Influence of Rotation Gains on Unintended Positional Drift during Virtual Steering Navigation in Virtual Reality

Hugo Brument
hugo.brument@tuwien.ac.at
VR&AR Research Unit, TU Wien
Vienna, Austria

Arthur Chaminade
achaminade6@gmail.com
Télécom Sud Paris
Évry-Courcouronnes, France

Ferran Argelaguet
ferran.argelaguet@inria.fr
Inria, Univ Rennes, CNRS, IRISA
Rennes, France

ABSTRACT

Unintended Positional Drift (UPD) is a phenomenon that occurs during navigation in Virtual Reality (VR). It is characterized by the user's unconscious or unintentional physical movements in the workspace while using a locomotion technique (LT) that does not require physical displacement (e.g., steering, teleportation). Recent work showed that some factors, such as the LT used and the type of trajectory, can influence UPD. However, little is known about the influence of rotation gains (commonly used in redirection-based LTs) on UPD during navigation in VR. In this paper, we conducted two user studies to assess the influence of rotation gains on UPD. In the first study, participants had to perform consecutive turns in a corridor virtual environment. In the second study, participants had to explore a large office floor and collect spheres freely. We compared the conditions between rotation gains and without gains, and we also varied the turning angle to perform the turns while considering factors such as sensitivity to cybersickness and the learning effect. We found that rotation gains and lower turning angles decreased UPD during the first study, but the presence of rotation gains increased UPD in the second study. This work contributes to the understanding of UPD, which tends to be an overlooked topic and discusses the design implications of these results for improving navigation in VR.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **User studies**.

KEYWORDS

Virtual Reality, Locomotion Techniques, Rotation Gains, Unintended Positional Drift

ACM Reference Format:
Hugo Brument, Arthur Chaminade, and Ferran Argelaguet. 2024. Influence of Rotation Gains on Unintended Positional Drift during Virtual Steering Navigation in Virtual Reality. In *30th ACM Symposium on Virtual Reality Software and Technology (VRST '24), October 09–11, 2024, Trier, Germany.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3641825.3687734

1 INTRODUCTION

Virtual Reality (VR) technology can transform human-computer interaction by immersing users in highly interactive and engaging Virtual Environments (VEs). Any VR application must provide methods to support unlimited and unconstrained virtual environment navigation and, if possible, provide a navigation experience like in real life [40]. However, how users navigate in VEs rarely matches how humans navigate in real environments (REs), mainly due to technical constraints such as additional hardware or the limited workspace. To overcome such limitations, many locomotion techniques (LTs) have been proposed, which can be classified according to the required motion involvement of the user [23]. Yet, due to the immersive nature of virtual reality experiences, users actively engage their entire bodies within these virtual realms, often involving physical movements, either consciously, such as walking or reaching, or unconsciously, as spontaneous reactions to virtual stimuli, without being able to see the limits and obstacles in the actual workspace due to wearing Head-Mounted Display (HMD). These movements, from now on referred to as *Unintended Positional Drift* (UPD), harm the VR user experience but are typically disregarded in the design of VR applications.

Studies have shown that techniques that do not require users' physical translational movements yield UPD (i.e., moving physically while virtually navigating in the VE) [4, 20, 31] and can lead to safety concerns, as users may come near to the physical boundaries or obstacles in the workspace without noticing, but also user experience concerns, as the actual boundaries of the workspace must be displayed to enable users to reposition themselves to a safer actual position [43]. While initial studies have been conducted to understand and model the UPD, they have only been focused on specific scenarios: only one type of trajectory [32] or one locomotion techniques [4] considered, and non-ecological situations (i.e., far from real life) [4, 20, 31]. This highlights the limited knowledge on UPD, where many other factors could still influence it. For instance, rotation gains are ordinary in Redirected Walking (RDW) techniques that enable infinite walking in a VE with a restricted workspace. In virtual steering, other works have explored the impact of rotational gains for virtual steering techniques [36, 37] on spatial orientation and navigation performance. Still, no studies have investigated the influence of rotation gains on UPD so far.

This paper reports the first study of UPD with rotation gains during virtual steering navigation in VR. We conducted two user studies to investigate how both angular speed and rotation gains could influence UPD in (1) a non-ecological task involving repetitive rotations and (2) an ecological task involving free user motion of the participants. Our results contribute to the understanding of

VRST '24, October 09–11, 2024, Trier, Germany

ACM ISBN 979-8-4007-0535-9/24/10
https://doi.org/10.1145/3641825.3687734

UPD during navigation in VR and are discussed concerning the design of LTs, which could improve users' experience.

2 RELATED WORK

2.1 Unintended Positional Drift

First introduced by Nilsson et al. [31], UPD is a phenomenon where users move unintentionally in the RE using a different technique than natural walking (e.g., walking-in-place or steering). Although research explicitly addressing the problem of UPD is rare, UPD could have a high impact during prolonged VR sessions due to the limited workspace in standard VR setups. Based on their observations, Nilsson et al. [31] split the potential approaches to reduce UPD into two categories, either by focusing on the navigation control law's input modalities or the workspace's physical constraints. For instance, Nilsson et al. investigated the impact of input gestures during WIP locomotion on UPD [29]. They compared three different gestures: Marching, Wiping, and Tapping. They differ in how the lower-body parts move to trigger virtual motion. Their results showed that the gesture impacted users' UPD. Tapping (alternately lifting each heel of the ground while keeping the toes in contact with the ground) led to less UPD than classical leg gestures such as marching or wiping. The authors argued that keeping constant contact of the feet with the ground could reduce UPD while using WIP techniques. Nilsson et al. obtained similar results in another study, in which the difference in UPD was probably caused again by the leg movements defined by common WIP gestures [30]. More recently, a study compared the influence of four different locomotion techniques (WIP, Running in Place, teleportation, and steering) on UPD. Results showed that it is easier to stay within the "safety zone" (i.e., the center of the workspace) with teleportation and steering than with WIP or Running in Place [20].

