usable VE experiences. Locomotion in VR has been supported in numerous ways, including joystick controls, omnidirectional treadmills [23], and powered shoes [24]. However, these techniques are undesirable for immersive VEs because they often involve unwieldy hardware or lack vestibular or proprioceptive feedback. It has been shown that natural walking is the most intuitive and beneficial locomotion technique in VR, as it improves users' sense of presence [59], memory, and performance [20, 45, 49].

One common locomotion technique that enables natural walking in VR is *redirected walking* (RDW) [47]. RDW involves imperceptibly manipulating the VE via rotations and translations so that a user subconsciously adjusts his or her real-world position to remain on the intended virtual path. Using RDW, we can steer users away from the edges of the tracked space while still giving them the benefits of real walking in the VE. This reduces the frequency of breaks in presence that occur when a user reaches the bounds of the tracked space which creates a more enjoyable and effective experience for the user.

RDW relies on estimated threshold gains, which define how much the VE can be transformed without users noticing. Previous work by Steinicke et al. [54] estimated thresholds for rotation, translation, and curvature gains; however, that study was conducted on VR hardware with a 40° field of view (FOV), which is no longer representative of modern VR systems.

Many RDW implementations have focused on imperceptibility, however current research is focusing on the usability of RDW [48]. Indeed, employing inclusive design practices is crucial to creating technology that is safe and practical for all users [11]. Take for example the design history of airbags. Initially, airbags were only designed with adult male passengers in mind which lead to fatal consequences for women and children [39].

When considering usability, factors including user gender, susceptibility to simulator sickness, and gaming frequency could influence not only imperceptible threshold gains, but also usable threshold gains that do not induce simulator sickness. Aside from individual differences, threshold gains may be influenced by characteristics of the VR system including HMD FOV and tracking latency. Improving our understanding of additional factors that influence threshold gains will enable customizable redirection gains according to the user and the VR system. Gains that are more suited for a particular user will increase the effectiveness and usability of RDW.

1.1 Redirection Techniques

Among the different locomotion interfaces developed for VR, interfaces that utilize redirection techniques show the most promise for providing a natural and intuitive experience. Redirection techniques allow users to

- *Niall L. Williams is with Davidson College. E-mail: niallw@cs.umd.edu.*
- *Tabitha C. Peck is with Davidson College. E-mail: tapeck@davidson.edu.*

explore VEs that are larger than the tracked workspace by manipulating the user's path in the virtual environment [35]. A multitude of redirection techniques have been developed [6, 22, 47, 57]. These techniques tend to be favored over other locomotion interfaces because they enable natural walking in the tracked workspace and require minimal training to be used effectively.

Suma et al. distinguished between redirection techniques based on the conspicuousness (overt or subtle) and continuity (discrete or continuous) of their implementations [56]. Subtle and continuous techniques are preferred because they have been reported to create fewer breaks in presence. However, depending on the user's projected path and position in the workspace, we cannot always rely on such techniques to keep users in the tracked workspace. In these situations redirection systems may sometimes be required to fall back on more overt techniques [35, 56].

One popular subtle and continuous redirection technique is redirected walking, which was first demonstrated by Razzaque et al. [47]. RDW relies on the fact that when they conflict, visual information often dominates over vestibular and proprioceptive information [2]. Thus, when users enter a VE, they rely primarily on the visual scene presented on the display to guide their movements and actions, rather than rely on their proprioceptive sense of position within the physical workspace. Subtly changing the mapping between a user's movements and their virtual agent causes the user to subconsciously alter their movements to align with the visual scene. For example, if there is no redirection applied, when a user wants to turn 180° in the VE he or she will physically rotate 180°. If redirection is applied such that some real-world rotation results in a larger rotation in the VE, the user will turn until his or her position in the VE has rotated 180°, but the physical rotation will be less than 180°. The same logic applies for real-world rotations that correspond to smaller rotations in the VE. When implemented properly, this discrepancy between the physical and virtual movements is imperceptible to the user.

Distractors—objects or sounds (or a combination of both) in the VE that aim to capture the user's focus to allow larger redirection amounts to be applied without the user noticing—are an overt redirection technique [43]. The effect of distractors on users' navigational ability and awareness of RDW has been studied [10, 44, 45]. Results from these studies indicate that, in general, redirection using distractors is effective and users perform tasks at least no worse than when redirected by RDW without distractors.

1.2 Detection Threshold Estimation

By applying RDW, users are able to walk naturally and explore VEs larger than the tracked workspace. However, we cannot simply amplify users' movements by a large, constant factor to maximize the size of the explorable VE without incurring negative repercussions such as disorientation or increased simulator sickness. The scaling of a user's movements must be small enough to maintain the VR application's usability and ensure the user's comfort. Thus, there exists a trade-off between redirection intensity and user experience [47]. Ideally, enough redirection is applied to maximize the explorable size of the VE and minimize discomfort and breaks in presence caused by manipulating the VE.

1.2.1 Terminology

The intensity of scaling applied to the VE is controlled by parameters called *gains*. Rotation gains increase or decrease a user's rotation in the VE relative to his or her real-world rotation, while translation gains increase or decrease a user's displacement in the VE relative to his or her real-world displacement. Both rotation and translation gains are expressed as a ratio of virtual motion to physical motion. A gain of 1 is applied when virtual motion to physical motion is mapped 1:1. Curvature gains, on the other hand, cause users to walk along a curved physical path while walking on a straight virtual path.

A *threshold* refers to the point at which the applied gain becomes noticeable to the user, and each threshold has an associated gain. In previous work by Steinicke et al. the threshold values of interest are users' 25% and 75% thresholds, which correspond to *decreased* and *increased* virtual rotations respectively [54]. When a gain is greater than 1, the virtual rotation is increased, and the resulting real-world rotation is smaller than the virtual rotation. Similarly, when a gain is less than 1, the virtual rotation is decreased, and the resulting real-world rotation is larger than the virtual rotation.

VE rotation is often discussed in relation to the user's physical rotation. VE rotation *with* the user's physical rotation direction corresponds to a real-world rotation that is larger than the virtual rotation, and VE rotation *against* the user's physical rotation direction corresponds to a real-world rotation that is smaller than the virtual rotation.

1.2.2 Rotation Gain Thresholds

Many studies have estimated threshold gains in VR [5, 8, 16, 25, 26, 36, 40, 55]. The most comprehensive study was conducted by Steinicke et al. [54], which estimated threshold gains for rotation, translation, and curvature gains. Since the present study only focuses on rotation gains, we will limit the discussion to previous work related to estimated rotation gains. See Langbehn et al. for a full review of redirection thresholds [31].

As defined by Steinicke et al. [54] a rotation gain $g_R = \frac{R_{virtual}}{R_{real}}$ such that $R_{virtual}$ is the virtual world rotation and R_{real} is the real world rotation. Steinicke et al. reported 25% and 75% rotation threshold gains at 0.67 and 1.24 respectively [54]. Since then, others have replicated or conducted studies similar to [54] and reported different gains. Bruder et al. [5] reported very similar gains at 0.68 and 1.26, meanwhile Paludan et al. [40] reported gains at 0.93 and 1.27. Nilsson et al. [36] estimated threshold gains to be at 0.77 and 1.1. Additionally, Jerald et al. [26], who studied perceptual thresholds during head rotations, reported that scenes can be rotated up to 11.2% with the direction of the user's rotation and 5.2% against the direction of the user's rotation (threshold gains estimated in [54] correspond to 49% rotation with and 20% against the user's rotation direction).

Rotation threshold gains have also been studied in different experimental conditions, again yielding different values. In addition to replicating [54], Nilsson et al. [36] studied threshold gains in the presence of static and moving audio and found values at 0.8 - 1.11 and 0.79 - 1.08 respectively. In work by Bruder et al. [5], threshold gains were evaluated for users traveling in electric wheelchairs. The gains in that study were reported at 0.77 and 1.26. Serafin et al. [51] conducted a study that evaluated threshold gains using only auditory stimuli, and reported values at 0.82 and 1.2.

Peck et al. [43] demonstrated that rotation gains can be increased while users are distracted, but we are currently unaware of any studies that formally estimate threshold gains with distractors.

1.3 Perception and Simulator Sickness

Understanding how perception influences people's interactions with their environment gives us a better understanding of how users interact with redirection techniques. Optical flow refers to the pattern of perceived motion of the surrounding environment that is projected onto the human observer's retina. Optical flow patterns serve as a visual signal of self-motion for the human observer. Numerous studies have shown that optical flow influences the observer's locomotion control depending on the speed and direction of optical flow [1, 42, 64]. Other signals for self-motion include vestibular and proprioceptive information about the observer's body. Optical flow patterns become more important than other signals for controlling the observer's locomotion and interpreting the moving surroundings when the perceived visual stimulus does not match the observer's actual body motion, as is the case when RDW is applied [32].

