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Strafing Gain: Redirecting Users One Diagonal Step at a Time

Christopher You* University of Florida
Brett Benda† University of Florida
Evan Suma Rosenberg‡ University of Minnesota
Eric Ragan§ University of Florida
Benjamin Lok¶ University of Florida
Jerald Thomas‖ Virginia Tech

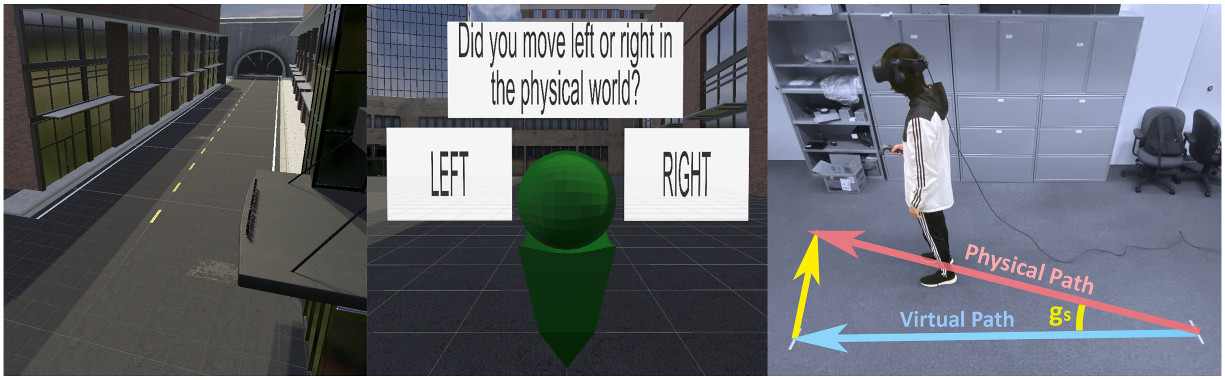

Figure 1: **Left**: The city environment used in our experiment was intended to help users explore infinitely large virtual environments using redirected walking. **Middle**: The way-point walked to by users and sign prompting them with a 2AFC question. **Right**: Redirected by strafing gain, users walk directly forward along a virtual path while walking along a diagonal physical path. As they walk, their path is shifted according to strafing gain, g_S.

ABSTRACT

Redirected walking can effectively utilize a user's physical space when traversing larger virtual environments by using virtual self-motion gains for a user's physical motions. In particular, curvature gain presents unique advantages in redirection but can lead to sub-optimal orientations. To prevent this and add additional utility in redirected walking, we formally present *strafing gain*. Strafing gain seeks to add incremental lateral movements to a user's position causing the user to walk along a diagonal trajectory while maintaining the original orientation of the user. In a study with 27 participants, we tested 11 values to determine the detection thresholds of strafing gain. The study, which was modeled on prior detection threshold studies, found that strafing gain could successfully redirect participants to walk along a 5.57° diagonal to the right and a 4.68° diagonal to the left. Furthermore, a supplementary study with 10 participants was conducted, verifying that orientation was maintained throughout redirection and validating the obtained detection thresholds. We discuss the implications of these findings and potential ways of improving these quantities in real-world applications.

Keywords: redirected walking, virtual reality, gain, strafing gain, detection threshold

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Computing methodologies—Computer graphics—Graphics systems and interfaces—Virtual reality;

1 INTRODUCTION

With the advances in virtual reality (VR) technology, VR experiences via head-mounted displays are becoming increasingly popular. While many would agree that VR has a multitude of benefits, there are challenges that research has pursued to improve. One such challenge is locomotion in VR. That is, how do we navigate through a seemingly endless virtual environment with respect to the user's physical environment?

Locomotion through the form of hand-held controllers or hand-based interfaces are an established method towards solving this problem; however, previous work has found that physical interaction may have a more positive impact in terms of presence [18]. Additionally, when locomotion is achieved through interactions more similar to physically walking, it can result in higher immersion and lower simulator sickness [15, 18]. Locomotion in the form of physically walking comes with its own set of challenges. The primary challenge is that the virtual environment is generally much larger than the physical environment, making physical walking a limited form of locomotion in VR. While methods such as walking-in-place [33] and devices such as omnidirectional treadmills have been used to approach this problem, they too come with their own set of obstacles such as level of immersion and cost.

Redirected walking (RDW) is a technique that attempts to address the problem of utilizing a user's physical space by changing the mapping between a user's physical and virtual movements [27]. The mapping between the user's physical and virtual movements are 1:1 by default. That is, movement in the physical world results in the same movement in the virtual world. By changing this 1:1 mapping, one can redirect or reorient the user along physical paths that differ from the virtual path. An example of a changed mapping is seen in the use of locomotion via teleportation using a joystick. Here, despite the user moving or reorienting virtually, the user's physical state is the same as it was before. RDW adopts this idea by changing the mapping between user's physical movements and virtual movement

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*e-mail: christopheryou@ufl.edu
†e-mail: brett.benda@ufl.edu
‡e-mail: suma@umn.edu
§e-mail: eragan@ufl.edu
¶e-mail: lok@cise.ufl.edu
‖e-mail: jeraldlt@vt.edu

when the user physically moves their body. To do this, RDW uses techniques, called gains, that support this manipulation.

