Sensitivity to Rate of Change in Gains Applied by Redirected Walking

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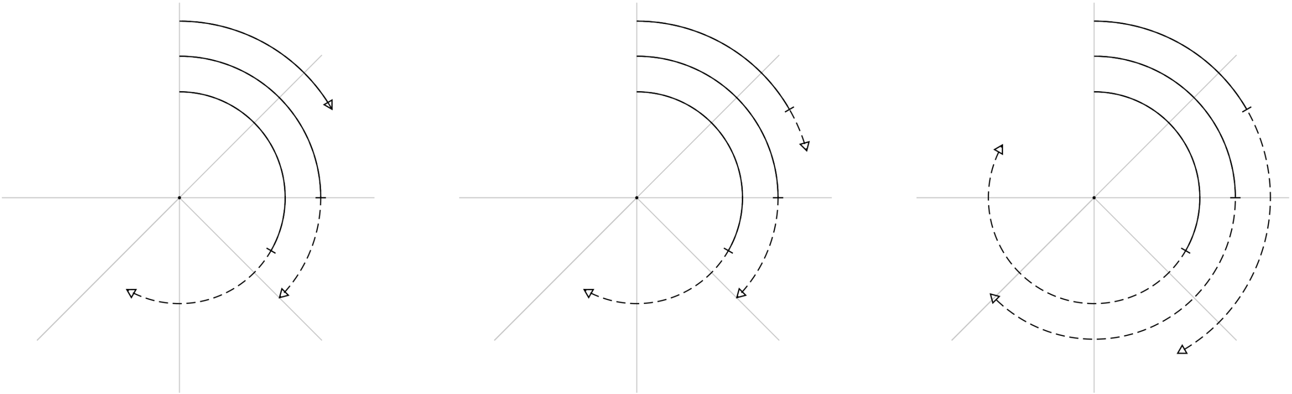

(a) Delay-Max **(b) Slow-Increase** **(c) Start-Max**

Figure 1: A participant's virtual (dotted) and physical (solid) turn angle for each of the three conditions. Starting from the outside, the concentric circles represent the angle of the participant after they have physically turned 60, 90 and 120 degrees respectively. Each condition increases gain at varying rates throughout the turn before reaching the same maximum level.

ABSTRACT

Redirected walking allows for natural locomotion in virtual environments that are larger than a user's physical environment. The mapping between real and virtual motion is modified by scaling some aspect of motion. As a user traverses the virtual environment these modifications (or gains) must be dynamically adjusted to prevent collision with physical obstacles. A significant body of work has established perceptual thresholds on rates of absolute gain, but the effect of changing gain is little understood.

We present the results of a user study on the effects of rate of gain change. A psychophysical experiment was conducted with 21 participants. Each participant completed a series of two-alternative forced choice tasks in which they determined whether their virtual motion differed from their physical motion while experiencing one of three different methods of gain change: sudden gain change, slow gain change and constant gain. Gain thresholds were determined by 3 interleaved 2-up 1-down staircases, one per condition. Our results indicate that slow gain change is significantly harder to detect than sudden gain change.

CCS CONCEPTS

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

KEYWORDS

virtual reality, redirected walking, head-mounted display

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1 INTRODUCTION

Human locomotion and spatial understanding depends on a wide range of sensory cues. With a head-mounted display (HMD) we can replace the visual information a user receives with that of a virtual environment, but associated cues (vestibular, proprioceptive) are harder to provide. Position and orientation data for the HMD can be generated through tracking systems, allowing us to navigate a virtual environment by physically walking in the real world. However, the layout of a virtual environment may not be a good match for the physical environment which will typically be smaller or divided by obstacles. Making larger virtual environments traversible is therefore currently an area of great interest.

A number of techniques emulate locomotion while the virtual reality user remains static. The simplest are those using joysticks,

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"wands" or gaze. Of the three, gaze based movement is the least preferable [Bowman et al. 1997] but all have been shown to increase cognitive load and simulator sickness [Suma et al. 2010b,a] while reducing presence [Ruddle and Lessels 2009; Usoh et al. 1999] when compared with real walking. The main problem appears to be conflict between the visual and vestibular/proprioceptive systems. This conflict is addressed by walking-in-place [Templeman et al. 1999], walking on the spot to move virtually and perhaps generating proprioceptive cues, and teleportation, moving instantaneously or very quickly between points in a virtual environment. Both techniques have been shown to be effective in increasing presence and reducing simulator sickness when compared with joystick movement [Freitag et al. 2014; Slater et al. 1995] but real walking remains preferable on both counts, as well as for navigation and spatial awareness [Cliburn et al. 2009; Ruddle and Lessels 2009; Usoh et al. 1999; Wilson et al. 2016].

Hardware solutions such as omni-directional treadmills [Bouguila and Sato 2002] and motorized walking tiles [Iwata et al. 2005] allow a user to really walk while remaining stationary. The devices supply correct proprioceptive information but are expensive and occupy a considerable amount of space. There is some evidence that they also provide mismatched vestibular cues [Steinicke et al. 2013].

Prior work in perception has shown that minor discrepancies between the visual and vestibular/proprioceptive systems are tolerated and that in some conditions the visual system dominates [Lappe et al. 1999; Warren et al. 2001]. This observation has led to the development of redirected walking [Razzaque 2005]. With this approach, as a user moves in the real world their tracked motion is modified before being applied to the virtual world. Due to visual feedback, this modification is unconsciously accounted for in the user's gait. This disrupts the traditionally 1:1 mapping between virtual and physical environments. In principle with carefully selected modifications users can explore large-scale virtual environments. For example, users can be guided in a circular path in the physical environment while walking in a straight line in the virtual environment. As long as modifications are kept to a low level, redirected walking appears to have no impact on cognitive load and navigational ability [Bruder et al. 2015; Hodgson et al. 2008; Peck et al. 2011; Suma et al. 2011].

