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Individualized Calibration of Rotation Gain Thresholds for Redirected Walking

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Abstract

Redirected walking allows the exploration of large virtual environments within a limited physical space. To achieve this, redirected walking algorithms must maximize the rotation gains applied while remaining imperceptible to the user. Previous research has established population averages for redirection thresholds, including rotation gains. However, these averages do not account for individual variation in tolerance of and susceptibility to redirection. This paper investigates methodologies designed to quickly and accurately calculate rotation gain thresholds for an individual user. This new method is straightforward to implement, requires a minimal amount of space, and takes only a few minutes to estimate a user's personal threshold for rotation gains. Results from a user study support the wide variability in detection thresholds and indicate that the method of parameter estimation through sequential testing (PEST) is viable for efficiently calibrating individual thresholds.

CCS Concepts

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

1. Introduction

With the emergence of low-cost consumer head-mounted displays, immersive virtual reality (VR) experiences are increasingly common. Exploration of virtual environments by physical walking can be powerful; however, the virtual area that can be explored through physical walking is constrained by the size of the tracking space. Redirected walking is technique that allows users in virtual reality to explore large virtual spaces within limited physical spaces by manipulating the mapping between real and virtual motion. Redirected walking is frequently described in terms of gains, which describe scaling factors that are applied to map real-world tracked motion to the virtual environment. An open problem for redirected walking is finding a level of manipulation that is high enough to minimize the necessary physical space, but low enough to remain imperceptible to the user and to avoid simulator sickness. Previous work has found general guidelines for perception thresholds, but these guidelines are insufficient due to the wide variance in susceptibility to redirection among users.

The main contribution of this work is the introduction and validation of a novel method to efficiently calculate rotation gain redirection thresholds for individual users. Two psychometric algorithms, an adaptive staircase technique and the method of parameter estimation through sequential testing (PEST), were each investigated as potential calibration procedures. A user study was conducted to evaluate the two calibration methods and compare the individual results with population averages obtained in prior research. The data confirm a wide variance in individual tolerance for redirection and suggest that the PEST method may be the most suitable for individually calibrating rotation gains.

2. Previous Work

The introduction of redirected walking by Razzaque included an informal examination of redirection thresholds; however, the small number of subjects prevented him from obtaining reliable thresholds [Raz05]. Subsequently, Engel et al. investigated thresholds for rotation gains, although the subjects were not naïve to the purpose of the experiment [ECT*08]. Interestingly, the authors noted vast differences in individual sensitivities to rotation gains. The most well-known examination of redirection thresholds was performed by Steinicke et al. for rotation, translation, and curvature gains [SBJ*]. Rotation gains in particular were calculated by turning in place and thus had very low space requirements. Subsequent research by Steinecke et al. refined their previous work using a two-alternative forced choice design to reduce participant bias [SBJ*10]. The thresholds were calculated using a psychomet-

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ric function to identify the point of subjective equality (PSE), which is the gain where a participant responds “smaller” in half of the trials. The threshold for increasing the rotation of the turn (positive gain) was estimated at 49%, and the threshold for decreasing the rotation of the turn (negative gain) was estimated at 20%. There was variability in individual detection thresholds among participants, which has been acknowledged as a limitation of these average thresholds [NSSN18]. This method provides a range of gains which are undetectable to a participant; however, it requires a participant to repeatedly experience many different levels of redirection. This time-consuming procedure is not conducive to calibrating redirection thresholds on an individual basis immediately prior to a virtual reality experience. Collectively, this supports the development of a method to calibrate thresholds on an individual basis.

Adaptive methods for estimating thresholds are common in psychophysical research and rely on knowledge of a participant’s response in previous trials to inform subsequent stimuli [Lee01]. Razzaque conducted a brief study using an adaptive staircase technique to estimate detection thresholds for rotation gains [Raz05]. While the study only included a handful of participants, it did demonstrate that an adaptive method can successfully converge to estimate a participant’s threshold level. Adaptive methods were also recently used in a study that examined combined detection thresholds for translation and curvature gains applied simultaneously [GTA*16].