Gains are redirection techniques that attempt to amplify, attenuate, or correct a user's motions in the physical world, often in attempt to utilize the user's space. *Curvature gain* is a technique that subtly causes the user to walk along a curve by rotating the user's perspective as they walk. While curvature gain can effectively help users avoid obstacles in their space, curvature gain causes the user's resulting orientation to differ from their original orientation prior to curvature gain. The resulting orientation can be problematic: users may be redirected to a more open-space, but the orientation may be sub-optimal (Fig. 2). This can potentially be rectified by the usage of additional gains. However, gains cannot always be applied as the necessary gain may exceed the perceptual threshold, resulting in the usage of a reset instead [36]. We propose redirection without largely disrupting orientation to allow for later redirection in a formal introduction of the technique, *strafing gain*. Originally presented in a poster by You et al. [38], strafing gain redirects users along a diagonal path by laterally shifting users as they walk. While this preliminary work introduced the initial concept, there have not yet been any empirical studies to determine the thresholds for detection required for this method to be adopted by the VR community.

This paper provides two novel contributions to VR and RDW.

- First, we expand upon the concept of strafing gain and present a formalized description and demonstrate potential applications of strafing gain.
- Second, this paper identifies the detection thresholds of strafing gain to determine the degree to which redirection can be applied, while validating the claims made regarding orientation maintenance.

The overarching goal is to increase the applicability of strafing gain and allow for greater adoption of RDW in practical usages of VR.

2 RELATED WORK

Prior work has investigated leveraging the user's physical space, and how this can be achieved through RDW. This work builds upon previous findings in RDW with strafing gain, which seeks to redirect users along a diagonal path while maintaining their original orientation. We highlight this work in the context of research in threshold detection and simulator sickness in RDW.

2.1 Redirected Walking

RDW attempts to address the problem of leveraging a user's physical space by changing the mapping between a user's physical and virtual movements [27]. By changing the 1:1 mapping of physical to virtual movements, it is possible to explore large virtual environments in more contained physical spaces. Redirection is achievable due to the ability of humans to perceive their perspective as stable when moving despite the natural head movements that occur while walking [7]. Human vision tends to dominate over the other senses that occur while walking when there is a mismatch between them. In more specific terms, the vestibular sense and proprioception will be less relied on in comparison to vision [30] [21]; thus, by subtly manipulating the user's perspective in VR, one can redirect the user. In the context of RDW, this redirection traditionally consists of three gains to manipulate the user's movements towards utilizing their physical space: *translation gain*, *rotation gain*, and *curvature gain*.

Translation gain affects the scaling between the virtual and physical translations [27]. A translation gain is defined by the quotient $g_T = \frac{T_{virtual}}{T_{real}}$, where $T_{virtual}$ refers to the virtual translation and T_{real} refers to the real or physical rotation [29]. If g_T is greater than 1.0, then virtual translations by a user would be greater than the physical translation. If g_T is less than 1.0, then the virtual translations by a user would be greater than the physical translation. *Rotation gain* affects the scaling between the physical and virtual rotations [27]. A rotation gain is defined by the quotient $g_R = \frac{R_{virtual}}{R_{real}}$, where $R_{virtual}$ is the virtual rotation and R_{real} is the real or physical rotation [29]. For instance, if the g_R is 0.5, then a 90 degree rotation by a user in the physical world would result in a 45 degree rotation in the virtual world. *Curvature gain* is distinct from rotation and translation gains as it is a change in path trajectory. While the user walks, a rotation is applied onto the user causing the user to believe they are no longer walking in a straight path [27]. As the visual sense dominates the other senses while walking, the user may naturally begin to walk in a curved path opposite of the applied rotation in order to correct the offset. Curvature gain is expressed as $g_C = \frac{1}{r}$ where r refers to the radius of the desired curved path the user is intended to walk along [29].

Beyond these three gains, other work has been done to enhance the field of RDW. Bending gain [16] which seeks to cause users to walk along a *bent* path exists through a modification of curvature gain. Turning gain [22], which holds similarities to rotation gain, gradient gain [20], which uses translation gains on a slope, and redirected jumping gains in VR [8] are other examples of novel redirection. Interestingly, gain thresholds can change depending on the direction of the user's walking, resulting in the ability to design virtual environments and simulation in robust ways [3]. Additionally, redirection has been achieved through scene manipulation based on the user's blinking [17] or saccades [32]. Each of these succeeding gains, in some part, attempt to bridge a gap between the original RDW gains and their applicability in real-world scenarios. Thus, our work introduces strafing gain in the context of prior gains to redirect users along a diagonal trajectory with respect to their original orientation.

It is worth noting that lateral redirection while maintaining orientation has been achieved in previous work. Notably, Xu et al. introduced an optimal pose guided RDW algorithm that attempts to redirect users such that their resulting orientation is posed to minimize future collisions [37]. They achieve this by alternating between leftward and rightward curvature gain to produce S-shaped curves. While this solves part of the orientation problem that occurs in redirection, Xu et al.'s work focuses primarily on the resulting pose and not on maintaining the user's current orientation. Another potential limitation of the Xu et al. method is that shifting between different gains, especially suddenly, is shown to be highly detectable to users which can affect the user's perception of control [4]. This is especially noticeable for experienced VR users. Strafing gain differentiates itself from the method presented by Xu et al. and other combination methods as it uses a single gain that can be used for obstacle avoidance without affecting the user's orientation and can be easily integrated with existing RDW algorithms.