Vection is the illusory feeling of self-movement provided by visual stimulation. It is typically felt when the observer visually perceives a moving environment, but his or her body moves in a manner that would not produce the perceived optical flow patterns. It is known that peripheral stimulation plays an important role in perceiving optical flow patterns [42]. Thus, one can infer that peripheral stimulation plays an important role in the degree of vection felt in the observer. In fact, many studies have demonstrated that optical flow perceived in the periphery increases feelings of vection [4, 21, 65]. However, it should be noted that there is evidence of feelings of vection when foveal, and not peripheral, stimulation is present [63].

Simulator sickness is commonly experienced when vection is experienced. It is also common for users to experience simulator sickness when using VR applications. Simulator sickness decreases the usability of VR and can potentially deter people from wanting to experience VR more than once. The exact cause of simulator sickness is not known, but the main theory argues that conflict between visual, proprioceptive, and vestibular stimuli is the source of simulator sickness [30]. Hettinger et al. [18] strengthened this theory when they provided data suggesting that simulator sickness is a product of vection.

It has been noted that FOV influences simulator sickness–specifically, decreasing FOV can decrease simulator sickness [13, 33]. A recent study by Fernandes et al. [14] further explored how FOV influences simulator sickness. In their study, they dynamically changed the FOV in VR using what they refer to as FOV restrictors. They concluded that changing the FOV based on visually perceived motion makes users feel more comfortable during their VR experiences [14].

It is important that we consider gender differences in visual perception. Halpern [17] highlighted gender comparative studies that show that compared to females, males generally have better dynamic visual acuity under the age of 40. Halpern also noted that, compared to females, males tend to perform better in spatiotemporal tasks involving judgments about and responses to moving visual displays [17]. A 5-year study by Burg [9] collected data on 17,479 people (62.8% male) and found that females have a slightly wider field of view. Furthermore, it has also been noted that, in general, females are more susceptible to motion sickness than males [28]. A study by Stanney et al. [53] found that females reported higher sickness scores, but it could not be determined if this was due to anatomical or hormonal differences. The authors of that study noted that females tend to report simulator sickness symptoms more readily than males, which may contribute to the higher intensity of simulator sickness seen in females. Gender role expectations, such as males not wanting to appear weak, may also explain the differences in simulator sickness scores between genders [67].

Few studies specifically look at interactions between RDW and gender. A study by Bruder et al. [7] investigated threshold gain differences between genders with a 40° FOV but did not find statistically significant differences. Hildebrandt et al. [19] studied human factors that influence simulator sickness after exposure to RDW applications. The results from that study support the claim that females are more susceptible to simulator sickness when experiencing RDW. The authors of that study concluded that human factors such as gender should be accounted for when implementing RDW. They also showed that users tolerated more simulator sickness if the VR application was exciting or practical.

2 Methods

2.1 Equipment

We used an HTC Vive Pro virtual reality headset with 6DOF position and orientation tracking in a $5m \times 4.2m$ tracking space. The system had about 110° diagonal FOV, a 90Hz refresh rate, and a 1440×1600 resolution per eye. The experiments were run on the Unity 2018.1.6f1 engine (with the SteamVR library) on a computer with an Intel i7-7820X processor (3.6 GHz), 32GB RAM, and NVIDIA GeForce GTX 1080 Ti GPU running on Windows 10 Pro edition. The experiments ran at 90 frames per second.

2.2 Experiment Design

We limited our study to rotation gains since these gains enable larger redirection amounts compared to translation and curvature gains [54]. Our experiment tested the following hypotheses:

H1 Participant discrimination between rotation gains is different in a 110° FOV compared to a 40° FOV.

H2 Participant discrimination between rotation gains is different for females compared to males.

H3 Participant discrimination between rotation gains is different when distractors are present compared to when they are not present.

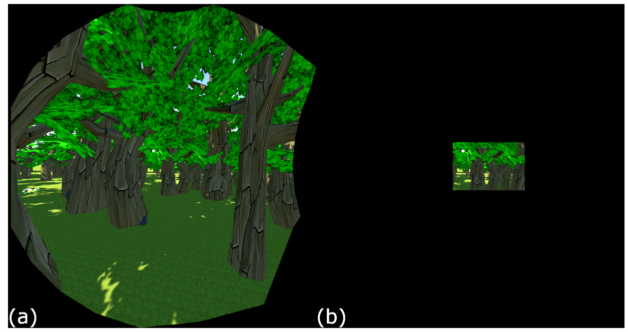

Fig. 2: (a) View of the VE in the left eye with no FOV modification (110°). (b) View of the VE in the left eye with a 40° FOV restrictor.

Fig. 3: Sample view of the scene and the corridor of trees during a trial.

We conducted a 2 (FOV: 40°, 110°) × 2 (Gender: female, male) × 2 (Distractor: without, with) user study with FOV and Distractor as within-participant variables, and Gender as a between-participant variable. Blocks were counterbalanced by FOV. We used the Vive Pro default diagonal FOV of 110° for the 110° block, and implemented an FOV restrictor similar to Fernandes et al. [14] to create the 40° FOV viewport used in the 40° FOV block. To more closely replicate Steinicke et al. [54], our FOV restrictor had a rectangular, hard-edge border instead of the circular, soft-edge border used by Fernandes et al. [14]. A comparison of the FOVs is shown in Fig. 2.

Each block consisted of 144 trials with the same FOV. Within each block, half of the trials (randomly distributed) featured a distractor to estimate threshold gains with a distractor present. Each trial had one of three distractor conditions: no distractor present (replication of [54]), distractor present and moves in the same direction that the user turns, or distractor present and moves in the opposite direction that the user turns. We chose a deer as the distractor because it was tall enough to be easily visible to the user, is an animal that appears in forests, and was not threatening and therefore was not likely to frighten the user. The distractor can be seen in Fig. 1. The deer moved along a 180° arc around the participant at a speed of about 6.2 m/s. The radius of the arc it traveled along was about 7.52m from the user.

In each FOV block, each gain was tested 8 times without distractors and 8 times with distractors. For the 8 trials with distractors, 4 distractors moved with the user, and 4 moved against the user. Excluding practice trials, this totaled 2 FOVs × 2 Distractors × 9 gains × 8 times totaling 288 trials per participant. The trial order per block was randomized for each participant.

The gains we applied ranged from 0.6 (150° physical rotation resulted in a 90° virtual rotation) to 1.4 (64.3° physical rotation resulted in a 90° virtual rotation), incremented in steps of 0.1. The VE rotated based on participant movement about their yaw axis. Note that, unlike Steinicke et al. [54], we did not test gains of 0.5 and 1.5. These gains were removed based on the gains reported in Steinicke et al. [54] and to keep the experiment duration within 2 hours. The original experiment by Steinicke et al. [54] tested all three gains, rotation, curvature, and

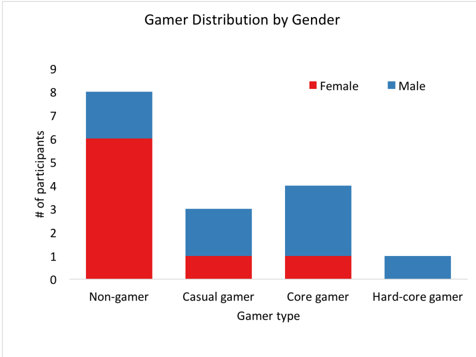

Fig. 4: The gamer-type distribution by gender for the experiment participants. Female participants are in red, and males are in blue.

translation in one three-hour experiment.

The task trials were a constant stimuli two-alternative forced choice (2AFC) task. As explained in [54], 2AFC tasks avoid participant response bias as participants are forced to guess even when they are unsure of VE rotation magnitude. On average, when participants do not know the answer, they will be correct 50% of the time. Each participant took about 2 hours to complete the entire experiment, including preliminaries, debriefing, trials, breaks, and questionnaires.

2.3 Virtual Environment

The virtual scene was designed to emulate optic flow conditions for both indoor and outdoor environments. The experiment scene was a virtual outdoor forest with trees, flowers and rocks and participants were able to see the horizon through the trees. The user was positioned in a corridor-like clearing in the forest where trees were positioned such that the corridor was at least 1 meter wide. The corridor width was chosen to emulate average hallway width [38,61]. Ambient background sounds were played through user worn headphones to mask real world sounds that could provide positional cues to the user. See Fig. 1 and Fig. 3.