The subtle sensory conflict introduced by redirected walking algorithms is known to be associated with motion sickness when applied at sufficiently high levels [Gol06]. In light of this, a “fast motion sickness score” (FMS score) was created to periodically monitor a participant’s level of discomfort throughout an experiment. The FMS score, originally presented by Keshavarz and Hecht, provides a quick method to estimate a user’s level of motion sickness without disrupting an experience [KH11]. This method has been shown to strongly correlate with a participant’s simulator sickness questionnaire (SSQ) score, a tool commonly used to measure motion sickness [KLBL93]. Thus, the FMS score provides a quantitative means to monitor a participant throughout an experiment.

3. Calibration Methods

Two psychometric algorithms, an adaptive staircase method and the method of parameter estimation through sequential testing (PEST), were selected for evaluation. These methods were chosen due to their success in determining thresholds in other forms of psychophysical testing, reasonable speed of termination, as well as their relative ease of implementation.

The adaptive staircase method adjusts the gain level by a fixed step size, 0.10 in this study, based on the participant’s response to the previous gain level [Lev71]. If the participant noticed the prior gain level, the method will reduce the subsequent gain level, and vice-versa if the participant did not detect the applied redirection. The PEST method begins with an estimated initial psychometric function that provides an estimation of the participants’ threshold. Subsequent thresholds are calculated to provide the most information about the participant’s true threshold, based on their previous responses [LP82]. This may lead to “jumping” from a high threshold to a low threshold. The staircase method terminates after 12 reversals have occurred, 6 each for the positive and negative thresholds. A reversal is defined as a change in response compared to the previous recorded response. The PEST method terminates after 18 iterations, 9 each for the positive and negative thresholds. The termination criteria was determined from informal tests examining the number of iterations each algorithm required to converge. Each algorithm was confined to a gain range from 0.5 to 2.6, where 1.0 is the point where real rotation matches virtual rotation.

Figure 1: *A screenshot of the virtual environment used in the study.*

4. User Study

Participant recruitment and experimental procedures were approved by the local Institutional Review Board (IRB). Participants were between 21 and 28 years old with a mean age of 24 years (two not reporting age); participants were required to have normal or corrected to normal vision. A total of 29 participants were recruited via mailing lists and word-of-mouth. They were financially compensated $20 for their time. Thirteen of the participants had prior experience with virtual reality systems, ranging from brief interaction with low-cost HMDs to development of VR applications.

Prior to the start of the experiment, participants were asked about their previous experience with gaming and virtual reality systems. They completed the Kennedy-Lane simulator sickness questionnaire (SSQ) to provide a baseline measurement [KLBL93]. Participants were introduced to the headset by the experimenter and given a brief overview of the experimental design. They were reminded that they were under no obligation to complete the experiment, and could stop or take a break at any time.

During the experiment, participants were immersed in an indoor, room-sized virtual environment shown in Fig. 1. An initial tutorial scene introduced participants to the environment, redirection, and the calibration procedure. The introduction to redirected walking allowed participants to walk along a short path with a 90 degree turn while high levels of redirection were applied to highlight the sensation. A calibration procedure was used to calculate a participant’s threshold. Participants were instructed to turn in place in the direction indicated by an arrow until facing a painting on the wall; the direction of the arrow alternated after each turn. Without redirection, the turn was 270 degrees. The participants were then asked to select one of two buttons: “same” if they felt their virtual rotation matched their physical rotation, or "different" if they felt their virtual rotation was greater than or less than their physical rotation. No redirection was applied during the tutorial, however, during the experiment the gain applied during the subsequent iteration would increase or decrease according to the algorithm being tested.