2.2 Detection Thresholds

The standard method that VR researchers have quantified the applicability of a gain is through the usage of detection thresholds, which attempt to effectively measure how much redirection can be subtly introduced without the user noticing. The detection of thresholds in the context of RDW has been proposed by Razzaque [27]. While there have been different criteria used to evaluate RDW gains (e.g., natural inductions [28]), one of the more standardized evaluations is performed by applying a psychometric analysis to obtain the detection thresholds. Steinicke et al. [29] used a method of constant stimuli with a 2-alternatives-forced-choice (2AFC) to measure detection [13]. In the method of constant stimuli, applied gains are randomly and uniformly distributed to the user. In a 2AFC (for RDW), a trial with the concerned degree of gain is tested. A user is then asked to answer yes/no to determine whether a gain was detected (e.g., "Was your physical rotation greater than your virtual movement: yes or no"). The user is unable to responds with answers other than yes/no. Literature has also used pseudo-2AFC questions

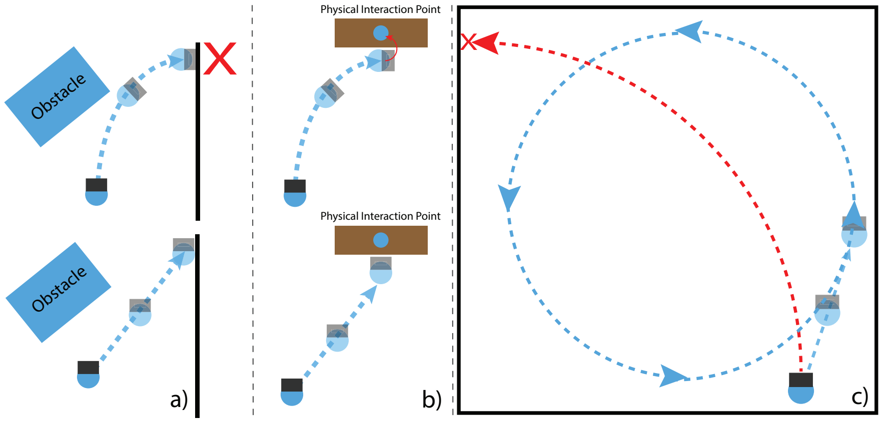

Figure 2: Potential usages of strafing gain with respect to curvature gain. **a)** demonstrates potential deficiencies of curvature gain and how they can be rectified by strafing gain. **b)** depicts how strafing gain can be used instead to potentially assist in redirection towards location-sensitive objects in the physical world (e.g., haptic feedback). Furthermore, strafing gain may assist in relevant fields of research such as realignment of physical and virtual orientations in addition to position [34]. **c)** demonstrates how strafing gain can be used in conjunction with curvature gain to allow for a greater range of locomotion. Strafing gain should be utilized in steering algorithms [1] [31] with other RDW gains for greater effectiveness.

that substitute the ”yes” and ”no” to more relevant responses to the task.

Due to the nature of how the 2AFC task is designed, if a user is unable to confidently identify the correct response, the user gives their best guess which theoretically should result in a correct response 50% of the time. The degree of gain used when a correct response is given 50% of the time is defined as the *point of subjective equality* (PSE), where the user perceives the physical and virtual movements as identical. Additionally, two other percentages to note are the 25% and 75% markers. The actual detection threshold are designated by these two markers. In the case of Was your physical rotation greater than your virtual movement: yes or no”, an example detection threshold would be when the user had a probability of answering yes 75% of the time and no 25% of the time. Any gain values with percentages higher than 75% or lower than 25% indicate a higher likelihood of being able to detect the gain. By using these detection threshold techniques for strafing gains, we aim to determine a conservative estimate of the degree of strafing that can be utilized.

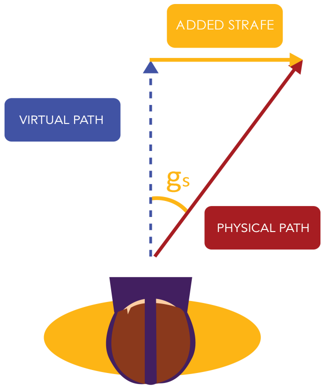

Figure 3: g_S refers to the angle to which a user is redirected, the length of the VIRTUAL PATH is defined as D_V (Eq. 1), and ADDED STRAFE is defined as D_S (Eq. 1)

3 STRAFING GAIN

3.1 Motivation

Strafing gain seeks to supplement some of the deficiencies of current gains in RDW. Naive implementations of curvature gain can effectively steer users from obstacles in their physical environment to a more advantageous position. However, the resulting orientation can be sub-optimal and lead to collisions or resets (Fig. 2a). Strafing gain can be used for collision and avoidance and maintaining orientation. While more advanced techniques may be able to preserve or even optimize orientation (e.g., combination of gains, optimal pose guided redirected walking [37]), a diagonal path provided by strafing gain may still be desirable for obstacle avoidance. Additionally, strafing gain allows for orientation maintenance throughout the entirety of its redirection rather than primarily at the starting and ending points of movement. Strafing gain may also be valuable for realignment. As the mapping between a user’s physical and virtual positions and orientations may no longer align during redirection, a designer can utilize reactive alignment with RDW to re-align the physical and virtual environments [34] (e.g., to interact with a physical object). Strafing gain can serve as another gain to assist in the alignment of the physical and virtual environments (Fig. 2b). In the context of consecutive gains, strafing gain could be applied alongside curvature gain to direct users onto a circular path fitting inside their physical space (Fig. 2c). If a maximal curve is applied from the user’s starting position without first applying strafing gain, the user may be eventually lead to a sub-optimal position or orientation. Strafing gain should ultimately be considered a supplement to existing techniques in RDW rather than a replacement of any gain.