The virtual environment used in this experiment was cartoon-like as opposed to photorealistic. Experiments studying the effects of VE realism on presence have shown that the level of realism does not significantly effect a user's feeling of presence [60, 68]. Furthermore, our VE featured dynamic shadows which have been shown to play an important role in creating a feeling of presence [52]. Our environment also had objects with textures that were sufficient to create adequate optical flow as the user turned, which is known to be important for evaluating feelings of self-motion [1, 32, 42, 64].

2.4 Participants

All participants were at least 18 years of age, had normal or corrected to normal vision, and were not knowingly pregnant. Additionally, all participants had normal or corrected to normal hearing and had no history of epilepsy, seizures, or strong susceptibility to motion sickness. Participants were proficient in written and spoken English.

Participants included students, faculty, and staff of Davidson College. Nineteen people participated in the experiment. Two participants were not naive to the purpose of the study including one of the authors. One participant's session was terminated early due to technical difficulties. An additional two participants' data were discarded as the participants appeared to have misunderstood the experiment task including one participant who replied "greater" to all but one trial.

Sixteen participants, age 19 - 48 (8 female ($M = 22$, $SD = 5$) and 8 male ($M = 26$, $SD = 11$)) successfully completed the experiment. One participant chose not to disclose his age. The HMD was adjusted to each participant's interpupillary distance (IPD), except for six participants (4 female) whose IPD was below the minimum setting of the HMD. In these cases, the HMD was set to the minimum IPD of $61.3mm$, and participants did not report display blurriness when asked.

Three participants had multiple VR experiences before, nine had briefly experienced VR before, and four had never experienced VR before. Five users self-reported themselves as either core or hard-core gamers (high experience), and eleven reported themselves as non or causal gamers (low experience). See Fig. 4.

2.5 Procedure

Upon arriving at the lab participants completed a participant eligibility checklist and consent form. Participants were offered compensation in the form of a $10 gift card. The experiment and procedure were approved by Davidson College's Human Subjects Institutional Review Board. Each participant's IPD was measured and the HMD was adjusted to match the measurement as closely as possible. Participants were briefed on the experiment task and were asked to repeat the task procedure to ensure comprehension.

Participants started in either the 40° or 110° FOV block with each block consisting of 144 trials. A trial consisted of rotating the whole body in place, not just the head, in the direction of an arrow at the center of the participant's vision. To encourage participants to focus on the VE, the direction arrow disappeared after the user began turning in the correct direction. The VE rotation was 90°, randomly ordered with half clockwise and half counter-clockwise rotations.

Participants rotated until a blue dot appeared at the center of their vision, signaling that they should maintain their position until they heard a bell sound indicating successful trial completion. If the participant rotated past the 90° virtual rotation, the blue dot's color changed to red and participants had to correct and maintain their orientation such that the dot changed to blue again. This orientation maintenance requirement was implemented to prohibit rapid turning and overshooting the 90° virtual rotation and to encourage participants to turn slowly enough to avoid overshooting the target orientation. At the beginning of each block participants completed three practice trials with a random gain applied (the same gain for all three practice trials) to familiarize themselves with the task and environment. The FOV during the practice trials was the same as the FOV for the current block. Users had an opportunity after the practice trials to ask questions or adjust the HMD if needed. Response accuracy feedback was not given on any trial.

Once a trial was completed, the HMD display faded to black and post-trial questions were displayed. Participants answered questions with the Vive Pro controller by using the left and right directions on the trackpad to select an answer from options displayed below the question. Answers were submitted using the controller's trigger button. Participants were first asked the same question as that used in [54]: "Was the virtual movement *smaller* or *greater* than the physical movement?" (smaller, greater). Participants were also asked, regardless of distractor presence,"Did you see an animal in the scene?" (yes, no) to determine if participants saw the distractor.

Before the next trial began, participants were reoriented to the starting orientation of their most recently completed trial. This was done to prevent participants from getting tangled in the HMD cable. To accomplish this reorientation, participants rotated in the direction indicated by an arrow on a black screen until a red dot at the center of their vision turned blue. Like the trials, participants had to maintain their orientation when the dot turned blue to proceed to the next trial.

As the experiment progressed participants slowly strayed away from their physical starting position. After finishing a trial, if a participant had strayed too close to the edges of the tracking space the experiment was paused and the experimenter guided the participant back to the center of the tracking area. This repositioning prevented the HTC Vive chaperone system from appearing in the VE, and the HMD wire from becoming taut. One participant mentioned feeling the taut wire during a portion of the experiment. Eight participants were repositioned at least once in their experiment session. Of those who were repositioned, they were repositioned on average 1.72 times, and no participant was repositioned more than 3 times per block.

Participants were allowed to take a break after any trial. If the user wanted a break, they communicated this verbally with the experimenter and the break started after completing the reorientation process. Nine participants took at least one break during their session. Three of these

ID	No Distractors 40° PSE	No Distractors 110° PSE	Distractors 40° PSE	Distractors 110° PSE
1	1.0071	1.0453	1.1315	1.0215
2	0.5560	-	-	-0.6501
3	0.9818	1.0375	1.1315	1.1893
4	1.0237	1.2419	1.0143	1.3850
5	-	0.4711	-	0.7330
7	0.9393	-	0.3522	-0.0458
8	0.9508	0.7485	1.0117	0.5300
11	0.7961	0.9586	0.7152	0.3361
12	-	1.3403	-	1.6478
13	0.8911	1.3779	1.0652	1.6428
14	0.7762	1.0947	0.7175	0.9403
15	1.0859	1.2343	1.1324	1.2473
16	1.0105	0.9526	1.0041	1.1778
17	0.5642	-	0.5390	-
18	0.9873	1.2513	0.9034	0.8571
19	1.0236	0.9807	1.0037	0.9494
μ	.8995	1.0565	.9015	.8641

Table 1: The PSE of the psychometric curve fit to each participant's $\Psi(g_i; greater)$. The - indicates participant data that was unable to be fit to a psychometric curve and was excluded from analysis.

participants took two breaks. All breaks lasted no more than 2 minutes, except for two breaks (for two different participants) which lasted about 7.5 minutes each.

After completing all trials for the first FOV block, all participants completed the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [29] and had a mandatory break of at least five minutes. After completing the second FOV block, another SSQ was completed, as well as a questionnaire about their demographics (age, gender, colorblind status, amount of experience playing video games, and amount of previous exposure to VR). Participants did not complete an SSQ before the experiment began. At the end of the experiment, participants filled out a demographics questionnaire including age, gender, colorblind status, and VR and video game experience.

3 Results

The probability, $\Psi(g_i; greater)$, of responding "*greater*" at gain g_i to the question, "Was the virtual movement *smaller* or *greater* than the physical movement?" was calculated for each participant, for each gain both with and without distractors. No significant effect of clockwise verses counter-clockwise rotations was found, and the rotation direction data were pooled for analysis. Additionally, we found no significant effect of distractor direction (with or against user rotation direction) and combined the with and against distractor directions for the analysis. Using maximum likelihood estimation, a psychometric curve, calculated with a cumulative normal distribution function, was fit to each participant's data and the point of subjective equality (PSE), σ, 25% and 75% threshold gains, and deviance were calculated. See Fig. 5.

The psychometric function in Equation 1 was fit to our data using the Quickpsy package in R. $\Psi(g_i;\theta)$ is the probability of responding "*greater*" when presented with the gain g_i. The vector $\theta = (\mu, \sigma, \gamma, \lambda)$, where μ and σ are the mean and standard deviation of the fitted function, and γ and λ represent the left and right asymptotes of Ψ. F is the cumulative normal distribution function, and the gain, $g = 1$ implies that virtual rotation is neither increased nor decreased.

$$\Psi(g_i;\theta) = \Psi(g_i;\mu,\sigma,\gamma,\lambda) = \gamma + (1-\gamma-\lambda)F(g_i;\mu,\sigma) \quad (1)$$

For each experimental condition, participants with data who were unable to be fit to a psychometric curve with a PSE centered within ± 100 from 1, or with a probability of fit less-than .05 were considered to have a bad fit and were removed from the analysis. See Table 1 for each participant's PSE and removed data.