The calibration procedure ran twice during the experiment, with an optional break after each algorithm had terminated. The procedure took approximately 5 minutes to complete. After completing the calibration procedure for each algorithm, the participant would walk along a short path with a 90-degree turn while redirection was applied at either the individual threshold or at the average threshold found in previous work. The type of threshold applied was counterbalanced to avoid confounding effects. At the end of the path, participants were asked if their virtual rotation was the same as or different than their physical rotation. This was repeated eight times, with an optional break offered after the first four turns.

FMS scores were obtained at eleven points throughout the study: at the conclusion of the tutorial, after each calibration procedure, and after each path. The participant provided a rating of their symptoms on a scale from 0 to 20 and was instructed to focus on feelings such as nausea, dizziness, and sweating. If a participant reported an FMS score of 15 or greater, they were required to remove the headset and take a break from the virtual environment. If a participant reported an FMS score of 20, the experiment stopped immediately.

At the conclusion of the experiment, an exit SSQ was administered and demographic information was collected. The entire experiment, including pre- and post-questionnaire, took approximately one hour per participant. The environment was designed in Unity 2017.1 and was run using an HTC Vive headset and controllers in a tracking space of 3 x 3 meters. Over-the-ear headphones played recorded instructions and dampened extraneous noise.

5. Results

Four participants repeatedly deviated from the instructions, suggesting that they did not understand the task, and were excluded from analysis. Five participants were unable to complete the study due to simulator sickness. In total, 20 participants (13 male, 6 female, 1 electing not to identify) completed the experiment.

For positive rotation gains, there was a significant difference between the thresholds found with the staircase method ($M = 1.92, SD = 0.30$) and the thresholds found with the PEST method ($M = 1.56, SD = 0.23$), confirmed by a paired-sample t-test, $t(19) = 6.143, p < 0.01$. Similarly, for negative rotation gains, there was a significant difference between the thresholds found with the staircase method ($M = 0.71, SD = 0.13$) and the thresholds found with the PEST method ($M = 0.81, SD = 0.12$), $t(19) = -4.06, p < 0.01$. The box plot in Fig. 2 illustrates the high variance seen in individual thresholds. The number of turns required for the staircase method ($M = 23.20, SD = 4.09$) were greater than those required by PEST, which terminated after 18 turns.

During the walk-through phase, the thresholds calculated by the staircase method were not noticed 30% of the time for positive thresholds and 60% of the time for negative thresholds. The thresholds calculated by the PEST method were not noticed 75% of the time for positive thresholds, and 70% of the time for negative thresholds. The population average thresholds were not noticed 80% of the time for positive thresholds, and 72.5% of the time for negative thresholds. Preliminary analyses indicate that neither gender nor previous VR experience had any significant effect on the thresholds calculated during the experiment. However, due to the low number of female participants, it is inadvisable to draw generalizable conclusions based on this data.

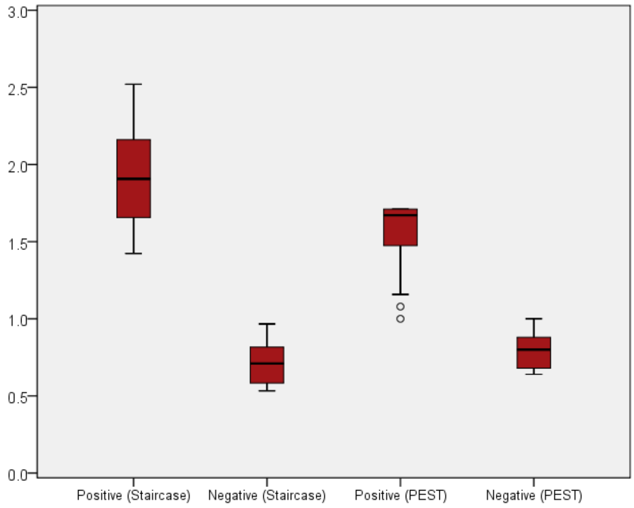

Figure 2: *Box plot of the individually calibrated thresholds observed during the study for each estimation method.*

Among participants that completed the experiment, there was a small but significant increase in SSQ scores from before the experiment ($M = 0.85, SD = 1.31$) compared to after the experiment ($M = 4.65, SD = 3.45$), confirmed by a paired-sample t-test, $t(19) = -5.83, P < 0.01$.