Redirected walking has a number of drawbacks and working around these is an area of active research. At high levels of modification the mismatch between visual and vestibular/proprioceptive cues increases and can be perceived by the user [Razzaque 2005]. The need to keep gains imperceptible leads to larger physical space requirements as users are led on wide, curved paths. Existing work estimates the physical space required for unconstrained straight line walking in a virtual environment to be a 22m radius [Steinicke et al. 2010] though some have had success with much smaller environments [Hodgson et al. 2008]. These estimates are guided by thresholds on the absolute rates of gain that are perceptible to humans [Bruder et al. 2012; Steinicke et al. 2010].

In this paper we present the results of an experiment on the effect of rate of gain change. Specifically, we are interested in whether sudden gain changes are more noticeable than slowly increasing gain. We performed a psychophysical study in which participants were asked to determine whether their virtual motion differed from their physical motion while experiencing one of three different methods of gain change. The aim of the study is to investigate whether different rates of gain change affect the level of gain at which users perceive inconsistencies between their virtual and physical motion.

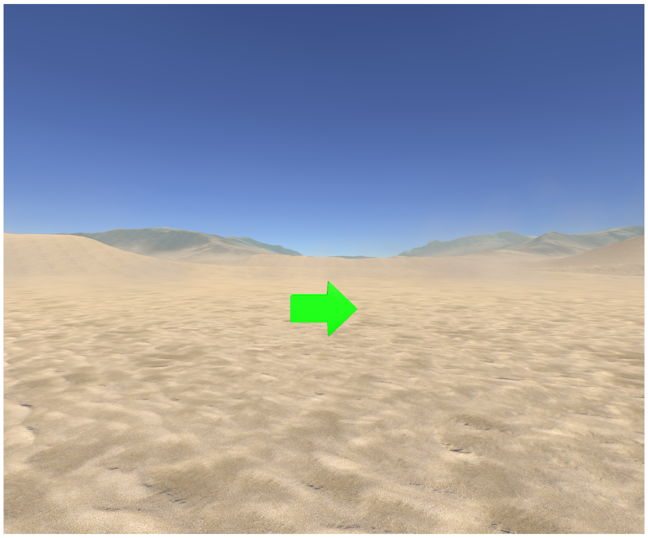


Figure 2: Example view of the virtual environment used for the study. Participant position and orientation were randomized between trials.

The structure of the paper is as follows. Section 2 describes related work on locomotion in virtual reality with particular attention to previous studies on perceptual limits. Section 3 covers the experiment in detail. Section 4 presents the results. Section 5 concludes the paper with a discussion of the results and thoughts on future work.

2 RELATED WORK

A great deal of prior work has found that navigation suffers in virtual environments when compared with reality. Performance in orientation and spatial awareness [Cliburn et al. 2009; Ruddle and Lessels 2009; Wilson et al. 2016], remote distance estimation [Interrante et al. 2006; M. Loomis 2002] and walking distance estimation [Bruder et al. 2012; Frenz et al. 2007; Steinicke et al. 2010]. These effects appear to be lessened when the locomotion interface is walking rather than a wand, teleportation, or walking in place [Freitag et al. 2014; Slater et al. 1995; Usoh et al. 1999].

Some discrepancies between virtual and physical movements appear to be tolerated [Warren et al. 2001]. Large (overt) discrepancies may be comfortable for the user in some circumstances as with *Seven League Boots* [Interrante et al. 2007] wherein physical translational movement is magnified to cover a greater proportion of the virtual environment. However, it was found that this gain had to be applied carefully; magnification needed to be limited to the user's intended direction so as not to exaggerate head sway, and while scale factors of 10 were comfortable, very high levels significantly disrupted user awareness [Williams 2008].

Redirected walking is a different approach which subtly modifies user motion and allows users to adapt to the change, thereby controlling user motion in the physical environment. With low levels of modification user cognition and navigation are not impaired [Hodgson et al. 2008; Peck et al. 2011; Suma et al. 2011]. Early redirected walking studies set values for rotation gain at a level the experimenters found to be imperceptible [Razzaque 2005]. Later work has established more general thresholds through user studies, finding participants could be turned physically in the region of 50% more or 20% less than the perceived virtual rotation [Bruder et al. 2012; Steinicke et al. 2010].

It is possible but not guaranteed that other factors affect these thresholds. Neth et al. found that sensitivity to rotation gains increases at higher walking speeds; i.e., that lower walking speeds allow greater rotation gains [Neth et al. 2012]. Serafin et al. found that with no visual stimulus, users could be virtually turned 20% more or 12% less than their physical rotation through spatialised audio cues [Serafin et al. 2013]. However, Nilsson et al. found that when both audio and visual information is available, redirection detection thresholds were the same for spatialised, static and disabled audio [Nilsson et al. 2016].

Rotation gain rate of change is a possible factor which has received only a small amount of research attention. Zhang examined the effect of rate of gain change on perception thresholds and found no significant difference between gradually changing rotational gains compared to instantaneously changing the gain during 360 degree turns [Zhang and Kuhl 2013]. These results run counter to typical redirected walking implementations which use a smoothing term to avoid instantaneous gain changes and increase rotation gain with walking speed [Hodgson et al. 2008; Peck et al. 2011; Razzaque 2005]. The purpose of this paper is to examine this discrepancy and to further investigate the effects of rate of gain change.

3 USER STUDY

Redirected walking allows the mapping between real and virtual motion to be modified by applying scaling ("gain") to user motion. In this section we present an experiment designed to identify whether rate of gain change affects user experience of motion gain. Each participant was exposed to 3 conditions representing alternative methods of gain change: sudden gain change, slow gain change and constant gain. Participants were divided into two groups, experiencing either larger or smaller virtual turns. For each trial participants physically turned on the spot and a corresponding virtual turn was calculated from the physical motion based on condition and group. Gain levels were selected by following a staircase procedure. One staircase was used per condition and all were interleaved. The result is three thresholds (one per condition) for each participant indicating the level at which a discrepancy between virtual and physical motion can be reliably detected. We expect to find significant differences between the thresholds for each condition.