To determine if our data replicated the results presented in Steinicke et al. [54], an estimated Bayes factor was calculated comparing the

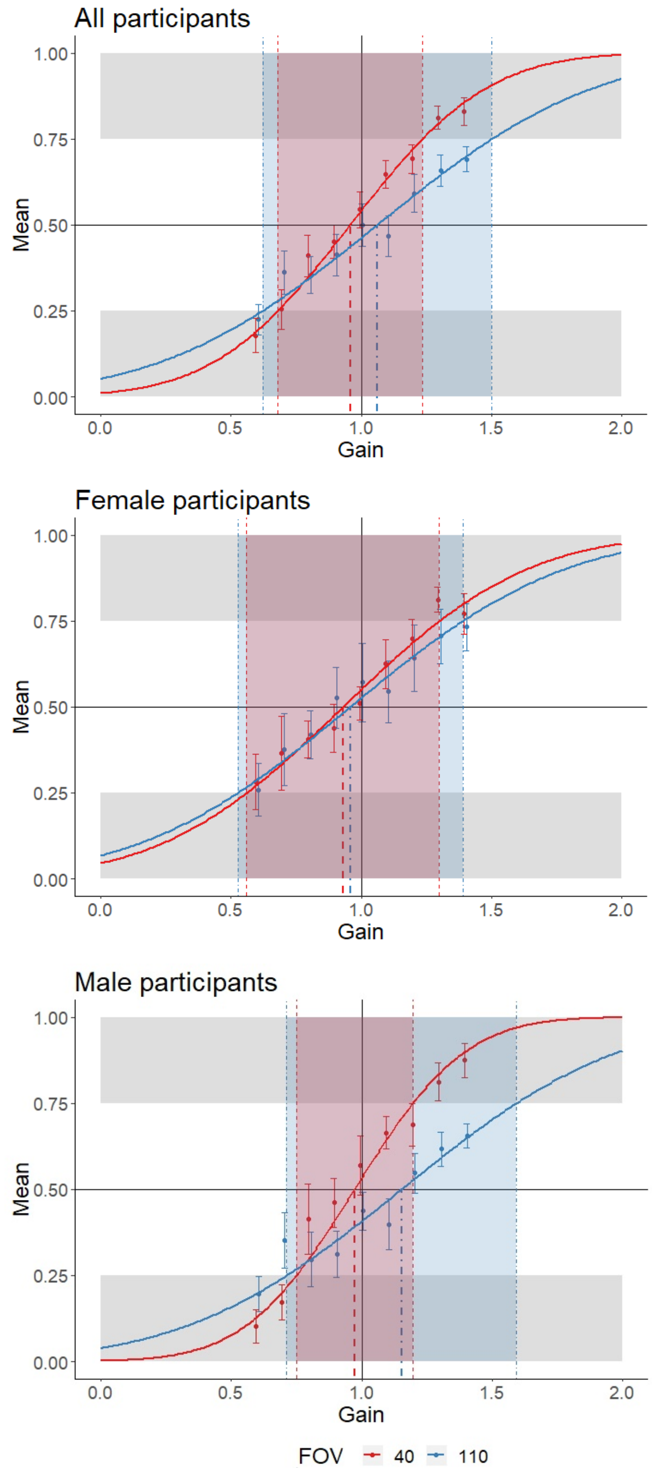

Fig. 5: The average probability of responding *"greater"* to the question, "Was the virtual movement *smaller* or *greater* than the physical movement?", with standard error, for each rotation gain, and the fitted psychometric curve. Responses for 40° FOV are in red, and 110° FOV are in blue. The vertical edges of the red and blue regions indicate the 25% (left edge) and 75% (right edge) thresholds. In each condition, gains that fall inside the colored regions are undetectable to users. (Top) Perceptual thresholds for all participants, (Middle) perceptual thresholds for female participants, (Bottom) perceptual thresholds for male participants.

PSEs from our experiment (40° FOV, without distractors condition) to the PSEs presented in Steinicke et al. [54]. We used Bayesian Information Criteria to compare the fit of the data under the null hypothesis—that there is no statistical significance between the two experiments, to the fit of the data under the alternative hypothesis—that there is a statistical significance between the two experiments [62]. The estimated Bayes factor=0.76. The data was only 1.31 times more likely to occur in our experiment than in the experiment from Steinicke et al. [54]. That is, there is weak evidence in support of the alternative hypothesis [46]. This supports that our data successfully replicated previous work. Additionally, using maximum likelihood estimation, a psychometric curve was fit to the pooled results of our participant $\Psi(g_i; greater)$ data, ($\mu = .95$, $\sigma = .40$, deviance= 4.70, $p = .89$) and the gains at the 25%, PSE, and 75% thresholds were calculated. See Table 2. All calculated gains were within .03 of the original gains calculated in Steinicke et al. [54].

Psychometric curves were also fit to the pooled results of participant $\Psi(g_i; greater)$ data by gender, (Female: $\mu = .9286$, $\sigma = .5253$, deviance= 7.3365, $p = .85$), (Male: $\mu = .9586$, $\sigma = .3267$, deviance= 8.2436, $p = .75$), and the gains at the 25%, PSE, and 75% thresholds were calculated. Comparison of gains at the 25%, PSE, and 75% detection thresholds to the gains presented by Bruder et al. [7] evaluating gender reveal that our gains are similar and within .02 at the 75% threshold and within .09 at the 25% threshold. Individual participant data was not provided in [7], and additional analysis could not be performed.

3.1 Analysis of response probability

To test our hypotheses (See Sect. 2.2) we compared the raw $\Psi(g_i; greater)$ data, the probability of responding "*greater*" at gain g_i, with a 2 (distractors: present, not present) x 9 (gain: 0.6:1.4:0.1) × 2 (FOV: 40°, 110°) × 2 (gender: female, male) ANOVA with distractor, gain, and FOV as within-participant variables and gender as a between participant variable. Mauchly's test indicated that the assumptions of sphericity had not been violated. See Fig. 5.

There was a significant main effect of gain, $F(8,72) = 46.98$, $p < .0001$, $\eta^2 = .52$. There was also a significant gender × FOV interaction, $F(1,9) = 8.97$, $p = .02$, $\eta^2 = .06$, and a gain × FOV interaction, $F(8,72) = 2.62$, $p = .01$, $\eta^2 = .01$. Finally, there was a significant 3-way gender × gain × FOV interaction, $F(8,72) = 2.96$, $p = .0064$, $\eta^2 = .05$, and a trending 3-way gender × gain × distractor interaction, $F(8,72) = 2.00$, $p = .0581$, $\eta^2 = .02$. The gender × gain × FOV interaction indicates that the 2-way gain × FOV interaction is different between male and female participants.

3.2 Gain analysis

To breakdown the interactions found in the raw $\Psi(g_i; greater)$ data, each participant's gains at the 25%, PSE, and 75% thresholds were estimated from their fitted psychometric curve. These thresholds were chosen based on previous threshold estimation. To determine if there were differences in gains at the 25%, PSE, and 75% thresholds we performed a 2 (distractors: present, not present) x 3 (Threshold: 25%, PSE, 75%) × 2 (FOV: 40°, 110°) × 2 (gender: female, male) ANOVA with distractor, threshold, and FOV as within-participant variables and gender as a between-participant variable. Mauchly's test was used to verify that sphericity was not violated. See Table 3 and Fig. 5.

Significant main effects of Gender, $F(1,9) = 5.22$, $p = .0482$, $\eta^2 = .05$, and Threshold, $F(2,18) = 17.11$, $p < .0001$, $\eta^2 = .39$ were found. A significant Threshold × FOV interaction was found, $F(2,18) = 4.28$, $p = .0302$, $\eta^2 = .09$. Post hoc analysis of pairwise comparisons was performed using estimated marginal means with Bonferroni adjustments. Results support significant differences at the 25% threshold, $t(22.85) = 2.10$, $p = .0473$, between the 40° FOV ($M = .73$, $SE = .12$) and the 110° FOV ($M = .44$, $SE = .12$), and at the 75% threshold, $t(22.85) = -2.62$, $p = .0152$, between the 40° FOV ($M = 1.25$, $SE = .12$) and the 110° FOV ($M = 1.62$, $SE = .12$). This supports H1, that participant discrimination between rotation gains is different in a 110° FOV compared to a 40° FOV. Rotation gain thresholds are significantly wider when using a 110° FOV compared to a 40° FOV.