Regarding the physical constraints, a first example is the work by Williams et al. [42], who conducted a study comparing gaze and torso-directed WIP. Even though the objective of this study was not to assess UPD, the authors tried to minimize it by placing a 1×1 meter cardboard pad taped on the ground. The authors suggested that the users could remain within the area by relying on the passive haptic feedback provided by the pad. Note that some steering approaches based on leaning exist to mitigate UPD by constraining user motion [26]. Nilson et al. assessed different modalities for minimizing UPD, including additional sensory feedback (auditory, visual, audiovisual, and passive haptic) [32]. The results showed that both passive haptic feedback and feedback types with gradual onset were the most efficient at reducing UPD. The passive haptic feedback tended to be more helpful and less distracting than some feedback with a gradual onset. Finally, Montano et al. demonstrated that the UPD could also occur using scale adaptive techniques (that dynamically adapt a user's displacements) during walking [24]. They noticed that due to the mismatch between the computed position in VR and the position in the workspace, these accumulated differences between the user's physical and (scaled) movements in VR resulted in UPD. They quantified the UPD using scale techniques and proposed a UPD correction model to minimize UPD while walking in VEs. They demonstrated that UPD could be reduced by increasing the distance traveled in the VE without being overtly redirected.

2.2 Side Effects and Mitigation of UPD

UPD can negatively impact locomotion in VR with an HMD. Due to eventual discrepancies between the physical and virtual motion in LTs, users may not be aware of their physical position in the workspace. For instance, some LTs involve jumping [45] and can yield to UPD as users might not land in the same position as where the jump was initiated. UPD can thus bring some safety issues, such as users reaching the boundaries of the workspace or obstacles without noticing them. One solution to encounter this issue would be to warn the user in the VE through sensory feedback such as visual (e.g., chaperone in SteamVR or the guardian barrier in the MetaQuest) [7, 12], audio (alarm or trigger), or haptic (e.g., vibration of the controllers or adding a physical rug so that user can feel when they leave the safe space) [42]. Yet, these solutions may create some breaks in presence that could disrupt users' VR experience [13]. Other solutions to mitigate UPD tried to focus on the continuity of the redirection. It means that the modifications of the mapping between the user's real and virtual translation and rotation or the manipulation of the VE are applied either instantaneously (discrete) or over time (continuous). Such approaches include redirected walking [33] or the use of rotations [33], translation [16], curvature [25] or bending [21] gains to manipulate the amount of physical rotation and translation performed by the user. The main issues about the use of gains in LTs are that it still requires a large workspace [2] and that they can generate UPD over time [4, 32].

2.3 Rotation Gains

Redirection techniques often involve scaling users' movements to keep them within the workspace. A common approach is to modify the control/display ratio by applying a "gain." Head movements can be scaled using a rotation gain ($g_r \in \mathbb{R}$), defined as the ratio between the virtual rotation $R_{virtual}$ and the real-world rotation R_{real} performed by the users: $g_r = \frac{R_{virtual}}{R_{real}}$. Thus, a rotation gain (different from 1) changes the virtual camera's rotation relative to the user's physical rotation: $R_{virtual} = R_{real} \times g_r$. A rotation gain $g_r > 1$ results in a faster virtual camera rotation than the user's head rotation, while a rotation gain $g_r < 1$ results in a slower virtual camera rotation [39]. In most VR setups, rotation gains are applied on the yaw axis [34], but they can also be applied to the pitch and roll axes [3]. Although the gain is generally applied continuously and constantly (i.e., the same g_r value throughout the head rotation), other methods exist for applying rotation gains if the amount of rotation is known *a priori* [8, 47]. For the rest of this paper, we will focus on constant rotation gains based on head movements applied on the yaw axis. Users' perception of rotation gains is typically evaluated through perceptual studies to estimate detection thresholds (DTs) using an alternative forced-choice (AFC) protocol. To make rotation gains usable in VR, they should be as subtle as possible to minimize break of presence [38] and cybersickness [15]. To this end, much research has focused on the impact of different experimental conditions on the perception of head rotation gains in VR. Three recent surveys summarize studies and their implementation in RDW systems, and you can refer to them for further information [10, 22, 28].

3 USER STUDY 1 - INFLUENCE OF ROTATION GAINS AND ANGLE TURN

One of the main challenges related to the analysis and reduction of UPD is to find the correct approach to evaluate it. Indeed, the UPD can appear after prolonged exposure and could also be user-dependent (no study about gender, age, or experience with VE effects in the literature has been presented yet) or task-dependent (the type of trajectories or the cognitive workload of the task could also influence UPD). In this paper, we aim to shed some light on the influence of rotation gains on UPD during steering navigation in VR. The motivations behind this study are that (1) there is no study regarding the influence of rotation gains on UPD, (2) rotation gains are primarily used in RDW techniques, but they can be promising for virtual techniques as well [36, 37].

3.1 Experimental Design and Hypotheses

The navigation task was to follow the path in a corridor-based environment Figure 1. We chose this task as it provides a restricted motion similar to each user. To investigate the influence of rotation gains on UPD, our experiment had a 3 **Rotation Gain** (0.8, 1, 1.2) × 3 **Turn Angle** (60°, 90°, 120°) repeated measures within-subject design. **Rotation Gain** was the gain applied to the torso during the virtual navigation, whereas **Turn** consisted of the type of trajectory to perform during the task (Figure 1). The experiment was composed of 2 blocks, each containing nine different trials. Each combination of **Rotation Gain** and **Turn Angle** was tested once per block and counterbalanced using a Latin square design, resulting in 18 trials. A trial consisted of navigating along the corridor containing 14 turns, with the first two turns always being right then left (for calibration purposes) and the 12 other turns being six right turns and six left turns in a randomized order.

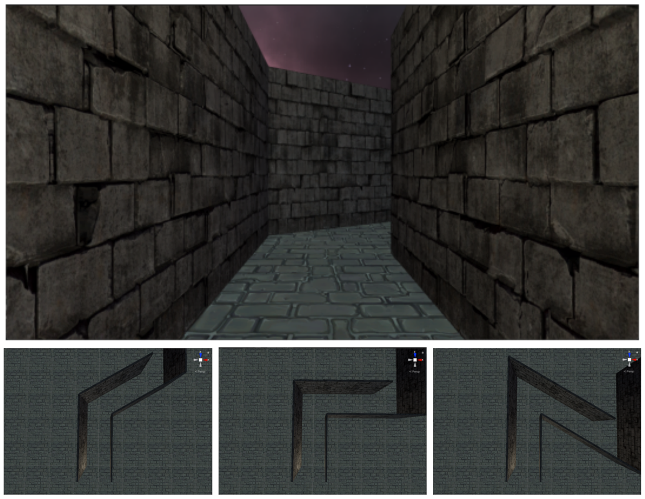

Figure 1: Top - First point of view of the participant. Bottom - The three types of Turn (Left - 60°, Center - 90°, Right - 120°) users had to perform.