3.1 Study Design

Participants were asked to complete a series of physical turns while in virtual reality. Each participant wore a HMD and held one controller. Participants were asked to turn only with their feet while looking directly forward and without moving their neck, shoulders, waist or hips. This was stipulated so that motion would be consistent across trials and participants. As participants turned their physical motion was mapped to virtual position as determined by their condition, further described in Section 3.3.

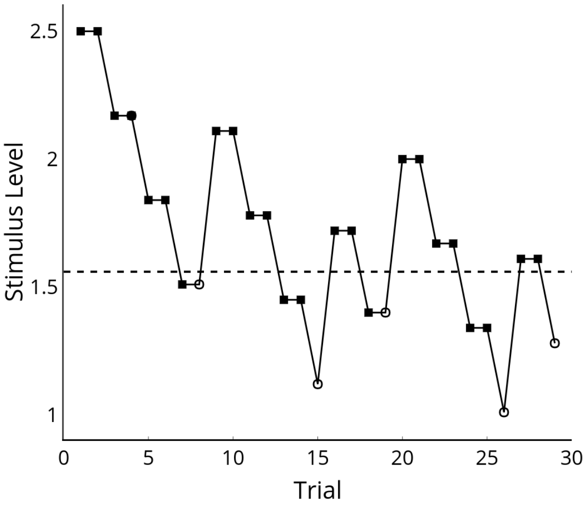


Figure 3: One participant's staircase for the *delay-max* condition. Markers indicate responses to the 2AFC question. Empty markers indicate the stimulus was not detected. The dashed line indicates the threshold estimate for this participant and condition.

Trials followed a precise series of stages within the virtual experience. Participants started each trial with their view faded to grey. Participants were asked to stand up straight and look forward, then invited to press a button on the controller when they were ready to progress. When participants pressed a button, the virtual environment faded in. A small grey sphere was placed in front of the participants. The sphere was replaced by a green arrow when participants' view had fully cleared. Participants then turned in the direction indicated by the arrow. Left and right turns were interspersed to prevent the participant becoming tangled in the HMD cable. Once the participant turned a pre-determined physical angle, the environment faded out. The participant was asked about the turn with a two-alternative forced choice (2AFC) question (further discussed in Section 3.2). Finally, the response was recorded and the participant given the opportunity to rest before the next turn.

Trials where the participant turned too quickly, slowly or inconsistently were rejected. For speed, participants were required to turn physically at between 20 and 80 degrees per second averaged across the entire turn. The test for inconsistency required that participants not turn more than 35 degrees in any 0.25 second window. Trials were also tested to ensure participants did not turn more than a total of 10 (physical) degrees against the desired direction of motion. Should a turn fail one of the tests the 2AFC question would be skipped and the participant informed which test had not been passed. As above, these tests were calculated based on physical turn, ignoring gain.

Participants were divided into two groups. Physical turns for the *virtual-larger* group and the *virtual-smaller* group were mapped to larger and smaller virtual turns respectively. The physical angle for each turn was selected randomly from a range of 100 to 130 degrees. The point at which a turn was deemed complete was based entirely on physical turn, ignoring gain magnitude and gain condition.

The gain for each turn was selected following a staircase procedure where levels of gain were adjusted up and down based on responses to the 2AFC question [Cornsweet 1962]. Additional "neutral" trials with no gain applied were also interleaved with the trials required for the staircases. The intention with these trials was to prevent participants acclimatizing to high levels of gain. Details of the staircases used including all parameters and the interleaving mechanism for neutral trials can be found in Section 3.2.

Each participant completed a short training step before the experiment began. A total of 8 training trials were used, 2 with no gain applied and 2 interspersed trials for each condition where the maximum gain was set to 5. Participants were told when a training turn was the same as their physical movement and when gain was applied. The intention behind the training step was to allow participants to familiarize themselves with the sense of movement in virtual reality and to practice the particular turning movement and speeds we required. Additionally, by using a very high level of gain during the training step the aim was for participants to be able to recognize gain being applied and not discount it as a problem with the equipment or software. Finally, before starting the experiment each participant completed 2 further trials with no gain applied to re-familiarize with normal turning motion.

The virtual environment was designed to allow participants to have a sense of their own motion while avoiding discrete markers that could be used to orientate across trials. We specifically aimed to avoid 90 degree angles (e.g., on buildings or crossroads). The result was the desert environment seen in Figure 2. The environment was textured and included gradual slopes and a skybox to provide enough information for both optical flow and landmark recognition [Warren et al. 2001]. A selection of 9 spawn points were chosen and the participant moved between these randomly while their view was faded to grey between trials. The participant's starting (virtual) orientation in the transverse plane was also randomized. No spawn point was visible from any other, with the intention of preventing participants from "learning" the environment as much as possible.

3.2 Staircase Procedure

Staircase procedures are adaptive psychophysical techniques that aim to estimate the level at which a stimulus (in this case, the maximum extreme of gain, high or low depending on group) is perceptible to a user. Following this method, gain levels were dynamically adjusted up and down between each turn based on participant responses. An example of a participant's staircase for one condition can be seen in Figure 3. Responses were in the form of a 2AFC where participants received the prompt "Compared with my physical movement..." and were asked to choose from two options. The first option was always "My movement in the virtual world was the same as my physical movement", indicating the participant did not detect the stimulus. The second option was either "My movement in the virtual world was smaller than my physical movement" or "My movement in the virtual world was larger than my physical movement" depending on whether the participant was in the *virtual-smaller* or *virtual-larger* group respectively. This option indicated the participant detected the stimulus.