With and Without Distractors

FOV	25%	PSE	75%	σ	D	p
40	0.6800	0.9572	1.2343	0.44	5.33	0.88
40 ♀	0.5604	0.9305	1.3006	0.55	4.43	0.92
40 ♂	0.7490	0.9726	1.1962	0.33	11.86	0.32
110	0.6207	1.0613	1.5019	0.65	8.69	0.70
110 ♀	0.5261	0.9579	1.3896	0.64	3.62	0.97
110 ♂	0.7122	1.1527	1.5932	0.65	11.05	0.54

Without Distractors

FOV	25%	PSE	75%	σ	D	p
40 [54]	0.67	0.96	1.24	-	-	-
40 ♀ [7]	0.66	0.96	1.29	-	-	-
40 ♂ [7]	0.69	0.94	1.19	-	-	-
40	0.6800	0.9481	1.2170	0.40	4.70	0.93
40 ♀	0.5742	0.9286	1.2829	0.53	7.34	0.85
40 ♂	0.7382	0.9586	1.1790	0.33	8.24	0.75
110	0.6702	1.0555	1.4407	0.57	4.04	0.95
110 ♀	0.6459	0.9839	1.3218	0.50	3.69	0.98
110 ♂	0.6999	1.1307	1.5616	0.64	4.58	0.88

With Distractors

FOV	25%	PSE	75%	σ	D	p
40	0.6810	0.9675	1.2541	0.42	4.31	0.91
40 ♀	0.5455	0.9327	1.3198	0.57	8.50	0.52
40 ♂	0.7619	0.9888	1.2156	0.34	6.95	0.78
110	0.5676	1.0678	1.5680	0.74	6.43	0.90
110 ♀	0.3692	0.9232	1.4772	0.82	3.74	0.96
110 ♂	0.7242	1.1727	1.6211	0.66	8.09	0.56

Table 2: The 25%, PSE, and 75% threshold gains derived from the psychometric curves (goodness-of-fit data (Deviance (D) and p-value)) calculated using maximum likelihood estimation, using a cumulative normal distribution function, of the pooled $\Psi(g_i; greater)$ data. Gains are presented by FOV and gender (female - ♀, male - ♂) for all trials regardless of distractors, trials without distractors, and trials with distractors.

Additionally, a significant Gender × FOV interaction was found, $F(1,9) = 11.19$, $p = .0086$, $\eta^2 = .04$. Post hoc analysis found a significant difference in gains between male and female participants at the 110° FOV, $t(14.66) = -3.67$, $p = .0023$, and a significant difference between the 40° FOV and 110° FOV for males, $t(9) = -3.37$, $p = .0082$. This supports H2, that participant discrimination between rotation gains is different for females compared to males.

3.3 Distractors

Gain analysis from Sect. 3.2 revealed four trending interactions involving distractors. See Table 3. Exploratory post-hoc analysis of the highest-order trending effect using estimated marginal means with Bonferroni adjustments, comparing gender and presence of distractor, pairwise, at each threshold and FOV was performed. Two significant comparisons were found in the 110° FOV at the 25% threshold. There was a significant difference in gains for females in the presence of distractors ($M = -.0822$, $SE = .2108$) versus no distractors present ($M = .6305$, $SE = .2108$), $t(48.87) = 3.488$, $p = .0062$. Additionally, there was a significant difference in gains in the presence of distractors between males ($M = .7120$, $SE = 1640$) and females, $t(70.61) = -2.968$, $p = .0245$. This suggests that distractors may affect males and females differently, however only in the 110° FOV at the 25% threshold. This weakly supports H3, that participant discrimination between rotation gains is different when distractors are present compared to when they are not, however further studies should be performed to investigate this result.

Effect	df	F	η^2	p
GEN	1, 9	5.22 *	.05	.05
THR	2, 18	17.11 ***	.39	<.0001
GEN×THR	2, 18	0.06	.002	.94
FOV	1, 9	0.52	.002	.49
GEN×FOV	1, 9	11.19 **	.04	.009
DIS	1, 9	0.45	.002	.52
GEN×DIS	1, 9	1.72	.006	.22
THR×FOV	2, 18	4.28 *	.09	.03
GEN×THR×FOV	2, 18	0.27	.006	.77
THR×DIS	2, 18	1.02	.010	.38
GEN×THR×DIS	2, 18	2.78 +	.03	.09
FOV×DIS	1, 9	3.82 +	.005	.08
GEN×FOV×DIS	1, 9	4.17 +	.005	.07
THR×FOV×DIS	2, 18	0.32	.002	.73
GEN×THR×FOV×DIS	2, 18	2.96 +	.02	.08

Table 3: Analysis of the 25%, PSE, and 75% gains calculated from each participant's psychometric curve with a 2 (distractors (DIS): present, not present) x 3 (Threshold (THR): 25%, PSE, 75%) × 2 (FOV: 40°, 110°) × 2 (Gender (GEN): female, male) ANOVA. Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, + $p < 0.1$.

	40° FOV		110° FOV	
Threshold	ρ_w	p	ρ_w	p
25%	-0.5579*	0.04	-0.2852	0.31
50%	-0.6416*	0.02	0.1031	0.72
75%	0.3732	0.19	0.6373*	0.01

Table 4: Winsorized correlations with 10% trimmed means comparing threshold gains to FOV for all participants.

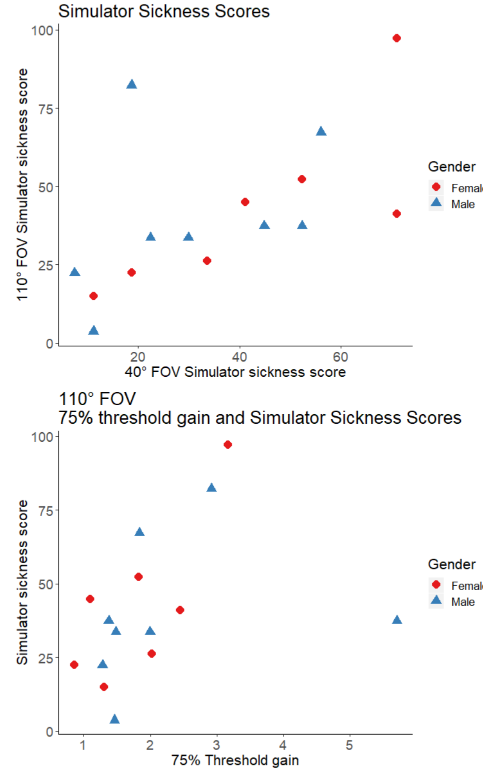

Fig. 6: (Top) The simulator sickness scores of each participant after the 40° FOV block (x-axis) and the 110° FOV block (y-axis). (Bottom) The simulator sickness scores of each participant after the 110° FOV block and the 110° FOV rotation gain at the 75% detection threshold. A male outlier is seen on the far right. Female participants are denoted with red circles, and male participants with blue triangles.

3.4 Simulator sickness

Simulator sickness scores for each participant can be seen in Fig. 6a. The simulator sickness data including nausea, occulomotor, disorientation, and total scores were independently evaluated in a 2 (SSQ order: first, second) × 2 (FOV order: 40° first, 110° first) × 2 (Gender: Female, Male) ANOVA with SSQ order as a within-participant variable and FOV order and gender as between-participant variables. No significant effects or interactions were found. Additionally, six participants had IPDs smaller than the HTC Vive IPD and completed the experiment with too large an IPD ($M = 2mm$ too large). Note that Steinicke et al. [54] did not adjust for IPD. The averaged simulator sickness scores over the two blocks for each participant was calculated, and the simulator sickness scores of participants wearing incorrect IPDs ($M = 44.88$, $SE = 6.18$) was compared to participants wearing correct IPDs ($M = 36.84$, $SE = 7.46$). No significant difference between groups was found, $t(13.85) = 0.83$, $p = 0.42$. Additionally, the estimated Bayes factor = 0.34 provides weak support of a difference in simulator sickness scores between participants wearing an HMD with the correct IPD compared to wearing an HMD with a slightly too large IPD.

Exploratory analysis was performed to determine if threshold gains were correlated with simulator sickness scores. Robust Winsorized correlations with 10% trimmed means were calculated comparing gains at the 25%, PSE, and 75% thresholds for the 40° FOV and the 110° FOV, with the corresponding FOV block simulator sickness score. See Table 4. At the 40° FOV significant negative correlations were found between participant simulator sickness scores at both the 25% and PSE threshold gains, $\rho_w = -.56$, $p = .04$ and $\rho_w = -.64$, $p = .02$ respectively. The significant correlation shows that at the 25% threshold, participants with a greater decrease in rotation gains had higher simulator sickness scores. Additionally, participants whose PSE was further decreased from 1 had higher simulator sickness scores. At the 110° FOV, a significant positive correlation was found at the 75% threshold, $\rho_w = .64$, $p = .01$. When removing the male outlier (see Fig. 6b) the correlation strengthened to $\rho_w = .74$, $p = .003$ Participants with a greater increase in rotation gains had higher simulator sickness scores.