3.2 Methodology

To better understand strafing gain, we discuss strafing gain in the context of prior gains. Translation and rotation gain are gains in the most traditional sense because one obtains an increase or decrease in output movement based on their input movement. For example, one can achieve a traversal of 2m virtually with only 1m physically through translation gain. Curvature gain differs from these gains because there is no direct gain in the output. Instead, curvature gain modifies the *trajectory* of the input movement.

Because strafing gain also changes the trajectory of the input movement, strafing gain can be considered similar to curvature gain in this sense. While curvature gain applies rotation on orientation to a walking user, strafing gain applies lateral shifts on position to a walking user. However, strafing gain is different in nature from curvature gain too as the physical path traversed by the user is longer than that of the virtual path traversed by the user (since the user must walk along the diagonal created by the tangent function); thus, strafing gain, by nature, involves translation gain. With strafing gain, users correct the offset in position by walking opposite of what would be the resulting virtual path in order to maintain their desired virtual heading. Because a lateral shift is being applied to a user's position while walking, no rotation of the user is necessary. This allows for the maintenance of the original orientation because the offset is corrected through lateral movements while walking forward. We define strafing gain (g_S) as follows:

$$tan(g_S) = \frac{D_S}{D_V} \tag{1}$$

where g_S is the angle to which a user is redirected, D_S refers to the distance (length) between the user's physical and virtual path end-points, and D_V refers to the distance (length) of the virtual path. We can simplify g_S to the following:

$$g_S = tan^{-1}(\frac{D_S}{D_V}) \tag{2}$$

4 EXPERIMENTS

As RDW was intended to explore large virtual spaces, we designed a virtual scene of a large city where participants would walk and be redirected. The virtual environment was composed of a roads surrounded by buildings, and pilot tests were used to determine and modify any potentially distracting scenery. Additionally, pilot tests helped to remove scenery that may have affected the detection of strafing gain. Audio of cars passing a highway was played in the headphones to prevent participants from distinguishing strafing gain based on auditory cues in the study room. Our design relied on previous RDW detection threshold work [29], utilizing a method of constant stimuli with 11 values, picked in random order 6 times (66 total trials). The simulation was designed to test the 11 values of strafing gain applied. Each trial consisted of four phases: Walking, 2AFC (and FMS), Re-staging, and Reset.

Walking. Participants were tasked with walking into a green waypoint, virtually straight ahead from the participant (Fig. 4.1). Participants walked along a 3m distance virtually while facing the waypoint. The 3m distance was chosen due to the size of the physical room and following similar work such as Grechkin et al. [7].

2AFC. After walking to the waypoint, participants answered the following 2AFC question: Did you move left or right in the physical world? (Fig. 4.2) Participants answered by using a controller to ray-cast and select the desired response (”Left” or ”Right”) on a GUI along the same axis as the waypoint. To measure motion sickness throughout the trials, every 5th trial had a Fast Motion Sickness scale [12] after the 2AFC. Participants were asked to rank their level of motion sickness from 0 (no sickness at all) to 20 (frank sickness). After the 2AFC or FMS, the simulation proceeded to the re-staging phase.

Re-staging. Participants were re-staged to set-up the following trial. During the re-staging phase, participants were instructed to walk to two preset waypoints that were placed in such a way such that users would be situated properly for the following trial without knowing if their previous answer to the 2AFC was correct (Figs. 4.3-5).

Reset. At the end of the re-staging process, participants were facing opposite the walking direction of the previous trial (Fig. 4.6). The reset re-aligns the user with respect to the virtual environment, matching it with the physical world. Participants were re-spawned into the city scene and once the waypoint appeared directly in front of them, participants could begin the walking phase again.

The Walking, 2AFC, Re-staging, and Reset steps were completed 66 times with a 5-minute break on completion of the 33rd trial.

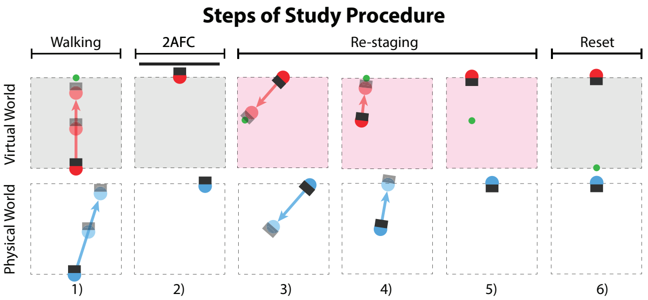

Figure 4: The procedure of the experiment with the bottom row corresponding to the participant and their movements in the physical world and the top row corresponding to the participant and their movements in the virtual world. The green dots refer to the waypoints that participants walked to and the target (Step 5) that the participant looked at.

