Estimation of Rotation Gain Thresholds for Redirected Walking Considering FOV and Gender

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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). We conducted a within-participant user study to estimate and compare thresholds for rotation gains. Significant differences in detection thresholds were found between FOVs. When using a 110° FOV, rotations can be decreased 31% and increased 49% compared to decreased 18% and increased 47% with a 40° FOV. Significant differences were found between female and male gains with a 110° FOV.

Index Terms: Virtual reality—Locomotion—Perception—Detection thresholds; Redirected walking—Gender differences

1 INTRODUCTION

Travel is essential for exploring virtual environments (VEs). Locomotion in virtual reality (VR) has been supported in many different ways, but it has been shown that locomotion interfaces that support real walking provide users with the most benefits. One locomotion interface that enables real walking is *redirected walking* (RDW) [1].

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 this technique, one can reduce breaks-in-presence caused by reaching the bounds of the tracked space by steering users away from the tracked-space edges while still giving users the benefits of real walking in the VE.

Previous work by Steinicke et al. [2] 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. Gains that are more suited for a particular system will increase the effectiveness and usability of RDW.

2 BACKGROUND

With RDW, there is a trade-off between redirection intensity and user experience [1]. 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. Thus, it is important to know how much redirection can be applied before it interferes with a user's experience.

Many studies have estimated the limits (referred to as *detection thresholds*) of this redirection. The most comprehensive of such studies was conducted by Steinicke et al. [2]. Previous studies have not compared different FOVs within participants, and they often feature more male than female participants.

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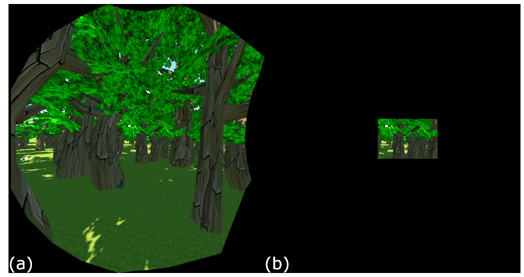

Figure 1: (a) View of the VE in the left eye with no FOV modification (110°). (b) View of the VE in the left eye with a 40° FOV restrictor.

When interpreting the moving surroundings and controlling the observer's locomotion, visual stimuli become more important than other signals if the perceived visual stimulus does not match the observer's actual body motion, as is the case when RDW is applied. This close relationship between the visual stimulus and an observer's locomotion suggests that changes in the observer's FOV, which will alter the amount of visual stimulus received, may alter how the observer locomotes. Feelings of vection have also been shown to change as FOV changes, which may further influence an observer's locomotion. Finally, there are known perceptual differences between males and females, including differences in FOV and performance in visual perception tasks.

3 METHODS

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 and the experiment ran at 90 frames per second. Sixteen participants, age 19 - 48 (8 female ($M = 22$, $SE = 5$) and 8 males ($M = 26$, $SE = 11$)) successfully completed the experiment.

Our experiment was a replication of the rotation gain estimation conducted by Steinicke et al. The experiment consisted of two blocks, one with a 110° FOV and one with a 40° FOV. See Fig. 1. Participants rotated 90° to the left or right in the VE, with different rotation gains applied per trial. Half of the trials had users turn to the left, and half to the right. We tested gains ranging from 0.6 to 1.4 in increments of 0.1. 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 in the same direction as the user's rotation, and 4 moved in the opposite direction. This totaled 144 trials for each FOV (288 trials per participant). The trial order per block was randomized for each participant. In this work, we will only discuss the "without distractors" condition.

4 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. No significant effect of clockwise verses counter-clockwise rotations was found, and the rotation direction data were pooled for analysis. Using maximum likelihood estimation, a psychometric

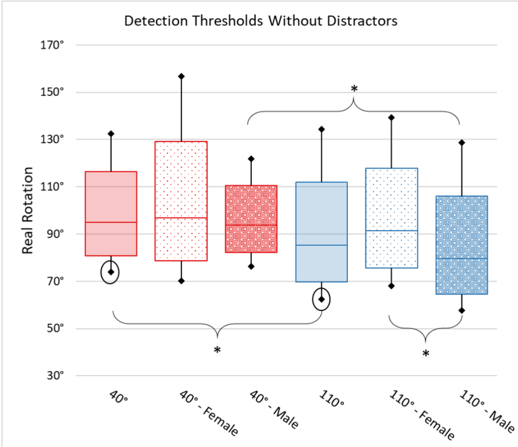

Figure 2: The real rotation that can be applied to a $90°$ virtual rotation when using the 25%, 33%, 50%, 66%, and 75% detection threshold gain values by FOV and gender. Significant differences were found between the $40°$ and $110°$ FOVs at the 75% detection threshold (circled), between the $40°$ and $110°$ FOVs for males, and between females and males at the $110°$ FOV. * $p \leq .05$

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.