Using confidence interval tests for correlation coefficients, we evaluated the equality of correlation coefficients for males and females at each threshold and FOV. No significant differences were found between genders.

4 Discussion

4.1 FOV

Gains at the 25% and 75% thresholds were significantly different in the 40° FOV compared to the 110° FOV. In a 40° FOV participants were unable to discriminate between 90° virtual rotations and real rotations ranging from 73° to 132°. In a 110° FOV participants were unable to discriminate between 90° virtual rotations and real rotations ranging from 60° to 145°, equating to a 33% decrease and 61% increase in rotations. This supports H1, that participant discrimination between rotation gains is different in a 110° FOV compared to a 40° FOV. Rotation gain thresholds are significantly wider when using a 110° FOV compared to a 40° FOV.

The threshold gains we found with a 40° FOV were very similar to those found by Steinicke et al. [54]. Our estimated threshold gains were within .03 of those reported in [54]. Additionally, the threshold gains we estimated for males and females with a 40° FOV were quite similar to those reported by Bruder et al. [7]. The largest differences in threshold gains between our work and [7] was at the 25% threshold, but those differences are still within .1. See Table 2 for a full comparison of threshold gains.

The difference in threshold gains between FOVs may be attributed to the increased visual information received with a 110° FOV viewport. Human perception literature makes two important observations about the effects of an increased FOV. First, it is noted that peripheral stimulation afforded by a wider FOV increases the observer's feelings of self-motion. Based on that observation, it is possible that participants' perceived self-motion increased between a 40° FOV viewport and a 110° FOV viewport. It is possible that this different sense of self-motion altered their sensitivity to the gains. However, no effects of FOV block order were found.

Second, the literature notes that when they conflict, visual information more strongly influences locomotion than vestibular and proprioceptive information do. To successfully complete the experiment task, participants needed to accurately compare perceived visual information (which signaled the magnitude of the virtual rotation) with the perceived extraretinal information (which signaled the magnitude of the real rotation). Compared to a 40° FOV, more visual information is generated in a 110° FOV viewport. However, since the rotations are the same, the amount of extraretinal information received remains the same across both FOVs. It is possible that compared to the 40° FOV viewport, the increased visual information received with a 110° FOV viewport diminishes the participants' ability to differentiate between visual and extraretinal information, thus making it harder for participants to successfully distinguish between rotation gains.

4.2 Gender

Previous research by Bruder et al. did not find gender differences with a 40° FOV [7]. Our results also did not find gender differences with 40° FOV. However, the 110° FOV condition found significant gender differences between threshold gains. Females were unable to discriminate between 90° virtual rotations and real rotations ranging from 65° to 171° equating to a 28% decrease and 90% increase in rotations. Males were unable to discriminate between 90° virtual rotations and real rotations ranging from 56° to 126°, equating to a 37% decrease and 40% increase in rotations. Additionally, male thresholds were significantly larger in the 110° FOV compared to the 40° FOV where males were only unable to discriminate between 90° virtual rotations and real rotations ranging from 75° to 120°. This supports H2, that participant discrimination between rotation gains is different for females compared to males, however this difference is only seen in the 110° FOV. In modern HMDs, designers should use different threshold gains for males and females.

While our results for differences in threshold gains between genders at the 40° FOV agree with those found in previous work [7], it is difficult to compare our results for 110° FOV with other work. Other experiments that we are aware of that studied rotation gain thresholds used displays with an FOV considerably smaller than 110° and did not test for differences between genders [26, 36, 40]. It should be noted, however, that gender differences in thresholds have been found in curvature gains with a 100° FOV [34]. That study did not look at differences in rotation gain thresholds, but it does support that gender differences exist in RDW thresholds with a wide FOV.

4.3 Distractors

When considering distractors, significant differences were found in the 110° FOV condition at the 25% threshold. In the presence of a distractor female participants were unable to discriminate between 90° virtual rotations and real rotations ranging up to 244° compared to only 139° when no distractor was present. Due to this significant difference, we recommend for a general RDW implementation to use the female 25% threshold without distractors present. Males, in the presence of a distractor, were significantly different from females in the presence of a distractor and were unable to discriminate between 90° virtual rotations and real rotations ranging up to 124°. The results provide some support of H3, that participant discrimination between rotation gains is different when distractors are present compared to when they are not.

Perceptual studies have shown that the observer's attention and cognitive load can either increase or decrease one's sense of vection, but those studies have provided mixed results [50, 58]. It is difficult to directly connect results found in these studies to the present study as participants in those studies were instructed to focus on a particular stimulus, or were asked to perform a memory exercise. In our experiment, we did not specifically instruct participants to focus on the deer as it ran across the VE, and therefore cannot know how much users attended to the distractor. We are confident that users at least partially attended to the distractor since they correctly reported seeing the distractor for 97% of the trials when it was present.

This work found no differences in rotation thresholds based on the direction of distractor movement compared to head rotation direction, while previous distractor research did suggest differences rotation thresholds [10, 45]. Previous work by Peck et al. [45] and Chen et al. [10] either specifically instructed users to look at the distractor, or implemented the distractor such that users attended to it in order to complete a different goal. In contrast, we designed the distractor in this study to emulate natural distractors that will not always capture users' full attention, such as a tour guide in a virtual house tour. The differences in results found between the present study and previous work are likely due to the difference in distractor attention. In Peck et al., users turned their head and followed the distractor while VE rotation alternated between with and against head rotation direction. Their findings were that distractors cause users to be less aware of VE rotations compared to VE rotations without distractors [45]. In our work, users were not instructed to attend to the distractor and head rotation and the world rotation was either with or against (not alternating) for each trial. We found some differences in how aware users were of the VE rotations with and without distractors, but only at the 110° FOV 25% threshold.

4.4 Simulator Sickness

Threshold gains were strongly correlated with simulator sickness scores. Participants with higher simulator sickness scores also had threshold gains farther from 1 compared to participants with lower simulator sickness scores. Follow-on research should explore the effect of simulator sickness on perception thresholds for RDW.

Previous work has noted that FOV influences users' feelings of simulator sickness [14, 30, 33]. Although we did not investigate the effects of FOV on simulator sickness in this study, we did not see a significant difference in simulator sickness scores between the 40° and 110° FOVs (see Fig. 6a). The most likely reason why we did not see differences in simulator sickness scores was because we repeatedly changed the rotation gain within the experiment. The order of gains applied was not held constant across FOV blocks, so we are unable to directly compare specific gains with sickness scores between the 40° and 110° FOVs. Future research should investigate the effects of simulator sickness on RDW thresholds.

4.5 Further Consideration

The five practice trials participants completed at the start of each FOV block may have been a potential source of bias as participants may recalibrate to the gain applied in the practice trials as the new norm in VR. To verify that the practice trials did not bias our results, we reran the analyses with the first five non-practice trials removed for each participant for each block. We found the same significant results which suggests that the practice trials did not negatively affect the results.

In our study, six participants had a measured IPD below $61.3mm$, which is the minimum IPD setting on the Vive Pro. Four of these participants were female. Although these participants stated that they were able to clearly see the VE, a correct IPD setting is likely to increase display sharpness. We acknowledge that IPD disparities between the user and the HMD could have an effect on thresholds, but we do not believe this disparity had a significant effect on our results. Previous research by Willemsen et al. [66] suggests that overall performance in egocentric distance estimation was not improved using measured IPDs compared to the average $65mm$ male IPD. Furthermore, we found weak evidence supporting the effect of IPD on simulator sickness. It may be the case that perceptual differences will only be seen if the difference between HMD and user IPD is above a threshold. By adjusting the IPD to the best of the hardware's ability, we may have been below an unknown threshold where incorrect IPD may significantly effect results. It could also be the case that the distances of objects from the observer in our VE meant that IPD disparities did not greatly impact their perception of the environment. Cutting claims that IPD plays an important role in visual perception of a VE for objects within a 1.5*m* radius from the user, and that beyond this distance other sources of visual perception information are more important [12]. In our experiment, most of the objects in the VE that provided motion cues (trees and the distractor) were more than 1.5*m* away from the user. More recent work studying IPD models showed that the method of IPD calibration can have a significant impact on the observer's ability to perform tasks within arm's reach (*i.e.,* within 1.5*m*) [27]. Future work should study the effects of IPD mismatch human perception in HMDs.