Based on our analysis, we hypothesized that rotation gains and turn's angle could affect participants UPD and, more precisely:

[H1] - The lower the **Rotation Gain**, the higher the UPD. Since a rotation gain lower than one will result in higher movements in the RE than the VE, whereas a rotation gain higher than one will result in lower movements in the RE than the VE, we may expect to observe users drifting more from the workspace's center with the low gain than the baseline or higher gain.

[H2] - The higher the **Turn Angle**, the higher the UPD. Similarly, to [4] who found an effect of curvature trajectory on UPD, we may expect similar results since higher **Turn Angle** would result in high users' physical movements.

[H3] - There is an interaction effect of **Rotation Gain** and **Turn Angle** on users' UPD. Since higher turns may require higher users' motion, rotation gain also influences the perception of virtual and real motion; we could imagine that some combination of **Rotation Gain** and **Turn Angle** could increase even more the UPD or eventually reduce it.

3.2 Participants and Apparatus

An a priori power analysis was conducted using G*Power version 3.1.9.7 [11] to determine the minimum sample size required to test the study hypotheses. Results indicated the required sample size to achieve 80% power for detecting a medium effect, at a significance criterion of $\alpha = .05$, was N = 18 for within-subjects analyzes of variances with repeated measures. A total of 21 participants (9 females) aged from 21 to 40 years old (M=25.8; SD=4.5) participated in the experiment. 11 participants had only one or no prior experience with VR, whereas 10 participants had regular experience with VR. They signed an informed consent form and were naive to the purpose of the experiment. The study conformed with the standards of the Declaration of Helsinki.

The experiment used a Valve Index headset and two Vive Trackers mounted on a backpack placed on the shoulders to track shoulder motion that is used as the heading direction for the LT. The experimental platform was guaranteed to run at the minimum of the HMD's frame rate (90Hz). The workspace for the experiment was $4m \times 4m$.

The VE was developed with Unity3D (version 2021.3.31f). The tracking system defined the reference coordinate system: the anteroposterior axis is referred to hereafter as the Z axis, the horizontal axis as the X axis, and the longitudinal as the Y axis. The VE was an infinite corridor where turns were generated in real-time as the user navigated Figure 1. To avoid linking different turns based on the anticipation of subsequent turns, we designed walls 3 meters high to block the view of the next turn, regardless of the user's height. This ensured no visual anticipation. We standardized the turn length across all conditions to eliminate bias and allow data comparison. A turn was defined as a 2-meter straight line before performing the turn. While rotation gain does not affect turn size, turn angle allows consistent turn length only in the corridor's middle. Therefore, we chose to maintain a consistent turn length in the middle of the corridor, and its dimensions were based on those of our research institute (1.5-meter width). In addition, textures have been added to the walls and floor to generate motion flow without any salient features.

3.3 Experimental Protocol

3.3.1 Locomotion Technique Design. The locomotion method used was torso steering, as it enables free head movements while navigating. The virtual movement was provided using the Valve Index controller's joystick, but the torso orientation defined the heading. The user moves according to the following control law when the joystick is pressed. Movement is initiated with an acceleration of $10m/s^2$ until a maximum tangential speed of $1m/s$ is reached, at which point the speed remains constant. If the joystick is released, a deceleration of $-10m/s^2$ is applied to reach a speed of $0m/s$ in approximately 0.30 seconds. The rotational gain is applied for torso and head rotation on the Y axis.

3.3.2 Procedure. Before starting the experiment, participants were briefed on the study (i.e., instructions and explanations about the task, including information about rotational gain), provided written consent, and completed a demographics questionnaire (covering age, gender, and experience to VR) as well as a Simulator Sickness Questionnaire (SSQ) [18]. Subsequently, participants were equipped with the necessary hardware and engaged in a training session to become familiar with the navigation task.

At the start of the trial, the users had to calibrate by aligning the direction of their head and torso with the Z axis and then pressing a button to start the trial. The users performed the navigation task by exploring the corridor with right and left turns of the same angle at regular intervals. After performing the 14 turns, the corridor disappeared, and the trial ended. Then, the users had to relocate to the center of the workspace physically. To not break the users' immersion and prevent users from taking off the HMD, the center of the workspace was represented by a black arrow in the virtual environment. After each trial, a new **Rotation Gain** and **Turn Angle** conditions were set for the next trial. After performing one block of 9 trials, a mandatory break of at least 5 minutes was done, where participants filled another SSQ. Users were allowed and encouraged to take breaks during the experiment between trials.

At the end of the experiment, participants filled out the last SSQ questionnaire. The experiment lasted approximately 45 minutes, including pauses, explanations, questionnaires, and the experimental protocol.

3.3.3 Data Collection. The data was collected relative to each turn. We recorded the users' position and orientation of the torso and the head in both RE and VE. We also recorded the user's instant rotation speed and the time since the start of the turn. In addition, 3 SSQs were conducted during the experiment (before starting, between the two blocks, and at the end of the experiment).

3.4 Data Processing and Analysis

All participants were able to finish the experiment except for two participants (one male and one female), whom we removed from the analysis, resulting in 19 participants (8 females). We removed each trial's first and last turn as we wanted to analyze UPD during continuous trajectories. We collected 171 trials, resulting in 2 052 turns (228 per **Rotation Gain** and **Turn Angle** combination). If there were no effects of turn direction (left versus right), we mirrored the trajectories for analyzing the dependent variables regardless of the turn direction, which was mostly the case except for the temporal analyses where we considered left and right turns separately. We defined a turn as the trajectory between two inflection points of the trial (i.e., until the users finished the straight trajectory after the turn). We resampled with 200 data points the position and orientations of the head and shoulders, then temporally normalized them. This number was set as the average number of data points encoding the turn during a trial. We recorded the time to perform the turn. UPD, recorded in meters, was defined as the physical displacement of the user in the workspace while navigating in the VE. We only focused on local analysis of the UPD (i.e., only analysis per turn and not an entire trial) as the task was nonecological; the observations between the UPD at the beginning and the end would not provide relevant information. We computed the relative UPD (i.e., the displacement between the beginning and the end of the turn) to assess whether **Rotation Gain** or **Turn Angle** could influence UPD towards a particular direction. Still, we also computed the norm of the UPD to assess whether users would have more physical movement after one turn. Regarding SSQ, we administer the Simulator Sickness Questionnaire (SSQ) before the experiment and after each block and compute a delta SSQ score for each scale and for each block (i.e., the first block score minus the pre-experiment score) to gain insights into cybersickness variations after each block.