Analysis of $\Psi(g_i; greater)$ found a significant effect of gain, $F(8,72) = 33.46$, $p < 0.0001$, $\eta^2 = .44$, and a gain × FOV interaction, $F(3.83, 34.45) = 2.88$, $p = .04$, $\eta^2 = .06$. This supports that there is a significant difference in gains between FOVs.

Post-hoc analysis of gain data was performed comparing FOVs pairwise for each threshold. A significant difference between gains at the $40°$ ($M = 1.21$, $SE = .11$) and $110°$ ($M = 1.60$, $SE = .11$) FOVs at the 75% threshold was found, $t(20.27) = -2.66$, $p = .05$, $r = .51$. No other significant differences were found. Imperceptible virtual rotations can be significantly increased with a $110°$ FOV with gain values ranging from .67 to 1.44 compared to a $40°$ FOV with gain values ranging from .68 to 1.22.

4.1 Gender

To determine if there were gender differences between threshold gains analysis of $\Psi(g_i; greater)$ with gender as a between-participant variable was performed. Trends were found in both gain × FOV, $F(8,64) = 1.97$, $p = .06$, $\eta^2 = 0.08$, and gender × gain × FOV, $F(8,64) = 1.84$, $p = .09$, $\eta^2 = 0.07$.

Gain analysis revealed threshold effects, $F(2,16) = 15.37$, $p = .0002$, $\eta^2 = 0.47$, a gender trend, $F(1,8) = 4.92$, $p = .06$, $\eta^2 = .04$, and a significant gain × FOV interaction, $F(2,16) = 3.81$, $p = .04$, $\eta^2 = .16$.

Post-hoc analyses of gain data comparing genders for each FOV support a significant difference in gains between females ($M = .96$, $SE = .06$) and males ($M = 1.19$, $SE = .06$) in the $110°$ FOV, $t(15.83) = -2.82$, $p = .02$, $r = .58$. Based on the psychometric curve of pooled $\Psi(g_i; greater)$ data, gains range from .65 to 1.32 for females and from .70 to 1.56 for males. This supports that, with a $110°$ FOV, imperceptible virtual rotation for males can be increased compared to females.

Comparing FOVs by gender found significant differences between the $40°$ FOV ($M = 1.0$, $SE = .06$) and $110°$ FOV ($M = 1.19$, $SE = .06$) for males, $t(8) = -3.03$, $p = .03$, $r = .73$, but not for females, $t(8) = -.06$, $p = .95$, $r = .02$. For males, in a $110°$ FOV, gains range from .70 to 1.56 and are *wider*, meaning the gains at the 25% and 75% thresholds are farther from 1, compared to the $40°$ FOV gains ranging from .74 to 1.18.

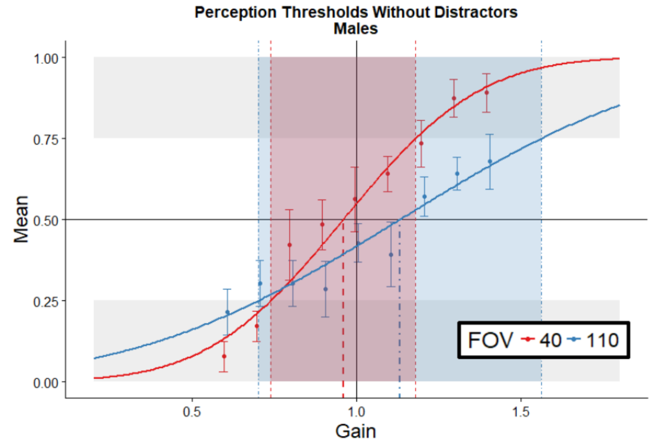

Figure 3: Detection thresholds for males by FOV. The vertical edges of the red and blue regions indicate the 25% (left edge) and 75% (right edge) thresholds. In each condition, gains that fall inside the colored regions are undetectable to users.

5 Discussion and Conclusion

Regardless of gender, with a $40°$ FOV participants were unable to discriminate between $90°$ virtual rotations and real rotations ranging from $74°$ to $132°$, however at the $110°$ FOV participants were unable to discriminate between $90°$ virtual rotations and real rotations ranging from $62°$ to $134°$. When using a $110°$ FOV, rotations can be decreased 31% and increased 49% compared to decreased 18% and increased 47% with a $40°$ FOV.

The $110°$ FOV condition found significant gender differences between threshold gains. This suggests that designers should use different threshold gains for males and females. Females were unable to discriminate between $90°$ virtual rotations and real rotations ranging from $68°$ to $139°$ equating to a 24% decrease and 55% increase in rotations. Males were unable to discriminate between $90°$ virtual rotations and real rotations ranging from $58°$ to $129°$ equating to a 36% decrease and 43% increase in rotations.

The difference in threshold gains between FOVs may be attributed to the increased visual information received with a $110°$ FOV viewport. 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. Greater inability to correctly answer the trial questions results in larger threshold gains, which is the result we found for the 75% threshold.

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