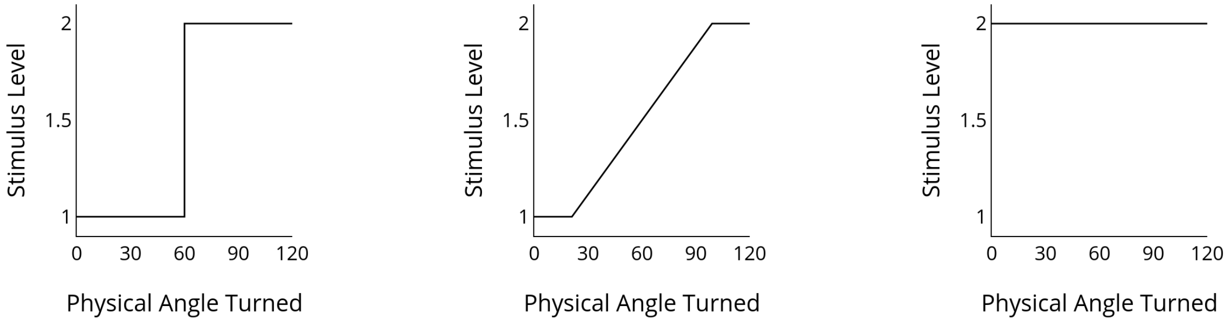
Often multiple "positive" responses are required to reduce the stimulus level when using staircase procedures. Different staircase designs provide thresholds at different levels on the psychometric curve, i.e., at different levels of user certainty. We used a 1-up 2-down staircase to approximate the level at which participants can identify whether the stimulus is present with a success rate of 70.7% [Leek 2001]. With this method the stimulus would be decreased if the participant indicated they detect the stimulus twice in a row, and would be increased if the participant indicates they do not detect the stimulus once. Thresholds were calculated by averaging the stimulus values at "reversal" points - the levels at which the staircase changes direction.

Each staircase was run until it had reversed 8 times, ignoring the first response where initial direction was determined, and the experiment continued until all three staircases were complete. The final 7 reversal values were averaged to generate the threshold for each condition. The spread is the range of stimulus values over which the underlying psychometric function is non-asymptotic. Based on existing studies [Bruder et al. 2012; Steinicke et al. 2010] we anticipated a spread of 1 based on stimulus levels between 1 and 2. For each downward step the stimulus was decreased by 0.32928 and each upward step the stimulus was increased by 0.6, for a ratio of 0.5488 [García-Pérez 1998]. The initial stimulus was set at 2.5, significantly above the presumed threshold, to give participants a sense of extremes of gain [M. Green et al. 1989]. The lower limit on stimulus was 1. Should the staircase reach this point positive detection responses were still accepted but the stimulus would not be decreased. No upper limit on stimulus was stipulated.

Three staircases were used to accommodate the three conditions. These staircases were interleaved, meaning that subsequent trials would be drawn from different staircases. Each staircase was entirely self-contained and the response to each trial only affected the staircase from which that trial was selected. The purpose of interleaving is to obfuscate the staircase mechanism from the perspective of the participant, encouraging them to rely on their observations rather than guessing at the staircase progression [Leek 2001]. The interleaving procedure was random except for the following constraints. Firstly, that every four trials included at least one turn for each incomplete staircase. Secondly, that every four trials included exactly one neutral trial. Finally, that no trial from already completed staircases was included.

3.3 Conditions

As participants follow the procedure outlined in Section 3.1 their physical turn is mapped to a larger or smaller virtual motion. The specifics of the mapping are dependent upon the condition selected for the trial. Each trial uses one of the three conditions described in this section. These conditions are not intended to be methods for achieving redirected walking but rather to be representative of different contexts in which users might experience gain change: either sudden gain change, slow gain change or no gain change at all (that is, constant gain). Physical and virtual head orientations consist of a 3-dimensional vector such that:



(a) Delay-Max **(b) Slow-Increase** **(c) Start-Max**

Figure 4: Stimulus levels at points during the participant's turn for each of the the three conditions assuming a g_{target} of 2. The gain applied is calculated from the stimulus level based on group (see Section 3.3). Due to randomized parameters the actual stimulus values for each trial may differ slightly.

$$\mathbf{r} = (\theta_s, \theta_t, \theta_f) \tag{1}$$

Where θ_s, θ_t and θ_f are the angles of orientation in the sagittal, transverse and frontal planes respectively (equivalently pitch, yaw and roll). Gain is applied to participant motion regardless of whether direction is with or against the direction specified by the trial. However, as is common with redirected walking, we only apply gain in the transverse plane [Razzaque 2005]. We therefore eschew a 3-dimensional gain vector and focus on the transverse gain g. Virtual turns are calculated from the physical with this gain factor:

$$\theta_{t,virt} = g \cdot \theta_{t,phys} \tag{2}$$

Should $g = 1$ a virtual turn will match the physical turn one-to-one. If $g > 1$ the virtual turn be larger, possibly giving a user the impression the world is turning against them. By contrast, when $g < 1$ the virtual turn will be smaller, giving users the sense that the virtual world is turning with them. For example, should a user physically rotate 180 degrees in the transverse plane while looking forward, gains of $g = 0.5$, $g = 1$ and $g = 2$ will cause the virtual camera to rotate 90, 180 and 360 degrees respectively, also in the transverse plane.

Section 3.1 describes how the stimulus level provided by staircases increases and decreases with participant responses. The stimulus level is bounded between 1 and infinity and always decreases when participants are aware of gain, increasing otherwise. Stimulus should therefore be considered a measure of the intensity of gain to be applied. We distinguish between stimulus and gain so staircases can increase or decrease in constant units, and so the two groups (*virtual-larger* and *virtual-smaller*) can be compared. Here we describe how gain is calculated from the stimulus level. Note that as the gain applied at any given moment during a turn depends upon the condition, stimulus s instead controls the target gain reached during a turn. This mapping varies by participant group:

$$g_{target} = \begin{cases} s & \text{if } \textit{virtual-larger} \\ s^{-1} & \text{if } \textit{virtual-smaller} \end{cases} \tag{3}$$

The study uses a within-subjects design with 3 conditions representing different approaches to rate of gain change. The condition determines moment to moment gain within a trial. Visualizations of the three conditions can be found in Figure 1 and Figure 4.

3.3.1 *Start-Max.*

In trials with the *start-max* condition gain is immediately set to the maximum gain determined by stimulus and remains at max until the trial is complete. This condition is intended to provide gain without abrupt gain change.

$$g = g_{target} \tag{4}$$

The gain is set before the participant's view has faded in and continues until the view has entirely faded out. The screen which participants observe between trials has no visual features to prevent the sensation of sudden gain change at the start or end of the trial.