For normally distributed metrics, assessed using the Shapiro-Wilk test, we analyzed variance (ANOVA) with repeated measures factors. Greenhouse-Geisser adjustments were applied to the degrees of freedom when the sphericity assumption was violated. For metrics that deviated from a normal distribution, we used the non-parametric Aligned Rank Transform (ART) test [44]. The post-hoc analysis involved pairwise t-tests with Bonferroni corrections for customarily distributed dependent variables or the multifactor contrast test procedure presented in [9] for the non-normally distributed ones. To evaluate the effects of **Rotation Gain** and **Turn Angle** on UPD over time, we used the Statistical Parametric Mapping (SPM) method [44]. This analysis facilitates the comparison of time-series data from different trials, accounting for variability at each time step. SSQ scores were analyzed with Friedman ANOVA with pairwise Wilcoxon post-hoc comparison with Bonferonni corrections.

3.5 Results

3.5.1 Performance. Regarding the time to perform a turn, we noticed a significant effect of **Turn Angle** ($F_{2,314} = 1193.35$, $p < 0.001$, $\eta_p^2 = 0.81$), where post-hoc tests showed that it took more time to perform the 120° turn (5.17±0.41) then the 90° (4.88±0.41) than the 60° one (4.55±0.32), ($p < 0.05$). Regarding angular speed, Figure 2-right shows the average angular speed profile per **Rotation Gain** and **Turn Angle** across time. SPM analyses did not reveal any effect of **Rotation Gain** and **Turn Angle** on the angular speed profiles, which enables us to exclude angular speed as a confounding factor for the UPD analyses.

3.5.2 SSQ. Table 1 reports the delta SSQ scores for each scale after each block concerning the baseline SSQ administrated at the beginning. We noticed that there was a significant effect of Block on the SSQ scores for the Nausea ($\chi^2(2) = 17.43$, $p < 0.001$), Oculomotor ($\chi^2(2) = 12.57$, $p < 0.001$), Disorientation ($\chi^2(2) = 17.61$, $p < 0.001$) and

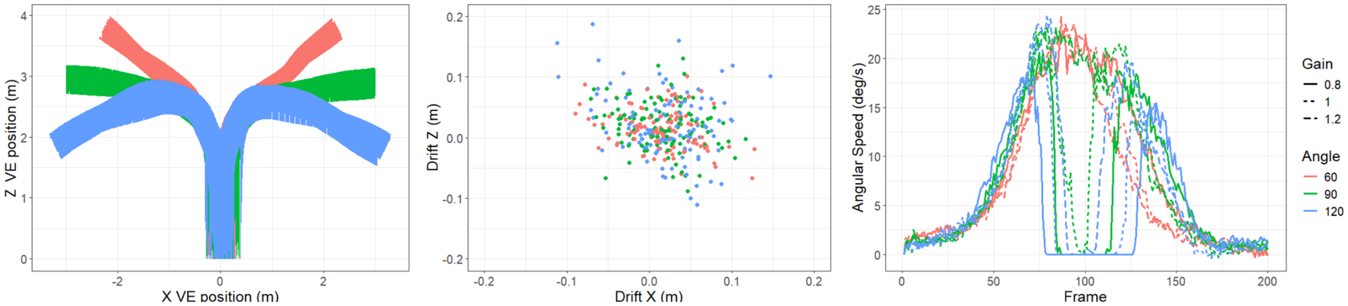

Figure 2: Left - Typical trajectories performed by one user grouped by Turn Angle. Center - Scatter plot of UPD at the end of one turn grouped by Turn Angle. Right - Angular speed profile per Rotation Gain and Turn Angle.

Total ($\chi^2(2) = 16.28$, $p < 0.001$) scales. Post-hoc tests showed that for each scale, the scores (referred in Table 1) from the second and third blocks were significantly higher than the first ($p < 0.05$), but not the scores between the second and third blocks, ($p > 0.05$).

Table 1: Delta SSQ scores per block for each scale.

Block	Nausea	Disorientation	Oculomotor	Total
1	6.7±12.96	9.81±11.29	5.73±12.11	9.02±12.75
2	25.25±37.85	20.51±17.93	34.39±36.86	29.26±30.59
3	33.11±40.21	27.64±23.04	44.21±49.27	38.50±38.13

3.5.3 UPD. Figure 2-left shows the turns performed by participants grouped by **Turn Angle**, and Figure 2-center shows the UPD at the end of a turn performed grouped by **Turn Angle**. There was a significant effect of **Rotation Gain** ($F_{2,314} = 6.26$, $p < 0.01$, $\eta_p^2 = 0.04$) and **Turn Angle** ($F_{2,314} = 49.36$, $p < 0.001$, $\eta_p^2 = 0.24$) on the norm of UPD (Figure 3). Post-hoc analysis revealed that the norm of UPD was the highest with a **Turn Angle** of 120° (0.12±0.06) than 90° (0.11±0.06) than 60° (0.09±0.05), ($p < 0.05$). Yet, we only noticed a significant difference between **Rotation Gain** where the norm of the UPD was higher with a gain of 0.8 (0.13±0.05) than 1.2 (0.11±0.04), and lower with a rotation gain of 1.2 (0.11±0.04) than 1 (0.12±0.05).

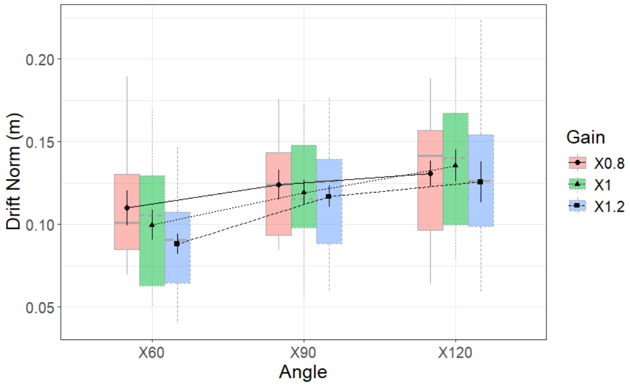

Figure 3: UPD norm (m) per Rotation Gain and Turn Angle.