Our experiment did not study RDW thresholds during walking and instead only studied thresholds for in-place rotations. This limitation to rotation gains could be a concern since the thresholds we found would only be applicable in situations where the user turns while they are stationary. However, we note that during head rotations, vestibular stimulation dominates over other sensory cues of motion [3]. Therefore it is unlikely that head rotations while walking will yield results different from ours since the vestibular system has already been saturated during these head rotations.

Different implementations of FOV restrictors may yield different threshold gains. Initial tests by Fernandes et al. [14] noted that hard-edge restrictors are more distracting and easier to notice than soft-edge restrictors. One participant in our study commented on trying to use the FOV restrictor edge to determine the rotation speed, which supports the observation made in [14]. Our study used a rectangular hard-edge restrictor for the sake of replication, but we believe different FOV restrictor edge softness and shapes are worth studying since there is evidence that the FOV restrictor parameters do not go unnoticed by users.

5 Conclusion

We tested our hypotheses (see Sect. 2.2) with a 2 (FOV: 40°, 110°) × 2 (Gender: female, male) × 2 (Distractor: without, with) user study with FOV and Distractor as within-participant variables, and Gender as a between-participant variable. We successfully replicated previous threshold estimations for rotation gains at the 40° FOV, and compared results to threshold gain estimations at the 110° FOV. See Sect. 4 for a summary of the threshold gains. Our results strongly supported H1 in that rotation gains are wider in a 110° FOV compared to a 40° FOV. Additionally, our results supported H2 in that females and males have different threshold gains in the 110° FOV. Finally, H3 was partially supported. Males did not have a significant difference in threshold gains comparing the presence of distractors, however females did have a significant difference in threshold gains in the presence of distractors at the 25% threshold in the 110° FOV.

Simulator sickness was highly correlated with threshold gains. Conservative practitioners may want to use threshold gains closer to 50% instead of the standard 25% and 75% thresholds until future research provides necessary insight into the relationship between simulator sickness and rotation gains.

Inclusivity in design is essential both in hardware and software [37]. The average American female IPD is 61.7*mm* [15] and the average Asian female IPD is 63.6*mm* [41]. The Vive Pro is designed such that almost 50% of the American female population and 20% of the Asian female population is unable to set the device to the correct IPD. This hardware limitation is a cause for concern and an example of non-inclusive design practices.

The significant difference in rotation threshold gains between 40° and 110° FOVs suggests that differences are likely to be found for translation and curvature threshold gains as well. Future work should estimate threshold gains for translation and curvature gains comparing a 40° FOV with a 110° FOV. Gender differences in thresholds have recently been found in curvature gains. Nguyen et al. found that females have higher curvature thresholds than men when wearing an HMD with a 100° FOV [34]. The significant differences found between genders in rotation gains, and the strong correlations with simulator sickness highlight the importance of considering gender and simulator sickness when evaluating translation and curvature gains.

Acknowledgments

The authors wish to thank Mary Whitton for expert consultation, the reviewers for their thoughtful feedback on this paper, and the Davidson College Faculty, Study, and Research grant for support of this work.

References

[1] B. Baumberger, M. Flückiger, and M. Roland. Walking in an environment of moving ground texture. *Japanese Psychological Research*, 42(4):238–250, 2000.

[2] A. Berthoz. *The brain's sense of movement*, vol. 10. Harvard University Press, 2000.

[3] J. Borah, L. R. Young, and R. E. Curry. Sensory mechanism modeling. Technical report, GULF AND WESTERN APPLIED SCIENCE LABS WALTHAM MA, 1979.

[4] T. Brandt, J. Dichgans, and E. Koenig. Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. *Experimental brain research*, 16(5):476–491, 1973.

[5] G. Bruder, V. Interrante, L. Phillips, and F. Steinicke. Redirecting walking and driving for natural navigation in immersive virtual environments. *IEEE transactions on visualization and computer graphics*, 18(4):538–545, 2012.

[6] G. Bruder, F. Steinicke, and K. H. Hinrichs. Arch-explore: A natural user interface for immersive architectural walkthroughs. 2009.

[7] G. Bruder, F. Steinicke, K. H. Hinrichs, H. Frenz, and M. Lappe. Impact of gender on discrimination between real and virtual stimuli. In *Workshop on Perceptual Illusions in Virtual Environments*, pp. 10–15. Citeseer, 2009.

[8] G. Bruder, F. Steinicke, K. H. Hinrichs, and M. Lappe. Reorientation during body turns. In *EGVE/ICAT/EuroVR*, pp. 145–152, 2009.

[9] A. Burg. Lateral visual field as related to age and sex. *Journal of applied psychology*, 52(1p1):10, 1968.

[10] H. Chen and H. Fuchs. Supporting free walking in a large virtual environment: imperceptible redirected walking with an immersive distractor. In *Proceedings of the Computer Graphics International Conference*, p. 22. ACM, 2017.

[11] P. J. Clarkson, R. Coleman, S. Keates, and C. Lebbon. *Inclusive design: Design for the whole population*. Springer Science & Business Media, 2013.

[12] J. E. Cutting. How the eye measures reality and virtual reality. *Behavior Research Methods, Instruments, & Computers*, 29(1):27–36, 1997.

[13] P. DiZio and J. R. Lackner. Circumventing side effects of immersive virtual environments. In *HCI (2)*, pp. 893–896, 1997.

[14] A. S. Fernandes and S. K. Feiner. Combating vr sickness through subtle dynamic field-of-view modification. In *3D User Interfaces (3DUI), 2016 IEEE Symposium on*, pp. 201–210. IEEE, 2016.

[15] C. C. Gordon, C. L. Blackwell, B. Bradtmiller, J. L. Parham, P. Barrientos, S. P. Paquette, B. D. Corner, J. M. Carson, J. C. Venezia, B. M. Rockwell, et al. 2012 anthropometric survey of us army personnel: Methods and summary statistics. Technical report, ARMY NATICK SOLDIER RESEARCH DEVELOPMENT AND ENGINEERING CENTER MA, 2014.

[16] T. Grechkin, J. Thomas, M. Azmandian, M. Bolas, and E. Suma. Revisiting detection thresholds for redirected walking: Combining translation and curvature gains. In *Proceedings of the ACM Symposium on Applied Perception*, pp. 113–120. ACM, 2016.

[17] D. F. Halpern. *Sex differences in cognitive abilities*. Psychology press, 2000.

[18] L. J. Hettinger, K. S. Berbaum, R. S. Kennedy, W. P. Dunlap, and M. D. Nolan. Vection and simulator sickness. *Military Psychology*, 2(3):171–181, 1990.

[19] J. Hildebrandt, P. Schmitz, A. C. Valdez, L. Kobbelt, and M. Ziefle. Get well soon! human factors influence on cybersickness after redirected walking exposure in virtual reality. In *International Conference on Virtual, Augmented and Mixed Reality*, pp. 82–101. Springer, 2018.

[20] E. Hodgson, E. Bachmann, and D. Waller. Redirected walking to explore virtual environments: Assessing the potential for spatial interference. *ACM Transactions on Applied Perception (TAP)*, 8(4):22, 2011.

[21] J. Hulk and F. Rempt. Vertical optokinetic sensations by limited stimulation of the peripheral field of vision. *Ophthalmologica*, 186(2):97–103, 1983.

[22] V. Interrante, B. Ries, and L. Anderson. Seven league boots: A new metaphor for augmented locomotion through moderately large scale im-