4.1 Experimental Design

Participants completed this study in person at the University of Florida. With respect to COVID-19, participants and experimenters followed COVID-19 sanitation policies instituted by the University of Florida for the duration of the study. Hand sanitizer was provided for participant and experimenter use. After each participant completed the study, HMDs and controllers were sanitized several times using UVC via the Cleanbox CX1 [1] and lenses were wiped. Mouse and keyboard were also sanitized.

Participants began the study by completing the Informed Consent, demographics questionnaires, and filled out the Simulator Sickness Questionnaire (SSQ) by Kennedy et al. [11]. They were then briefed on the experiment task in detail and were instructed to carefully try to discern whether they moved left or right during each trial.

To assess detection, we used the method of constant stimuli in 2AFC methodologies, where each gain was randomly chosen from a list of 11 total values of strafe. We tested the following 11 values (increments of ±2.5°): -12.5°, -10.0°, -7.5°, -5.0°, -2.5°, 0.0°, 2.5°, 5.0°, 7.5°, 10.0°, 12.5°. The 11 values were selected after pilot testing with 10 participants indicated that the extreme values in this list were highly distinguishable. The negative values indicate a user shifted to the left in their virtual environment resulting in a diagonally-right physical path. The positive values indicate a user shifted to the right in their virtual environment resulting in a diagonally-left physical path. The zero-value (0.0°) indicates when no redirection is applied. Because strafing gain involves a natural induction of translation gain (due to walking along a longer physical path than virtual path, as created by the tangent function), the detection thresholds of strafing gain will naturally be affected by translation gain. Because values further from 0.0° will result in a longer physical path, the amount of strafing gain that can be applied without detection may be hampered by one's ability to perceive translation gain. Thus, a user's ability to detect strafing gain relies on their perception of walking along a path varying both in length and trajectory of the unmodified path.

4.2 Measures & Analysis

Below we summarize the measures involved for the analysis.

- *Demographics Questionnaire*. Participants answered questions regarding their age, gender, race, hand and foot dominance, and video game experience.
- *Detection Thresholds*. Thresholds are simply the points in which participants can detect a discrepancy between their physical movements and virtual movements. Detection thresholds

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[1] https://cleanboxtech.com/cx-series

are determined via the 2AFC task described by Steinicke et al. [29]. To calculate the detection thresholds, we determine the Point of Subjective Equality (PSE) which refers to the point where the physical movements and virtual movements are perceived as 1:1 or identical. Thus, in our work, the detection thresholds are the gain values that participants will select ”Left” 75% of the time and ”Right” 25% of the time. We used a total of 1782 trials for the detection threshold analysis, which is on par or better than related studies (e.g. [7, 10, 23, 29]).

- *Simulator Sickness Questionnaire*. The Simulator Sickness Questionnaire (SSQ) is composed of 16 questions on a 4-point scale used to measure simulator sickness [11]. Participants completed the SSQ immediately before (Pre SSQ) and after (Post SSQ) the VR simulation. The Pre and Post SSQs are compared for analysis.
- *Fast Motion Sickness Scale*. The Fast Motion Sickness (FMS) Scale is a single question which asks participants to rate their level of simulator sickness on a scale of 0 (no sickness at all) to 20 (frank sickness) [12]. Participants completed the FMS Scale on every 5th trial throughout the study.
- *Heading Error*. Orientation data was collected in a supplementary experiment (see Section 4.4) to verify that users maintained a forward orientation when strafing gain was applied.

4.3 Primary Experiment

4.3.1 Participants

Participants were undergraduates recruited from the University of Florida and were compensated with class credit by their instructor in compliance with university policies. Two participants were graduate students recruited via word of mouth. We collected data from a total of 27 participants (13 female). Participant ages ranged from 19 to 26 with a mean and median of 21 years. Regarding hand-dominance and foot-dominance, 20 participants self-reported being right-hand dominant and 23 participants self-reported being right-foot dominant.

4.3.2 Procedure

Each participant (n = 27) completed 6 trials of each strafe value for a total of 66 trials (total of $66 \times 27 = 1782$ trials). Additionally, a minimum of two practice trials (±15.0°) were included at the start of the experiment to ensure understanding of the task and questions to be asked throughout the study. The practice trials were intentionally designed with higher strafe values to ensure the task and questions were understandable. These practice trials were repeated until participants clearly understood the task and 2AFC question asked of them. The practice trials were not included in analysis.

After completing the 66 trials, participants immediately filled out a second SSQ questionnaire. The survey concluded with several essay-style questions to measure if participants used any mechanism to help distinguish left and right, determine the overall experience, and receive any open-ended feedback.

4.4 Supplementary Experiment

After conducting the Primary Experiment, it was brought to our attention that it may be possible for strafing gains to induce unwanted physical rotation [35]. Unfortunately, we were not able to examine if this effect was present with the data the was recorded in the original study. To address this issue and attempt to validate the thresholds obtained from the Primary Study, we conducted a Supplementary Experiment at the University of Florida to verify the claim that the user’s orientation, specifically their heading, is maintained when strafing gains are applied. This Supplementary Experiment was conducted using the same experimental design as the Primary Experiment; however, participants completed each of the original 11 gain values twice instead of six times as orientation was the primary focus.