Since we noticed that the SSQ scores were relatively high and that we had almost a balanced sample in terms of gender and experience with VR, we considered **Gender** (male, female) and **Experience** (score lower than 5 out of 10 (daily basis) on the demographics questionnaire regarding exposure to VR) and **SSQ** scores (by considering the median value of the total score scale, and sorting half of the sample below the median in the low SSQ group and the other half as high SSQ group) as a between-subject factor to investigate eventual UPD differences between those groups further. While we found no gender or VR experience effect, we noticed that there was a significant effect of **SSQ** on the UPD norm $F_{1,323} = 6.83$, $p < 0.01$, $\eta_p^2 = 0$. In particular, the high SSQ group got a higher UPD norm (0.14±0.06) than the low SSQ group (0.11±0.04).

Regarding SPM, Figure 4 shows average temporal drift profiles of every condition (**Rotation Gain** x **Turn Angle**) for each axis (X, Z) and turn direction (left, right). We noticed a significant interaction effect of **Rotation Gain** and **Turn Angle** UPD on the X axis during left turns. Still, post hoc analysis did not show any significant effect ($p > 0.05$). We notice a significant interaction effect of **Rotation Gain** and **Turn Angle** UPD on the X axis during right turns. Posthoc analysis showed a significant effect between (reported as **Turn Angle-Rotation Gain**: 60-0.8 × 90-1; 60-1 × 90-0.8; 60-1 × 120-0.8; 60-1.2 × 90-0.8; 60-1.2 × 120-0.8, ($p < 0.05$). We noticed a significant interaction effect of **Rotation Gain** and **Turn Angle** UPD on the Z axis during left turns. Still, post hoc analysis did not show any significant effect. We did not notice a significant effect of UPD on the Z axis during right turns, ($p < 0.05$).

3.6 Discussion

In this experiment, we focused on the influence of **Rotation Gain** and **Turn Angle** on UPD. While we considered relative UPD measures, we only found significant results on the norm of UPD that was, on average, about 10cm after a turn. As observed on Figure 2-center, we can observe that UPD occurs in most of the trials, ranging in a rectangle (5cm on the X and 10cm on the Z axis). Yet, it is difficult to understand clearly what leads to UPD precisely on each axis, considering the repetitiveness of movements that can compensate for each other (e.g., one turn will generate UPD towards a direction while another turn would generate UPD towards the opposite direction, resulting in resetting the user at the same position before initiating the turns).

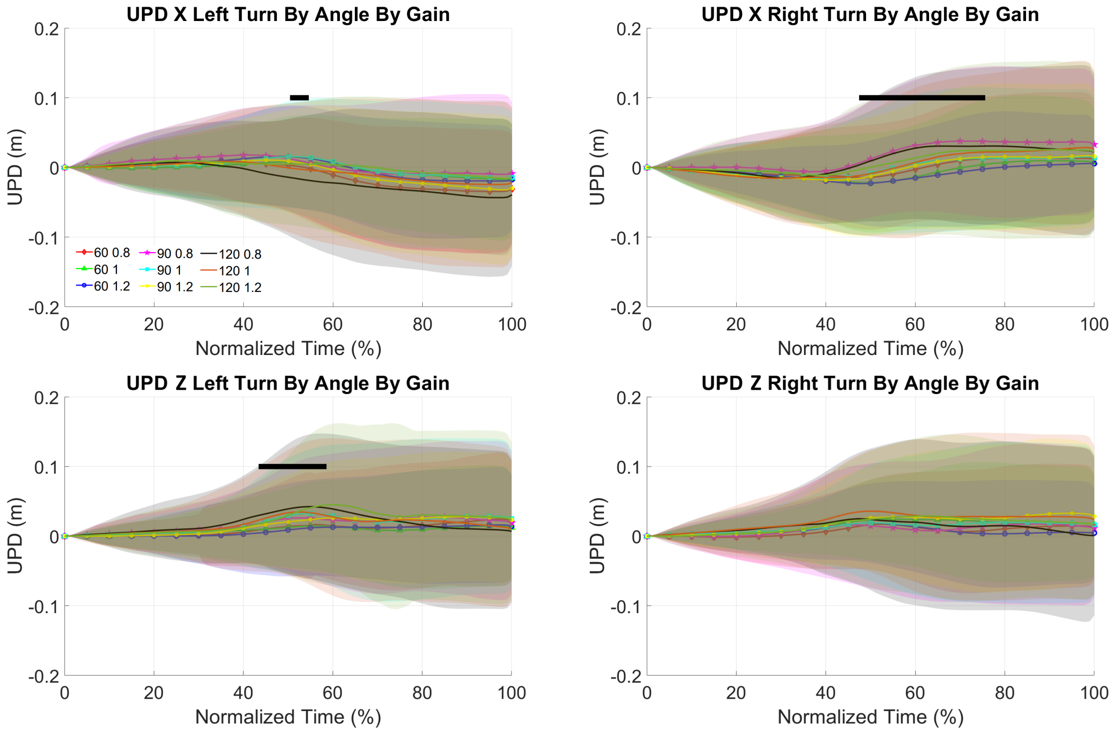

Figure 4: Average UPD profile per axis (X first line, Z second line) and turn (left column for left turns and right column for right turns). Each sample of the temporal sequence is a dependent variable. The black line represents the part where the variable has a significant effect, meaning that the F value for this sample is higher than the F* computed.

We observed an effect of **Rotation Gain** on the norm of UPD, where the lowest UPD occurred when the gain was 1.2. We did not observe a significant difference between 0.8 and the baseline (gain of 1), suggesting that the additional amount of rotation required when using a gain lower than one did not increase the UPD compared to the baseline (Figure 3. Even though the differences are pretty low (in the range of 1cm between **Rotation Gains**), it is worth noticing that an accumulation of several turns during a lengthy VR session could lead to a UPD of several dozens of centimeters, eventually reaching more than a meter, as already observed in previous work [19, 32]. We can partially confirm **[H1]**, and future work should deepen the understanding of the influence of **Rotation gain** on UPD.

We noticed higher differences in terms of UPD regarding **Turn Angle**, where the higher the turn angle, the higher the norm of the UPD, confirming **[H2]**. Performing turns with higher curvature requires better anticipation and speed adaptation. There exists a power law relationship between the curvature of the trajectory and the navigation speed [41]. However, our locomotion technique provided the constant speed used during our experiment. It may cause more UPD to correct the heading trajectory as participants had to regulate speed by releasing the controller's joystick.