3.3.2 *Slow-Increase.*

Initially no gain is applied (i.e., $g = 1$). As the participant turns the gain is slowly interpolated towards the target. The target gain will always be reached before the trial is complete. This condition was intended to provide gain through a long period of very low gain change.

$$g = 1 + (g_{target} - 1) \cdot \text{clamp}\left(\frac{\theta - \theta_{begin}}{\theta_{complete} - \theta_{begin}}\right) \tag{5}$$

Where θ is the angle currently turned, θ_{begin} is the angle at which interpolation is started and $\theta_{complete}$ is the angle at which interpolation ends. The angles θ, θ_{begin} and $\theta_{complete}$ all refer to the participant's physical angle before gain is applied. The function clamp limits the input to a value between 0 and 1 inclusive. Turning against the target direction did not increase θ. The value of θ_{begin} and $\theta_{complete}$ depended upon the θ_{total}, the total physical angle selected for the trial:

$$\theta_{begin} = s_0 \cdot \theta_{total} \tag{6}$$

$$\theta_{complete} = \theta_{begin} + s_1 \cdot (\theta_{total} - \theta_{begin}) \tag{7}$$

Where s_0 and s_1 are configuration values. In our experiment s_0 was a randomized variable between 0.125 and 0.175 and s_1 was set to 0.65. The intention was that the user experience the target level of gain for some time before the turn was complete. Turns against the target direction did not increase the gain.

3.3.3 Delay-Max. Initially no gain is applied. Once the participant reaches a pre-determined point in their turn, gain is immediately set to the target. This condition was intended to provide gain through a short period of very high gain change.

$$g = \begin{cases} 1 & \text{if } \theta < \theta_{delay} \\ g_{target} & \text{if } \theta \geq \theta_{delay} \end{cases} \tag{8}$$

Where θ is the physical angle currently turned and θ_{delay} is the physical angle at which gain is set to the target. Turning against the target direction did not increase θ. The value of θ_{delay} depended upon θ_{total}, the total physical angle selected for the trial:

$$\theta_{delay} = d \cdot \theta_{total} \tag{9}$$

Where d is a configuration value. In our experiment d was a randomized variable between 0.35 and 0.65.

3.4 Outcome Measures

The primary outcome measures were the thresholds generated by the staircases for each condition (see Section 3.2). Participants were also asked to complete a short questionnaire on their age, gender and level of virtual reality experience. This information was collected for analysis alongside the thresholds to see if there was an effect on general threshold levels or response to individual conditions. Information on participant's level of virtual reality experience was gathered via multiple choice question with the options: "Never", "1-2 times", "3-5 times", "6-10 times", "10-50 times" and "50+ times". For the purpose of analysis, participants who chose one of the first three responses were considered "inexperienced" while those who selected one of the final three responses were considered "experienced". Additionally, participant responses to the 2AFC were recorded during neutral trials to get a sense of each participant's general level of accuracy. Telemetry data (head position and orientation) was gathered throughout each trial.

3.5 Study Setup

Participants wore a HTC Vive Pro headset and held one Vive hand controller. The display has a resolution of 1440 x 1600 per eye, a refresh rate of 90hz and a vertical field of view of 110 degrees. The Vive native tracking system was used for position and orientation information. The HMD was set to the mean interpupillary distance of 63mm [Dodgson 2004]. The virtual environment was developed in Unity3D with the SteamVR plugin. The system running the experiment was using the Windows 10 operating system and was powered by a 6 core Intel CPU, 16GB of memory and an NVIDIA GTX 2080. The maximum refresh rate of 90 frames per second was maintained throughout the study.

The HMD was connected to the system via wire. Occasionally participants would drift from the center of the room. When this occurred the experimenter would pause the experiment and guide the participant back. With the exception of this and the training step, all information relevant to the experiment was contained within the virtual environment such that no communication or intervention was required between participant and experimenter and participants were able to proceed at their own pace.

3.6 Study Protocol

The study took approximately 30 minutes per participant. On arrival the experimenter gave the participant an information sheet describing the study and invited the participant to read the sheet and ask any questions they may have. The experimenter then asked the participant to complete the pre-questionnaire (see Section 3.4).

The experimenter briefly described visual/vestibular conflict and the participant was told the goal of the study was to better understand this conflict. The mechanics of virtual gain were explained to the participant and they were told whether to expect a *virtual-larger* or *virtual-smaller* stimulus. The individual conditions (described in Section 3.3) were excluded from the discussion.

The participant was shown to the track space and provided with the HMD and their controller which were adjusted for fit. The experimenter loaded the virtual environment and proceeded with the training step. The experimenter then started the core study step and allowed participants to proceed at their own pace. Both training and study steps are as described in Section 3.1.

The study step continued until the virtual environment reported all staircases had concluded. The experimenter asked participants to remove the HMD. The participant was debriefed and their travel expenses compensated. Finally, they were given the opportunity to ask questions and give feedback.

3.7 Participants

Participants were recruited from graduate study mailing lists and external advertisements and paid £5 to cover travel expenses. Participants were required to be between the ages 18 and 65 and to be able to walk unassisted.

A total of 23 participants were recruited. 2 participants became nauseous and were not able to complete the study. These results were excluded from analysis. Of the remaining 21 participants, 8 were female and 13 male and the mean age was 28.57 with a standard deviation of 7.72. This study was approved by the University College London Research Ethics Committee.

4 RESULTS

Table 1 shows the mean and standard deviation for each combination of group and condition. Note that these refer to stimulus values

Table 1: Threshold stimulus levels for each combination of group and condition.