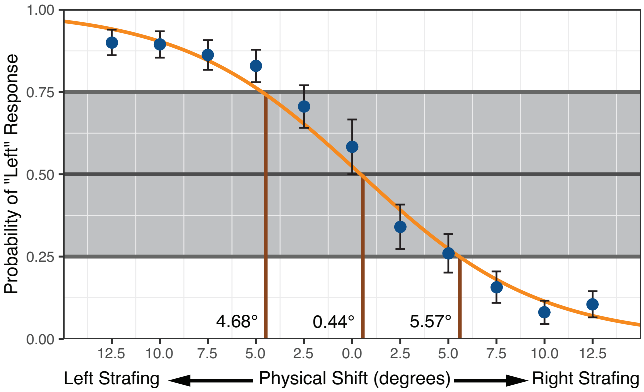

Figure 5: Psychometric curve fit to our 2AFC response data. Brown dropdown lines indicate the thresholds for left (4.68°) and right (5.57°) strafing, and the point of subjective equality. Points represent the average response probability for each strafe angle, and associated error bars indicate 95% confidence interval for this response. ”Left Strafing” refers to redirection causing the user to walk in a leftward diagonal. ”Right Strafing” refers to redirection causing the user to walk in a rightward diagonal.

4.4.1 Participants

Participants were undergraduates recruited from the University of Florida and were compensated with class credit by their instructor in compliance with university policies. We collected data from an additional 12 participants (12 male). Participant ages ranged from 20 to 22 with a mean of 20.8 years and median of 21 years. Regarding hand-dominance and foot-dominance, 11 participants self-reported being right-hand dominant (1 did not answer) and all participants self-reported being right-foot dominant. Two participants were excluded in our analysis due to participant error and technology issues that occurred during the study.

4.4.2 Procedure

Each participant (n = 12) completed a shortened version of the Primary Experiment which consisted of 2 trials of each of the original 11 strafe values for a total of 22 trials in the same environment and scenario as the Primary Experiment (total of $22 \times 10 = 220$ trials). SSQ and FMS scores were not analyzed due to their being fewer trials completed and therefore less time spent in VR. However, the heading error was analyzed and reported in our results, along with a brief analysis on the detection thresholds from these 220 trials as validation.

5 RESULTS

In this section, we present our detection threshold estimates for left and right strafing gains as well as effects on user sickness while using the technique. All results except for the results included in Section 5.3 are from the Primary Experiment only. The results in Section 5.3 are from the Supplementary Experiment only.

5.1 Detection Threshold Estimates for Strafing Gain

We utilized the *quickpsy* R package [19] to conduct our threshold analysis. Participant responses to the 2AFC question where used to fit a curve modelling the likelihood participants would detect a leftward physical shift in their walking (Fig. 5). Specifically, the logistic function was used as its horizontal asymptotes at y = 0 and y = 1 accurately model data collected during 2AFC psychophysical experiments [6], though the choice of function can vary depending on the quality and form of the data [14]. The logistic function takes the form:

$$F(x;\alpha,\beta) = \frac{1}{1+e^{-\beta(x-\alpha)}} \tag{3}$$

where α is the center of the curve and β is an indicator of the curve's sensitivity to change. To verify we selected an appropriate function, we compared the use of this function against other sigmoid curves (the cumulative normal function and Weibull function) and found the logistic function to have the smallest Akaike information criterion indicating it had the best fit.

Using the fitted curve, we identify the angle producing a 50% response as the PSE, a 75% response as the threshold value for right physical strafing (Right), and 25% as the threshold value for left physical strafing (Left). In other words, the PSE is the angle which users can strafe with an approximately equal likelihood of feeling like they are moving left or right (i.e., still feeling like they are walking straight) and the thresholds are the strafe angles where, when exceeded, users will begin to reliably detect their physical movement being effected by the strafing gains. These values were found to be:

- **Left**: 4.68° to the left
- **PSE**: 0.44° to the right
- **Right**: 5.57° to the right

Overall, we see that rightward strafing tends to be less detectable than leftward strafing as indicated by the PSE being slightly to the right and a higher right strafing threshold. Additionally, positional data demonstrated largely diagonal paths as expected and no distinct variations in rotation were observed by experimenters.

5.2 Sickness

We assessed sickness through two questionnaires: the Fast Motion Sickness Scale (FMS) [12] which was assessed during the experiment, and the Simulator Sickness Questionnaire (SSQ) which was administered before and after the experiment.

5.2.1 Fast Motion Sickness Scale

After every five trials in our study, we collected an FMS sickness rating from participants. FMS scores increased over time, lowered following the break at the halfway point, and increased over time again. All scored averaged less than 2 (out of a maximum 20), suggesting that participants experienced very little sickness over the course of the study.

5.2.2 Simulator Sickness Questionnaire

SSQ scores were calculated based on the components of the SSQ [11]. Prior to our experiment, we measured an average Pre SSQ score of M = 5.68 (SD = 7.86). Afterwards we measured an average Post SSQ score of M = 22.58 (SD = 24.00). A paired-samples t-test revealed this to be a significant increase in sickness after participants completed the experiment: $t(26) = -4.39, p < 0.001$. This increase in sickness is not unexpected. Other detection threshold studies [30] [7] demonstrated significant increase in SSQ scores. The increase has been previously accredited to using gain values well beyond the threshold or longer-periods spent in VR. Our SSQ scores are similar to those presented in other RDW studies (e.g., [2,7,29]), illustrating potential use of strafing gain without excessive burden to users.