Regarding **[H3]**, the absolute UPD after a turn did not reveal any interaction effects, but the temporal analysis with SPM did. As shown on Figure 4, there are some combinations of **Rotation Gain** x **Turn Angle** that yielded higher UPD during a right turn on the X axis. We can notice that the combination that resulted in the highest UPD for each turn on each axis always has either the lowest value of **Rotation Gain** or highest **Turn Angle**, and the lowest UPD profiles the highest value of **Rotation Gain** and lowest **Turn Angle**. Goal-directed locomotion can be characterized as a stereotypic task [14]: for a given initial and final position and orientation, participants walked in a very similar manner. This property was also demonstrated in VEs using different body-based steering techniques [6], suggesting common principles that govern the control of the trajectory. As observed on Figure 2-left, we can observe visually a similarity of trajectories across the different **Turn Angle**). Still, we could also suggest that the rotation gain provides some cognitive load that affects the motor awareness and the kinematics of the trajectory [17] and might be a factor that could increase or decrease UPD. These observations are consistent with what was observed with the absolute analysis of UPD in **[H1]** and **[H2]**, but are not sufficient enough to confirm **[H3]**.

Last, we observed an expected result where participants with higher cybersickness scores had higher UPD during the experiment. As rotation gain can generate cybersickness, and human factors can also influence the navigation experience, we could imagine that UPD is the result of a postural instability that could become a cybersickness predictor as already demonstrated for walking in VR [1].

4 USER STUDY 2 - SHORT-TERM EFFECT OF UPD IN ECOLOGICAL SETUP

Based on the results of the first user study, we wanted to conduct an exploratory study to investigate whether we could see an impact of **Rotation Gain** higher than one on more prolonged VR exposure during a more ecological task. The objective was to understand the potential benefits of rotation gains in addressing UPD issues.

4.1 Experimental Design and Hypotheses

Our experiment had a 2 **Rotation Gain** (1, 1.2) repeated measures within-subject design. Each **Rotation Gain** was tested twice and counterbalanced, resulting in 4 trials. A trial consisted of exploring an indoor VE that looked like a big office floor (100x100 meters) and gathering spheres randomly spread for three minutes (Figure 5). Similarly to the first user study, we hypothesized **[H4]** - **Rotation Gain** would decrease UPD compared to the baseline (no gain)´.

Figure 5: Top view of the user study's 2 VE. White spheres were procedurally generated.

4.2 Participants and Apparatus

An a priori power analysis was conducted using G*Power version 3.1.9.7 [11] to determine the minimum sample size required to test the study hypotheses. Results indicated the required sample size to achieve 80% power for detecting an extremly large effect, at a significance criterion of $\alpha = .05$, was N = 8 for within-subjects analyzes of variances with repeated measures. A total of 8 participants (4 females) aged from 21 to 40 years old ($M = 29.1$; $SD = 10.8$) participated in the experiment. Four participants had only one or no prior experience with VR, whereas four participants had regular experience with VR. They signed an informed consent form and were naive to the purpose of the experiment. The study conformed with the standards of the Declaration of Helsinki. We used the same apparatus for the first user study (one HMD, two trackers to track the torso, 4×4 workspace).

4.3 Experimental Protocol

We used the exact implementation for the gains and the locomotion technique (torso steering) as in the first user study. Before starting the experiment, participants were briefed on the study (i.e., instructions and explanations about the task, including information about rotational gain), provided written consent, and completed a demographics questionnaire (covering age, gender, and experience of VR). Subsequently, participants were equipped with the necessary hardware and engaged in a training session to become familiar with the navigation task. At the start of the trial, users placed themselves at the center of the workspace, aligning the direction of their head and torso with the Z axis and pressing a button to start the trial. The center of the workspace was represented by a black arrow in the virtual environment. Once users were at the center of the physical workspace, they were teleported at a random location in the VE, then they could freely navigate within the VR for three minutes. The task consisted of collecting as many spheres as possible by navigating through them. At the end of the trial, the users had to relocate to the center of the workspace physically. Users were allowed and encouraged to take breaks during the experiment between trials. The experiment lasted approximately 20 minutes, including pauses, explanations, questionnaires, and the experimental protocol.

4.4 Data Processing and Analysis

For each trial, we recorded the users' position and orientation of the torso and the head in both RE and VE. We collected 32 trials (16 per **Rotation Gain**). Since all the trials lasted the same amount of time, resampled at 72hz, the position and orientations of the head and shoulders were then temporally normalized. We used the same statistical analysis pipeline as in the first user study.

4.5 Results

Table 2 reports for each participant and conditions the average absolute UPD per axis (X, Z) as well as the UPD norm (i.e., distance from the center) at the end of the trial.

Table 2: Mean UPD on X, Z, and norm per User and Condition.

User ID	Condition	X	Z	Norm
1	N	0.37±0.10	0.61±0.17	0.38±0.04
1	G	0.46±0.15	0.76±0.01	0.52±0.34
2	N	0.23±0.21	0.86±0.95	1.03±0.75
2	G	1.49±0.81	0.96±0.07	1.49±0.52
3	N	0.56±0.13	0.73±0.18	0.40±0.17
3	G	1.24±0.45	0.92±0.23	0.84±0.52
4	N	0.90±0.16	0.85±0.40	1.04±0.01
4	G	1.15±0.49	0.70±0.01	0.84±0.52
5	N	0.60±0.03	0.72±0.03	0.41±0.04
5	G	0.63±0.35	0.76±0.10	0.51±0.22
6	N	1.35±0.07	0.97±0.06	0.91±0.21
6	G	1.17±0.57	1.16±0.56	0.86±0.62
7	N	0.73±0.10	1.07±0.36	1.13±0.29
7	G	0.48±0.20	0.65±0.50	0.53±0.42
8	N	0.84±0.15	0.41±0.06	0.52±0.02
8	G	0.77±0.30	1.25±0.51	1.23±0.32

Regarding statistical analysis, we did not find any effect of **Rotation Gain** on the relative drift on the minimal and maximal UPD Z axes and the UPD norm. Yet, we found an effect of **Rotation Gain** on the absolute UPD on the X axis ($F_{1,16} = 7.31$, $p < 0.05$,

$\eta_p^2=0.11$), where the presence of gain increased the drift (0.93±0.5) than without gain (0.70±0.35) (Figure 6).

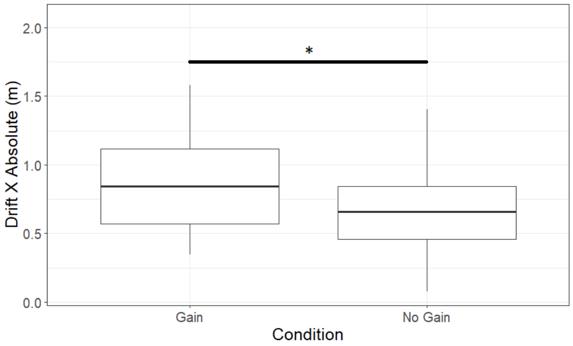

Figure 6: Absolute UPD on the X axis (m) per condition.