6. Discussion

Significantly, both the PEST method and the staircase method found a wide range in individual thresholds. This variance in tolerance of redirection strongly supports the need for a method to calculate redirected walking thresholds on an individual basis.

The results of the user study illustrate there are several clear advantages to the PEST algorithm in comparison to the staircase algorithm. Notably, compared to the staircase method, the PEST method identified positive gain thresholds that were more likely to remain imperceptible to users. In addition, despite the relative simplicity and speed of PEST, these thresholds were comparable to the average thresholds calculated using the PSE, which is a much longer procedure. Thresholds calculated using the staircase method, however, were likely to be substantially more noticeable.

The PEST method required fewer turns-in-place than the staircase method, indicating it is slightly more expedient for calculating an individual's threshold level. Both methods require less time and fewer turns-in-place than the process required to find the PSE while maintaining the same minimal space requirements. The space

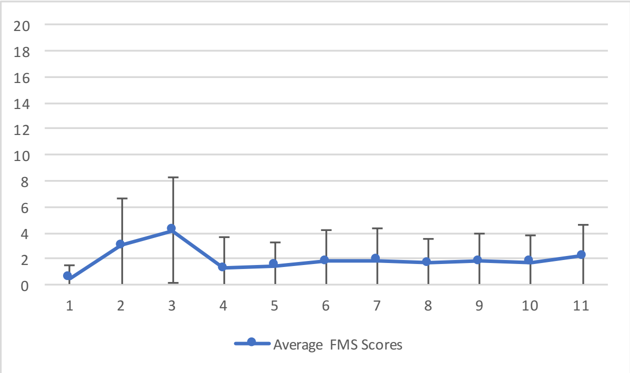

Figure 3: *Average FMS scores at checkpoints shown with standard deviation. The small drop seen after checkpoint 3 can be attributed to the completion of the calibration phase, where redirection levels varied wildly.*

requirements for current redirected walking applications are large, and this method of individualized calibration does not add to these requirements. As long as users have enough room to turn in place, this method for calculating rotation thresholds could be used.

While the PEST method generally outperformed the staircase method, the high rotation gain values calculated by the staircase method are intriguing. The average threshold level found by this method for positive gains corresponds to a 92% increase in rotation, a value which is far higher than those observed in previous work. One interesting possibility is that the small step size in the gain being tested provided participants with the chance to acclimate to progressively higher levels of redirection. Recent work investigating translation gains and walking speed suggests users exhibit compensation behaviors even when the redirection level is below the threshold of perception [NCK17]. Additionally, prior work examining curvature gains reported similar behavior [NSE*12]. The progressive acclimation to rotation gains observed in this study may be a similar form of adaptation that merits future investigation.

The majority of participants were able to successfully complete the experiment without experiencing significant side effects. However, the five participants that reported simulator sickness should not be disregarded. An analysis of negative side effects and the conclusions drawn from their data is reported separately in [HZMR18]. Overall, the SSQ and FMS scores suggest that the proposed calibration method is safe for most users, as shown in Fig. 3.

7. Conclusions

Results have demonstrated substantial variability in individual tolerances for rotation gains applied during redirected walking. The main goals of redirection include remaining imperceptible to the user and avoiding excessive visual-vestibular conflict that may lead to motion sickness. With these objectives in mind, an efficient method for calibrating personalized rotation gain thresholds benefits both developers and users. In future work, we plan to develop and evaluate estimation procedures for curvature and translation gains and further investigate factors that may contribute to individual variability, such as gender and prior experience. Additionally, the acclimation behavior observed during the staircase method is intriguing and requires further investigation to determine if gains can be progressively increased to further maximize space.

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