5.3 Heading Error and Validation from Supplementary Study

Orientation information was collected in the Supplementary Experiment (see Section 4.4) to verify that the user's heading is not affected by the strafing gain redirection. For each trial, the mean heading error (the difference between the heading the user should be facing and the user's actual heading) was calculated (Fig. 7). The first second of data from each trial was omitted to guarantee the user was in the midst of performing the task. Ideally, we would conduct a full factor analysis of all the possible strafing gain values, but we concluded that this is not a feasible approach due to the number of permutations. Instead, we consider the case in which no strafing gain is being applied to be the "ground truth", and analyzed the strafing gain value of 0.0° against the all other strafing gain values by conducting a Mann-Whitney U test. The strafing gain value of 12.5° had a greater heading error than no strafing gain ($U = 95.0$, $p = 0.027$). All other pairs had no statistically significant difference.

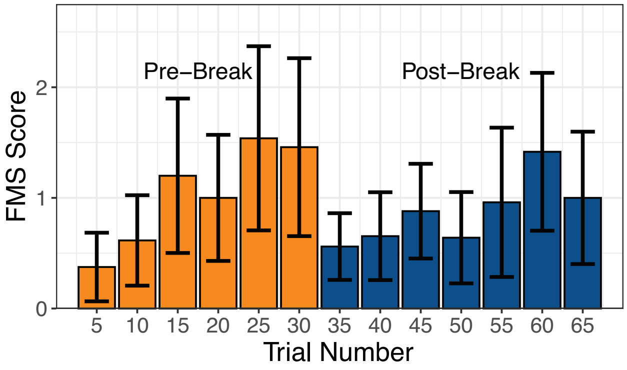

Figure 6: Average FMS score at each trial it was administered (out of a maximum 20). Scores from each block (before and after the break) are colored separately. Error bars indicate 95% confidence interval for the score.

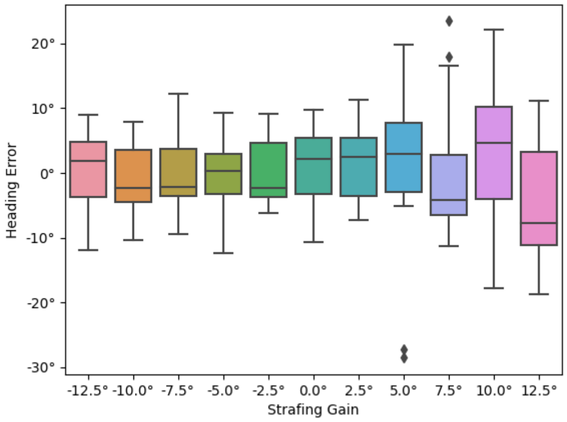

Figure 7: Average Heading Error values for each of the presented strafing gain values. The bar represents the median, the box represents the IQR, and the whiskers represent the total distribution excluding outliers.

Additionally, the data resulting from the 2AFC tasks in the Supplementary Study was analyzed using the same process described in Section 5.1. The Supplementary Study found a similar pattern in the thresholds (4.84° left, 0.69° PSE, and 6.23° right), demonstrating validity to the original and 4.68° left, 0.44° PSE, 5.57° right. A marginal increase in the detection thresholds can be seen, potentially due to learning effects as their were fewer trials in the Supplementary Study. Ultimately, we recommend the usage of the original **4.68°** and **5.57°** as the detection thresholds.

6 DISCUSSION

Our results indicate that participants could be shifted to walk along a 4.68° diagonal to the left and a 5.57° diagonal to the right after walking along a 3m distance. We discuss the implications of these results and how they may be increased in scenarios where the user is unaware of the redirection.

6.1 Detection Threshold Estimates for Strafing Gains

Our results demonstrate that we can redirect users to a 4.68° diagonal to the left along a 3m distance, where 3m is the length of the virtual path. This redirection on the 3m virtual path results in an end position 0.25m to the left or approximately 0.08m to the left per 1m traveled virtually. In the right direction, users can be redirected 5.57° diagonally along a 3m distance resulting in an end position 0.29m to the right or approximately 0.10m to the right per 1m traveled virtually. Similar to that of [29], the detection thresholds derived from our experiment should likely be considered conservative estimates, due to the nature of the 2AFC task.

The results indicate that participants were less sensitive to redirection resulting in a left-ward strafe. One reason for this may be linked to foot dominance. Peters [26] found that participants who are right-foot/right-hand dominant tend to lead with their right-foot when walking. Furthermore, right-handed people tend to utilize their right-foot for tasks that require more attention. Thus, when they are redirected to the left and lead with the left foot, the left-ward strafe may be more detectable (due to being unaccustomed with a leading left foot). Prior work has found that hand dominance played no role in detection of curvature gain [25]. However, with walking, foot dominance may be more relative as people have a tendency to walk in varying directions depending on their dominant foot [5]. This would make sense as our population was primarily composed of right-foot dominant participants. Some participants also noted that they attempted to use strategies such as focusing on the weight or direction of their feet to discern left or right in some trials. Additionally, while the PSE, 0.75, and 0.25 may be true for our population, prior work has demonstrated variability in thresholds for specific populations [24]. Hutton-Pospick et al. [10] used an individualized calibration method to identify detection thresholds personalized to users. However, since no statistical comparison can be performed with left-foot dominant participants, due to sample size (n = 4), no definitive conclusions can be drawn. Additionally, a preliminary analysis of the data observed no gender effects in the detection task. We leave these as future work for both strafing gain and RDW.