4.6 Discussion

The experimental results showed that UPD occurred in all participants after navigating freely for three minutes with a torso steering technique in VR (Table 2). Some participants were surprised to drift that much while using a technique that may not require walking. We also observed that the **Rotation Gain** can alter UPD during free navigation in VR, which contradicts the results from the first user study and thus rejects **[H4]**. We suggest that three mains reasons might explain those results.

First, the exposure time to the gain might be too short to be familiar with them. Some recent studies showed that inexperienced participants with VR became more sensitive to rotation gains after four weeks of VR exposure [35]. We may observe similar results if we asked participants to perform again the task across time, they may be more familiar with gain and then understand how to optimize their motion. In addition, we noticed that participants experienced the highest UPD during the second trial with gain, meaning that their first trial was without gain due to our counterbalanced design. This abrupt change may have influenced their navigation behavior, thus having a higher UPD with **Rotation Gain** than without. Second, the two tasks and trajectories performed were different: while the first study was achieved in a more controlled environment, participants could freely navigate and we could not control the way participants would turn (i.e., resulting in no constraints regarding angular speed or curvature of trajectories). By repeating similar turns in the first study as done in a similar experience (slalom turns) [5], rotation gains may have been more efficient to eventually mitigate UPD during a trial compared to a task that could not ensure repetition of trajectories.

Since UPD has never been assessed in the free ecological tasks, it is hard to compare our results to the literature, but we can observe that the drift on the Z axis is higher than the one observed in studies investigating UPD [4]. One reason could be that the task did not constrain the users regarding trajectories, leading to a UPD that is harder to model or generalize. It is worth noticing that we observed some participants stepping forward also to get faster due to the competitiveness of the task. While this approach is not a problem for navigating, the workspace limitations may prevent it.

5 GENERAL DISCUSSION

5.1 Influence of UPD on User Experience

On one hand, the accumulation of UPD can become problematic for safety purposes (reaching limits of the workspace or colliding with physical obstacles), but also user experience (resetting requires breaks in presence). Ignoring the side effects of UPD might not be ideal if we want to provide the best VR experience during navigation with virtual LTs. However, there may still be many factors that we are not aware of that could influence UPD. One exciting point our studies raised is the relation between cybersickness, rotation gains, turn angle, and UPD. Which came first? And how are they all connected? Previous research showed that UPD, using a constant navigation speed, increased once the trajectory curvature increased. Yet, we cannot conclude which one is at the origin of the other.

On the other hand, since UPD is an overlooked topic in the literature, does it mean it is worthless to address it? We could argue that we may not need to address UPD since most people in the second study remained in a 3x3 meters workspace. However, such dimensions are already above the minimum requirements of workspace size for room-scale VR applications using SteamVR (2x1.5m) or Meta Quest (2x2m). Thus, we could not have conducted the second user study with the minimum workspace requirement without interrupting the participant or using guardian methods. While we can report the UPD phenomenon on short-term interaction, we still struggle to provide general theories about UPD, and we might not be able to since the design space of factors and tasks to assess is too sparse. We suggest that one direction to take in investigating UPD in the future is to consider its long-term impact. For instance, the user might learn or be more aware of UPD over more prolonged exposure and thus change their motion to stay in the center of the workspace. Even though we could "train" users and raise awareness about UPD, the potential interaction between the usage of gain and cybersickness may prevent users from adapting their steering behavior to mitigate it.

Last, should we care about UPD when overt redirection techniques are one solution to mitigate it? We could ignore UPD and continue to design virtual LTs as it has been done over the last three decades. Still, the recent progress regarding simulation-based experiments might accelerate the research to understand why UPD occurs and how to solve it. So far, we can still argue that drifting a meter from the starting position after a short (three minutes) VR exposure can be problematic. As shown on Table 2, every user experienced UPD, which may affect a consequent sample of VR users. Most VR setups use a guardian system to keep users safe that breaks immersion. While this work does not provide a proof of concept idea of a subtle UPD-redirection controller as it has been done with RDW, we believe that the 1cm UPD per turn mitigated by using rotation gains of UPD could pave the way to find a better solution to solve UPD issues.

5.2 Workspace Optimization of VR setups

UPD was discovered more than ten years ago, but it only started to be addressed again in the past few years. While optimizing users' workspace is a trending topic in VR, it has been chiefly investigated for physical LTs [10, 48]. However, UPD is one constraint that prevents reducing users' workspaces, and solving UPD issues would help minimize users' workspaces, which would be considerable progress in VR research and improve VR experiences for mass consumers. Thus, issues with the standardization of evaluation methodology for virtual LTs, such as steering or teleportation, still have to be explored.

Rotation gains could be promising for optimizing users' workspace. Since physical movements are one of the sources of UPD, it seems intuitive first to aim at reducing the amount of physical movement to reduce UPD. Drift from the center of the workspace may increase over time, as well as the distance traveled in the virtual environment (VE). Compensating for this drift during navigation could help keep the user closer to the workspace center. A first naive approach would be to prevent high curvature turns during the application, but it constraints the design of the VR experience and is only task-specific. The second approach would rely on gain: our results from the first experiment suggest that compressing the natural motion is more efficient than compressing the virtual motion. Yet, our studies showed that rotation gains higher than one would help reduce UPD, while it was increasing during the second study, which makes the design of a generalized UPD-controller hard. We argue that rotation gains could be a promising approach to control participant orientation in the workspace and develop new heuristics for minimizing UPD during steering navigation.

Other approaches could be considered; in particular, we could imagine a virtual equivalent of the strafing gain recently introduced in [46] to reposition the user by influencing the heading direction or eliciting postural changes by applying gains on the pitch axis [27]. In addition, UPD might not be reduced by only considering motion perception and kinematics of human walking. Multi-sensory feedback combining visual and haptic cues that could provide subtle body reconfiguration might be a promising research avenue to investigate.

5.3 Limitations and Future Work

The analyses of **Rotation Gain** and **Turn Angle** provided exciting insights about how they could influence users' navigation in VR. However, future work should investigate additional research to address a few limitations in our current work. First, we are aware that numerous could be responsible for UPD. In particular, further user studies should consider how the implementation of virtual steering could alter UPD, including the heading (head versus torso versus hand steering) or the speed update (different transfer functions).