Condition	Group	N	Mean	SD
delay-max	virtual-smaller	11	1.842	0.704
slow-increase	virtual-smaller	11	3.139	1.932
start-max	virtual-smaller	11	2.515	1.378
delay-max	virtual-larger	10	3.576	2.599
slow-increase	virtual-larger	10	4.037	2.904
start-max	virtual-larger	10	3.049	1.630
delay-max	experienced	11	1.563	0.325
slow-increase	experienced	11	1.972	0.481
start-max	experienced	11	2.005	1.027
delay-max	inexperienced	10	3.883	2.411
slow-increase	inexperienced	10	5.321	2.503
start-max	inexperienced	10	3.610	1.504
delay-max	combined	21	2.668	2.019
slow-increase	combined	21	3.567	2.423
start-max	combined	21	2.769	1.490

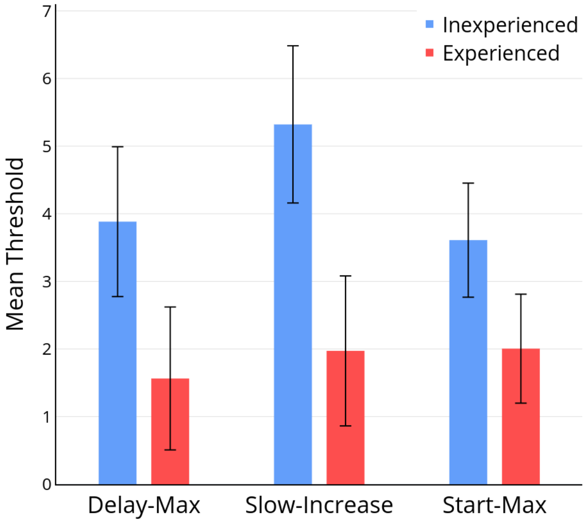


Figure 5: Mean stimulus thresholds across conditions for the *experienced* and *inexperienced* groups. Error bars are 95% CI.

rather than gain. Higher stimulus threshold values indicate that a further extreme of gain is required to make the condition perceptible (i.e., that the condition is harder to detect). Two participants in the *virtual-larger* group were found to have very high threshold values (>8 stimulus). As the results showed clear differences between conditions and accuracy when responding to neutral trials was good (>90%) it appeared that the participants had understood the task so the results were included in the analysis.

A four-way mixed ANOVA with one within-subjects factor and three between-subjects factors was conducted to investigate the effect of rate of gain change on detection thresholds. The within-subjects factor was the threshold stimulus level under the three gain conditions: *slow-increase*, *delay-max* and *start-max*. The between-subjects factors were gain direction, gender and virtual reality experience. The gain direction groups were: *virtual-larger* (N = 10) and *virtual-smaller* (N = 11). Gender groups were: male (N = 13) or female (N = 8). Virtual reality experience groups were delineated using the methodology described in Section 3.4 and were: experienced, (N = 11) and inexperienced (N = 10).

No statistically significant three- or four-way interactions were found. A narrowly significant two-way interaction was found between virtual reality experience and gain condition, F(2,26) = 3.544, p = 0.044, partial η^2 = 0.214. Post hoc tests were conducted to calculate the simple main effect for virtual reality experience, indicating a significant difference between stimulus threshold at each gain condition: *slow-increase*, F(1,19) = 19.021, $p < 0.001$, partial η^2 = 0.5, *delay-max*, F(1,19) = 10.034, p = 0.005, partial η^2 = 0.346, *start-max*, F(1,19) = 8.294, p = 0.01, partial η^2 = 0.304. The simple main effect for gain condition was also evaluated. For the inexperienced group the difference between threshold values was statistically significant, F(2,18) = 7.978, p = 0.003, partial η^2 = 0.470. Post hoc pairwise comparisons with Bonferroni adjustment indicate a significant difference between *slow-increase* and both the *delay-max* condition, p = 0.042, and the *start-max* condition. In the experienced group the difference between threshold values was not statistically significant, F(2,20) = 3.168, p = 0.064, partial η^2 = 0.241. We include pairwise comparisons due to the narrow margin, finding a significant difference between *slow-increase* and *delay-max* only, p = 0.005. No other statistically significant two-way interactions were found.

The main effect of condition showed a statistically significant difference in thresholds between gain conditions, F(2,26) = 5.121, p = 0.013, partial η^2 = 0.283. Post hoc pairwise comparisons with Bonferroni adjustment indicated a significant difference between *slow-increase* and *delay-max* conditions, p = 0.025. No significant pairwise differences were found between the *start-max* condition and the other conditions.

The main effect of virtual reality experience showed a statistically significant difference in stimulus thresholds between the experienced and inexperienced groups, F(1,13) = 12.106, p = 0.004, partial η^2 = 0.482. The main effect of gender showed no significant difference in stimulus thresholds, F(1,13) = 1.7, p = 0.215. The main effect of gain direction also showed no significant difference in stimulus thresholds, F(1,13) = 1.379, p = 0.261.

5 DISCUSSION

Our results indicate there is a significant difference between thresholds for *delay-max* and *slow-increase*. This supports the hypothesis that users are highly sensitive to sudden changes in gain. While there was a large variance between participants in absolute thresholds, all 21 participants had a higher threshold for *slow-increase* than *delay-max*. The *slow-increase* and *delay-max* conditions can be effectively compared as they fundamentally operate similarly. Participants started trials for these conditions at no gain and ended trials at the gain target, with the gain level increasing as they turned. Likewise trials with these conditions covered approximately similar total virtual angles, with slight variation due to the randomized parameters. We can be confident that the observed difference between these two conditions is caused by users detecting the sudden gain change.

We found no significant difference between *start-max* and any other condition in our main effect analysis. We did, however, find a significant difference ($p < 0.05$) between *start-max* and *slow-increase* in the inexperienced group only. Comparison between *start-max* and the other conditions is difficult as while the maximum gain level reached during a turn is the same, the total gain applied is greater. Gain is introduced immediately in this condition, so it could be possible that users are detecting the difference between the gain used in previous trials or during the 2AFC question rather than a mismatch between visual and vestibular cues, particularly as it was the inexperienced group who experienced higher levels of gain. The findings for *start-max* should be considered inconclusive. It would be an extremely interesting finding if, as is suggested by results for the *experienced* group, at low levels of gain participants are primarily sensitive to rate of gain change and not absolute gain level. This suggests a promising avenue for further work.