mersive virtual environments. In *3D User Interfaces (3DUI), 2007 IEEE Symposium on*, pp. 167–170. IEEE, 2007.
[23] H. Iwata. The torus treadmill: Realizing locomotion in ves. *IEEE Computer Graphics and Applications*, 19(6):30–35, 1999.
[24] H. Iwata, H. Yano, and H. Tomioka. Powered shoes. In *ACM SIGGRAPH 2006 Emerging technologies*, p. 28. ACM, 2006.
[25] P. Jaekl, R. S. Allison, L. R. Harris, U. Jasiobedzka, H. Jenkin, M. Jenkin, J. E. Zacher, and D. C. Zikovitz. Perceptual stability during head movement in virtual reality. In *Virtual Reality, 2002. Proceedings. IEEE*, pp. 149–155. IEEE, 2002.
[26] J. Jerald, T. Peck, F. Steinicke, and M. Whitton. Sensitivity to scene motion for phases of head yaws. In *Proceedings of the 5th symposium on Applied perception in graphics and visualization*, pp. 155–162. ACM, 2008.
[27] J. A. Jones, D. Edewaard, R. A. Tyrrell, and L. F. Hodges. A schematic eye for virtual environments. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 221–230. IEEE, 2016.
[28] R. S. Kennedy and L. H. Frank. A review of motion sickness with special reference to simulator sickness. Technical report, CANYON RESEARCH GROUP INC WESTLAKE VILLAGE CA, 1985.
[29] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3):203–220, 1993.
[30] E. M. Kolasinski. Simulator sickness in virtual environments. Technical report, Army research inst for the behavioral and social sciences Alexandria VA, 1995.
[31] E. Langbehn and F. Steinicke. Redirected walking in virtual reality. *Encyclopedia of Computer Graphics and Games. Springer International Publishing*, 2018.
[32] M. Lappe, F. Bremmer, and A. Van den Berg. Perception of self-motion from visual flow. *Trends in cognitive sciences*, 3(9):329–336, 1999.
[33] J.-W. Lin, H. B.-L. Duh, D. E. Parker, H. Abi-Rached, and T. A. Furness. Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. In *Proceedings ieee virtual reality 2002*, pp. 164–171. IEEE, 2002.
[34] A. Nguyen, Y. Rothacher, B. Lenggenhager, P. Brugger, and A. Kunz. Individual differences and impact of gender on curvature redirection thresholds. In *Proceedings of the 15th ACM Symposium on Applied Perception*, p. 5. ACM, 2018.
[35] N. C. Nilsson, T. Peck, G. Bruder, E. Hodgson, S. Serafin, M. Whitton, F. Steinicke, and E. S. Rosenberg. 15 years of research on redirected walking in immersive virtual environments. *IEEE computer graphics and applications*, 38(2):44–56, 2018.
[36] N. C. Nilsson, E. Suma, R. Nordahl, M. Bolas, and S. Serafin. Estimation of detection thresholds for audiovisual rotation gains. In *Virtual Reality (VR), 2016 IEEE*, pp. 241–242. IEEE, 2016.
[37] L. L. Nussbaumer. *Inclusive design: A universal need*. Fairchild Books, 2012.
[38] D. of Justice. Ada standards for accessible design. *Title III regulation*, 28, 2010.
[39] S. Olbrich, E. M. Trauth, F. Niederman, and S. Gregor. Inclusive design in is: Why diversity matters. *CAIS*, 37:37, 2015.
[40] A. Paludan, J. Elbaek, M. Mortensen, M. Zobbe, N. C. Nilsson, R. Nordahl, L. Reng, and S. Serafin. Disguising rotational gain for redirected walking in virtual reality: Effect of visual density. In *Virtual Reality (VR), 2016 IEEE*, pp. 259–260. IEEE, 2016.
[41] D. H. Park, W. S. Choi, S. H. Yoon, and C. H. Song. Anthropometry of asian eyelids by age. *Plastic and reconstructive surgery*, 121(4):1405–1413, 2008.
[42] A. E. Patla. Understanding the roles of vision in the control of human locomotion. *Gait & Posture*, 5(1):54–69, 1997.
[43] T. C. Peck, H. Fuchs, and M. C. Whitton. Evaluation of reorientation techniques and distrators for walking in large virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 15(3):383, 2009.
[44] T. C. Peck, H. Fuchs, and M. C. Whitton. Improved redirection with distractors: A large-scale-real-walking locomotion interface and its effect on navigation in virtual environments. In *Virtual Reality Conference (VR), 2010 IEEE*, pp. 35–38. IEEE, 2010.
[45] T. C. Peck, H. Fuchs, and M. C. Whitton. An evaluation of navigational ability comparing redirected free exploration with distractors to walking-in-place and joystick locomotion interfaces. In *Virtual Reality Conference (VR), 2011 IEEE*, pp. 55–62. IEEE, 2011.
[46] A. E. Raftery. Bayesian model selection in social research. *Sociological methodology*, pp. 111–163, 1995.
[47] S. Razzaque, Z. Kohn, and M. C. Whitton. Redirected walking. In *Proceedings of EUROGRAPHICS*, vol. 9, pp. 105–106. Citeseer, 2001.
[48] M. Rietzler, J. Gugenheimer, T. Hirzle, M. Deubzer, E. Langbehn, and E. Rukzio. Rethinking redirected walking: On the use of curvature gains beyond perceptual limitations and revisiting bending gains. In *2018 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 115–122. IEEE, 2018.
[49] R. A. Ruddle and S. Lessels. The benefits of using a walking interface to navigate virtual environments. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 16(1):5, 2009.
[50] T. Seno, H. Ito, and S. Sunaga. Attentional load inhibits vection. *Attention, Perception, & Psychophysics*, 73(5):1467–1476, 2011.
[51] S. Serafin, N. C. Nilsson, E. Sikstrom, A. De Goetzen, and R. Nordahl. Estimation of detection thresholds for acoustic based redirected walking techniques. In *Virtual Reality (VR), 2013 IEEE*, pp. 161–162. IEEE, 2013.
[52] M. Slater, M. Usoh, and Y. Chrysanthou. The influence of dynamic shadows on presence in immersive virtual environments. In *Virtual environments 95*, pp. 8–21. Springer, 1995.
[53] K. M. Stanney, K. S. Hale, I. Nahmens, and R. S. Kennedy. What to expect from immersive virtual environment exposure: Influences of gender, body mass index, and past experience. *Human Factors*, 45(3):504–520, 2003.
[54] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Estimation of detection thresholds for redirected walking techniques. *IEEE transactions on visualization and computer graphics*, 16(1):17–27, 2010.
[55] F. Steinicke, G. Bruder, T. Ropinski, and K. Hinrichs. Moving towards generally applicable redirected walking. In *Proceedings of the Virtual Reality International Conference (VRIC)*, pp. 15–24. IEEE Press, 2008.
[56] E. A. Suma, G. Bruder, F. Steinicke, D. M. Krum, and M. Bolas. A taxonomy for deploying redirection techniques in immersive virtual environments. In *Virtual Reality Short Papers and Posters (VRW), 2012 IEEE*, pp. 43–46. IEEE, 2012.
[57] E. A. Suma, S. Clark, D. Krum, S. Finkelstein, M. Bolas, and Z. Warte. Leveraging change blindness for redirection in virtual environments. In *Virtual Reality Conference (VR), 2011 IEEE*, pp. 159–166. IEEE, 2011.
[58] L. C. Trutoiu, S. Streuber, B. J. Mohler, J. Schulte-Pelkum, and H. H. Bülthoff. Tricking people into feeling like they are moving when they are not paying attention. In *Proceedings of the 5th Symposium on Applied Perception in Graphics and Visualization*, pp. 190–190. ACM, 2008.
[59] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks Jr. Walking $>$ walking-in-place $>$ flying, in virtual environments. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, pp. 359–364. ACM Press/Addison-Wesley Publishing Co., 1999.
[60] M. Usoh, E. Catena, S. Arman, and M. Slater. Using presence questionnaires in reality. *Presence: Teleoperators & Virtual Environments*, 9(5):497–503, 2000.
[61] K. Vasylevska, H. Kaufmann, M. Bolas, and E. A. Suma. Flexible spaces: Dynamic layout generation for infinite walking in virtual environments. In *3D user interfaces (3DUI), 2013 IEEE Symposium on*, pp. 39–42. IEEE, 2013.
[62] E.-J. Wagenmakers. A practical solution to the pervasive problems ofp values. *Psychonomic bulletin & review*, 14(5):779–804, 2007.
[63] W. H. Warren and K. J. Kurtz. The role of central and peripheral vision in perceiving the direction of self-motion. *Perception & Psychophysics*, 51(5):443–454, 1992.
[64] W. H. Warren Jr, B. A. Kay, W. D. Zosh, A. P. Duchon, and S. Sahuc. Optic flow is used to control human walking. *Nature neuroscience*, 4(2):213, 2001.
[65] N. A. Webb and M. J. Griffin. Eye movement, vection, and motion sickness with foveal and peripheral vision. *Aviation, space, and environmental medicine*, 74(6):622–625, 2003.
[66] P. Willemsen, A. A. Gooch, W. B. Thompson, and S. H. Creem-Regehr. Effects of stereo viewing conditions on distance perception in virtual environments. *Presence: Teleoperators and Virtual Environments*, 17(1):91–101, 2008.
[67] E. A. Wise, D. D. Price, C. D. Myers, M. W. Heft, and M. E. Robinson. Gender role expectations of pain: relationship to experimental pain perception. *Pain*, 96(3):335–342, 2002.
[68] P. Zimmons and A. Panter. The influence of rendering quality on presence and task performance in a virtual environment. In *IEEE Virtual Reality, 2003. Proceedings.*, pp. 293–294. IEEE, 2003.