In practical uses of strafing gain, the threshold of detection theoretically should increase. The same detection threshold method found that a radius of 22.03m for curvature gain was undetectable by Steinicke et al. [29]. However, if the participants are not aware of the manipulation a greater amount of redirection could be applied. Steinicke et al. [30] also found that participants were able to be redirected up to 15° in a 3m walking distance for curvature gain if their attention was focused on another task. Hodgson et al. [9] notably found a radius as small as 7.5m could be used for curvature gain. Similarly, we expect the amount of redirection for strafing gain would increase if users are focused on other tasks. Users would not be focusing on discerning redirection in real-world applications of RDW but instead on the primary objective or task of their simulation.

Recall that the detection thresholds calculated in this study may have been affected by the user's ability to detect translation gain. The strafing gain values in this study that would result in the longest physical path were ±12.5°. Either of these values would result in a physical path of length 3.073m – which is 0.073m longer than the unmodified 3m path. It is worth noting that this increase in path length is technically *within* the detection threshold found by Steinicke et al. [30], who found a g_T of 1.26; however, because there is a combination of both a change in path length and trajectory in strafing gain, strafing gain may have been more detectable. In this study we observed users walking along a 3m virtual path, but the degree of the gain that can be applied may also vary based on shorter or longer virtual paths.

6.2 Heading Error

Depending on how the findings from [35] are interpreted, it might be expected that lateral optical flow (like that found when adding strafing gain) could induce rotation onto the user. Induced rotation would be counter-productive to the purpose of using strafing gains, which has the goal of moving a user laterally while maintaining their heading. However, our results show that this is not the case, at least within the determined gain thresholds. The only strafing gain value that was found to be significantly different than the no strafing gain condition was +12.5°. This level of strafing gain is largely noticeable to the users, and it was observed that their behavior was more erratic when experiencing this level of strafing gain. With the results that we received from the supplementary experiment, we have no reason to believe that strafing gain will induce undesired rotations onto the user when used within the recommended detection thresholds. However, we would like to note that the supplementary experiment had a fairly small number of participants, and further research that explores the relationship between the results presented in this paper and those found by Warren et al. [35] in greater depth would be valuable. Interestingly, the heading errors for right-ward strafing gain values seems less consistent in general than the heading errors for left-ward strafing gain. This could be an effect of the fact that the vast majority of users self reported to be right foot dominant, but it could also be a result of having a small sample size.

7 LIMITATIONS & FUTURE WORK

While the design was based on previous literature, one limitation is that we did not control for travel speed in this study. As participants indicated that their walking speed may have served as a strategy towards detecting strafing gains, controlling for walking speed may modify the detection thresholds. Previous work has determined that walking speed can negatively correlate with detection thresholds and attempt to control for it [23] [25]. One way of controlling speed in future work is by having participants walk to a beat. Furthermore, the work described in this paper was in a controlled setting where participants were tasked to walk along a 3m space while actively attempting to detect strafing gain. Future work should attempt to use strafing gain in longer path lengths and durations. Practical scenarios where the participant is not aware of the redirection should be investigated to further quantify the effectiveness of strafing gain. In doing so, strafing gains should also be utilized in the context of the potential usages suggested in Fig. 2. When combined with other gains in succession, strafing gain could potentially be used to achieve greater maximization of the user's physical space. Along with this, comparing strafing gain with other redirection methods that could possibly maintain the user's orientation, such as [37], will be beneficial. In our work, simulator sickness increased, which is not unique nor unusual for a redirection gain. Interestingly, FMS scores were generally low and our average SSQ scores are slightly lower than that of curvature gain as described by Steinicke et al. [30]. Since strafing gain utilizes lateral translations as opposed to rotations, simulator sickness may be less prevalent. However, we cannot confirm this currently and leave this as an area to explore in the future as well. Finally, deeper analysis on how foot/leg dominance affects the amount of redirection that can be applied should prove to be an interesting area of research within the scope of RDW.

8 CONCLUSION

This paper contributes to the field of VR and redirected walking with the formal introduction of strafing gain. Utilizing a psychometric analysis, it was found that participants were able to be redirected 5.57° to the right and 4.68° to the left. We replicated the study and found similar detection thresholds on a smaller sample size. Additionally, despite being redirected along a diagonal, users' head orientations were largely maintained, indicating its effectiveness to be used in conjunction with other redirection techniques and validating the claims made in You et al. [38]. While no definitive conclusion on the higher sensitivity to left-ward redirections could be made, one potential reason could be due to foot/leg dominance. The resulting simulator sickness also align with previous research, potentially indicating no significant sickness beyond what is present in VR. Future work should attempt to examine strafing gain in both practical usages and in coordination with other redirection techniques to continue to expand on the field of RDW in VR.

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