Our results also indicate that level of virtual reality experience has a significant effect on a user's ability to identify gain. The more experienced participants in our study were able to determine whether gain was present with much greater accuracy leading to considerably lower thresholds in all gain conditions as seen in Figure 5. We also found a change in the experienced users' perception of the gain conditions. Unlike the inexperienced group a statistically significant difference between gain conditions was not found ($p = 0.064$) and effect size was smaller (partial $\eta^2 = 0.241$ as opposed to partial $\eta^2 = 0.470$). This could be a factor of the lower levels of gain the experienced group encountered.

Thresholds were higher than those found in similar psychophysical studies. This is particularly true for the *virtual-larger* group. There is not a wealth of data for comparison with for the *slow-increase* or *delay-max* conditions, but the *start-max* condition is the same approach used by Steinicke [Steinicke et al. 2010] and Bruder [Bruder et al. 2012], so we would expect similar thresholds. As we were looking for differences between conditions the absolute values of the thresholds are less important but worth considering. In our experiment participants only experienced either higher or lower gain, depending on their group, and the gain experienced was entirely within the control of the user through the staircase. It seems possible that participants were adapting to the higher levels of gain they reached; by contrast, participants in [Bruder et al. 2012; Steinicke et al. 2010] were exposed to a range of gains centered around 1 causing each participant to be exposed to virtual rotations both smaller and larger than their physical turns. The virtual environment used could also be a contributing factor. As vision is partially dependent on landmark recognition [Warren et al. 2001] and our desert environment is relatively simple (see Figure 2), it may have been harder for participants to understand how far they had turned than in the city environments used in [Bruder et al. 2012; Steinicke et al. 2010].

6 CONCLUSION

In this paper we described a study that investigated the effect of rate of gain change as measured by a within-subjects psychophysical experiment with adaptive 2-up 1-down staircases. We compared sudden gain change, slow gain change and constant gain. Our results indicate that rate of gain change has a significant effect on user experience of motion gain. In particular, slow gain change appears significantly more subtle than sudden gain change. We also found that more experienced users of virtual reality were able to identify levels of gain significantly more accurately than less experienced users. These finding should be helpful for future redirected walking implementations by confirming that gain smoothing is an important factor in keeping redirected walking imperceptible.

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REFERENCES

Laroussi Bouguila and Makoto Sato. 2002. Virtual locomotion system for large-scale virtual environment. In *Proceedings IEEE Virtual Reality 2002*. 291–292. https://doi.org/10.1109/VR.2002.996544

Doug A. Bowman, David Koller, and Larry F. Hodges. 1997. Travel in Immersive Virtual Environments: An Evaluation Motion Control Techniques of Viewpoint. *Proc. IEEE Virtual Reality Annual Symposium* (1997). https://doi.org/10.1109/VRAIS.1997.583043

Gerd Bruder, Victoria Interrante, Lane Phillips, and Frank Steinicke. 2012. Redirecting walking and driving for natural navigation in immersive virtual environments. *IEEE Transactions on Visualization and Computer Graphics* 18, 4 (2012), 538–545. https://doi.org/10.1109/TVCG.2012.55

Gerd Bruder, Paul Lubos, and Frank Steinicke. 2015. Cognitive Resource Demands of Redirected Walking. *IEEE Transactions on Visualization and Computer Graphics* 21, 4 (2015), 539 – 544. https://doi.org/10.1109/TVCG.2015.2391864

Daniel Cliburn, Stacy Rilea, David Parsons, Prakash Surya, and Jessica Semler. 2009. The Effects of Teleportation on Recollection of the Structure of a Virtual World. In *Proceedings of the 15th Joint Virtual Reality Eurographics Conference on Virtual Environments (JVRC'09)*. Eurographics Association, Aire-la-Ville, Switzerland, Switzerland, 117–120. https://doi.org/10.2312/EGVE/JVRC09/117-120

Tom N. Cornsweet. 1962. The staircase-method in psychophysics. *The American journal of psychology* (1962).

Neil A. Dodgson. 2004. Variation and extrema of human interpupillary distance. In *Proc. SPIE 5291*. 36–46.

Sebastian Freitag, Dominik Rausch, and Torsten Kuhlen. 2014. Reorientation in virtual environments using interactive portals. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*. 119–122. https://doi.org/10.1109/3DUI.2014.6798852

Harald Frenz, Markus Lappe, Marina Kolesnik, and Thomas Bührmann. 2007. Estimation of Travel Distance from Visual Motion in Virtual Environments. *ACM Trans. Appl. Percept.* 4, 1 (jan 2007). https://doi.org/10.1145/1227134.1227137

Miguel A. García-Pérez. 1998. Forced-choice staircases with fixed step sizes: Asymptotic and small-sample properties. *Vision Research* (1998). https://doi.org/10.1016/S0042-6989(97)00340-4

Eric Hodgson, Eric Bachmann, and David Waller. 2008. Redirected Walking to Explore Virtual Environments: Assessing the Potential for Spatial Interference. *ACM Trans. Appl. Percept.* 8, 4 (dec 2008), 22:1—-22:22. https://doi.org/10.1145/2043603.2043604

Victoria Interrante, Brian Ries, and Lee Anderson. 2006. Distance Perception in Immersive Virtual Environments, Revisited. In *IEEE Virtual Reality Conference (VR 2006)*. 3–10. https://doi.org/10.1109/VR.2006.52

Victoria Interrante, Brian Ries, and Lee Anderson. 2007. Seven league boots: A new metaphor for augmented locomotion through moderately large scale immersive virtual environments. In *IEEE Symposium on 3D User Interfaces 2007 - Proceedings, 3DUI 2007*. 167–170. https://doi.org/10.1109/3DUI.2007.340791

Hiroo Iwata, Hiroaki Yano, Hiroyuki Fukushima, and Haruo Noma. 2005. CirculaFloor: A Locomotion Interface Using Circulation of Movable Tiles. In *Proceedings of the 2005 IEEE Conference 2005 on Virtual Reality (VR '05)*. IEEE Computer Society, Washington, DC, USA, 223–230. https://doi.org/10.1109/VR.2005.11

Markus Lappe, Frank Bremmer, and Albert van den Berg. 1999. Perception of self-motion from visual flow. *Trends in Cognitive Sciences* 3 (1999), 329–336.

Marjorie R. Leek. 2001. Adaptive procedures in psychophysical research. *Perception & Psychophysics* 63, 8 (nov 2001), 1279–1292. https://doi.org/10.3758/BF03194543

David M. Green, Virginia M. Richards, and Timothy Forrest. 1989. Stimulus step size and heterogeneous stimulus conditions in adaptive psychophysics. *Acoustical Society of America Journal* 86 (1989), 629–636. https://doi.org/10.1121/1.398759

Jack M. Loomis. 2002. Visual Perception of Egocentric Distance in Real and Virtual Environments. (2002).

Christian T. Neth, Jan L. Souman, David Engel, Uwe Kloos, Heinrich H. Bülthoff, and Betty J. Mohler. 2012. Velocity-dependent dynamic curvature gain for redirected walking. *IEEE Transactions on Visualization and Computer Graphics* 18, 7 (2012), 1041–1052. https://doi.org/10.1109/TVCG.2011.275

Niels Christian Nilsson, Evan Suma, Rolf Nordahl, Stefania Serafin, and Niels Christian Nilsson. 2016. Estimation of Detection Thresholds for Audiovisual Rotation Gains. January (2016), 1–3.

Tabitha C. Peck, Henry Fuchs, and Mary C. Whitton. 2011. An evaluation of navigational ability comparing Redirected Free Exploration with Distractors to Walking-in-Place and joystick locomotio interfaces. In *Proceedings - IEEE Virtual Reality*. 55–62. https://doi.org/10.1109/VR.2011.5759437

Sharif Razzaque. 2005. *Redirected Walking*. Ph.D. Dissertation. Chapel Hill, NC, USA.

Roy. A. Ruddle and Simon Lessels. 2009. The benefits of using a walking interface to navigate virtual environments. *ACM Transactions on Computer-Human Interaction* 16, 1 (2009), 1–18. https://doi.org/10.1145/1502800.1502805

Stefania Serafin, Niels C. Nilsson, Erik Sikstrom, Amalia De Goetzen, and Rolf Nordahl. 2013. Estimation of detection thresholds for acoustic based redirected walking techniques. *Proceedings - IEEE Virtual Reality* April 2016 (2013), 161–162. https://doi.org/10.1109/VR.2013.6549412

Mel Slater, Martin Usoh, and Anthony Steed. 1995. Taking steps: the influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction* 2, 3 (1995), 201–219. https://doi.org/10.1145/210079.210084 arXiv:arXiv:1011.1669v3

Frank Steinicke, Gerd Bruder, Jason Jerald, Harald Frenz, and Markus Lappe. 2010. Estimation of detection thresholds for redirected walking techniques. *IEEE Transactions on Visualization and Computer Graphics* 16, 1 (2010), 17–27. https://doi.org/10.1109/TVCG.2009.62

Frank Steinicke, Yon Visell, Jennifer Campos, and Anatole Lécuyer. 2013. *Human Walking in Virtual Environments: Perception, Technology, Applications*. Springer. https://doi.org/10.1007/978-1-4419-8432-6

Evan Suma, Samantha Finkelstein, Myra Reid, Sabarish Babu, Amy Ulinski, and Larry F. Hodges. 2010b. Experimental Evaluation of the Cognitive Effects of Travel Technique in Immersive Virtual Environments. *IEEE Transactions on Visualization and Computer Graphics* 16, 4 (2010), 690–702. https://doi.org/10.1109/TVCG.2009.93

Evan A. Suma, Samantha L. Finkelstein, Seth Clark, Paula Goolkasian, and Larry F. Hodges. 2010a. Effects of travel technique and gender on a divided attention task in a virtual environment. In *3DUI 2010 - IEEE Symposium on 3D User Interfaces 2010, Proceedings*. 27–34. https://doi.org/10.1109/3DUI.2010.5444726

Evan A. Suma, David M. Krum, Samantha Finkelstein, and Mark Bolas. 2011. Effects of redirection on spatial orientation in real and virtual environments. *3DUI 2011 - IEEE Symposium on 3D User Interfaces 2011, Proceedings* April 2016 (2011), 35–38. https://doi.org/10.1109/3DUI.2011.5759214

James N. Templeman, Patricia S. Denbrook, and Linda E. Sibert. 1999. Virtual Locomotion: Walking in Place through Virtual Environments. *Presence: Teleoperators and Virtual Environments* 8, 6 (1999), 598–617. https://doi.org/10.1162/105474699566512

Martin Usoh, Kevin Arthur, Mary Whitton C., Rui Bastos, Anthony Steed, Mel Slater, and Frederick P. Brooks Jr. 1999. Walking > walking-in-place > flying, in virtual environments. *SIGGRAPH '99 Proceedings of the 26th annual conference on Computer graphics and interactive techniques* (1999), 359–364. https://doi.org/10.1145/311535.311589

William H. Warren, Bruce Kay, Wendy D. Zosh, Andrew P. Duchon, and Stephanie Sahuc. 2001. Optic flow is used to control human walking. *Nature Neuroscience* 4 (2001), 213–216.

Betsy Williams. 2008. *Design and evaluation of methods for motor exploration in large virtual environments with head-mounted display technology*. Ph.D. Dissertation. Vanderbilt University.

Preston Tunnell Wilson, William Kalescky, Ansel MacLaughlin, and Betsy Williams. 2016. VR Locomotion: Walking > Walking in Place > Arm Swinging. In *Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry - Volume 1 (VRCAI '16)*. ACM, New York, NY, USA, 243–249. https://doi.org/10.1145/3013971.3014010

Ruimin Zhang and Scott A. Kuhl. 2013. Human Sensitivity to Dynamic Rotation Gains in Head-mounted Displays. In *Proceedings of the ACM Symposium on Applied Perception (SAP '13)*. ACM, New York, NY, USA, 71–74. https://doi.org/10.1145/2492494.2492514