Second, future works must consider expanding the range of tasks and environments beyond repetitive turns. For instance, UPD is likely task-dependent, preventing our results from being generalized. UPD might be related to a higher cognitive load, and additional experiments could investigate it by considering tasks involving upper body part movements, like selecting and manipulating virtual objects. We are also aware that the sample size of our second user study is quite low, but was apriori enough to detect extremely large effect size. This study was mainly exploratory to provide a first insight and raise awareness about the impact of UPD in a more ecological setup, and more extensive experiment should be conducted to confirm our findings.

Last, the insights regarding the correlation between cybersickness and UPD should be considered, as we could not conclude whether cybersickness is the causation of UPD or vice versa. The long-term effects of UPD should be investigated, too. UPD might decrease over time based on experience or awareness of the phenomenon, and further studies considering the user adaption to UPD would help to understand how to mitigate UPD.

6 CONCLUSION

UPD has some significant practical implications, including breaks in the presence of reset mechanisms and potential safety issues from reaching the boundaries or obstacles in the workspace. Yet, the analysis of UPD in the literature is limited, in particular in finding the main reasons that such a phenomenon occurs. This paper addressed the impact of rotation gains on UPD while navigating VEs. This work aims to provide new insights regarding the little knowledge regarding UPD with LTs. However, this is only a tiny step toward the precise understanding of UPD, with limitations such as generalization to more prolonged VR exposure, consideration of different LTs, and potential human factors such as learning. This work opens new perspectives on understanding UPD and could help to propose UPD correction methods based on rotation gains without impacting the user experience.

REFERENCES

[1] Benjamin Arcioni, Stephen Palmisano, Deborah Apthorp, and Juno Kim. 2019. Postural stability predicts the likelihood of cybersickness in active HMD-based virtual reality. *Displays* 58 (2019), 3–11.

[2] Mahdi Azmandian, Timofey Grechkin, Mark T Bolas, and Evan A Suma. 2015. Physical Space Requirements for Redirected Walking: How Size and Shape Affect Performance.. In *ICAT-EGVE*. 93–100.

[3] Benjamin Bolte, Gerd Bruder, Frank Steinicke, Klaus Hinrichs, and Markus Lappe. 2010. Augmentation techniques for efficient exploration in head-mounted display environments. In *Proceedings of the 17th ACM Symposium on Virtual Reality Software and Technology*. 11–18.

[4] Hugo Brument, Gerd Bruder, Maud Marchal, Anne Helene Olivier, and Ferran Argelaguet. 2021. Understanding, modeling and simulating unintended positional drift during repetitive steering navigation tasks in virtual reality. *IEEE Transactions on Visualization and Computer Graphics* 27, 11 (2021), 4300–4310.

[5] Hugo Brument, Anne-Hélène Olivier, Maud Marchal, and Ferran Argelaguet. 2020. Does the control law matter? characterization and evaluation of control laws for virtual steering navigation. In *ICAT-EGVE 2020-International Conference on Artificial Reality and Telexistence & Eurographics Symposium on Virtual Environments*. 1–10.

[6] Hugo Brument, Iana Podkosova, Hannes Kaufmann, Anne Hélène Olivier, and Ferran Argelaguet. 2019. Virtual vs. physical navigation in vr: Study of gaze and body segments temporal reorientation behaviour. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 680–689.

[7] Gabriel Cirio, Maud Marchal, Tony Regia-Corte, and Anatole Lécuyer. 2009. The magic barrier tape: a novel metaphor for infinite navigation in virtual worlds with a restricted walking workspace. In *Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology*. 155–162.

[8] Ben J Congdon and Anthony Steed. 2019. Sensitivity to Rate of Change in Gains Applied by Redirected Walking. In *Proc. of the 25th ACM Symposium on Virtual Reality Software and Technology*. 3.

[9] Lisa A Elkin, Matthew Kay, James J Higgins, and Jacob O Wobbrock. 2021. An aligned rank transform procedure for multifactor contrast tests. In *The 34th annual ACM symposium on user interface software and technology*. 754–768.

[10] Linwei Fan, Huiyu Li, and Miaowen Shi. 2022. Redirected walking for exploring immersive virtual spaces with HMD: a comprehensive review and recent advances. *IEEE Transactions on Visualization and Computer Graphics* (2022).

[11] Franz Faul, Edgar Erdfelder, Albert-Georg Lang, and Axel Buchner. 2007. G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods* 39, 2 (2007), 175–191.

[12] Jana Franceska Funke, Anja Schikorr, Sukran Karaosmanoglu, Teresa Hirzle, Frank Steinicke, and Enrico Rukzio. 2023. Tiles to Move: Investigating Tile-Based Locomotion for Virtual Reality. *Proceedings of the ACM on Human-Computer Interaction* 7, CHI PLAY (2023), 1044–1067.

[13] Jeremy Hartmann, Christian Holz, Eyal Ofek, and Andrew D Wilson. 2019. Realitycheck: Blending virtual environments with situated physical reality. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*.

1–12.

[14] Halim Hicheur, Quang-Cuong Pham, Gustavo Arechavaleta, Jean-Paul Laumond, and Alain Berthoz. 2007. The formation of trajectories during goal-oriented locomotion in humans. I. A stereotyped behaviour. *European Journal of Neuroscience* 26, 8 (2007), 2376–2390.

[15] Julian Hildebrandt, Patric Schmitz, André Calero Valdez, Leif Kobbelt, and Martina Ziefle. 2018. Get well soon! human factors' influence on cybersickness after redirected walking exposure in virtual reality. In *International Conference on Virtual, Augmented and Mixed Reality*. Springer, 82–101.

[16] 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 *2007 IEEE Symposium on 3D User interfaces*. IEEE.

[17] Oliver Alan Kannape, Arnaud Barré, Kamiar Aminian, and Olaf Blanke. 2014. Cognitive loading affects motor awareness and movement kinematics but not locomotor trajectories during goal-directed walking in a virtual reality environment. *PloS one* 9, 1 (2014), e85560.

[18] Robert S. Kennedy, Norman E. Lane, Kevin S. Berbaum, and Michael G. Lilienthal. 1993. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology* 3, 3 (1993), 203–220.

[19] Donghyeon Kim, Hyeong-geon Kim, and Myungho Lee. 2021. Effects of User's Gaze on the Unintended Positional Drift in Walk-in-Place. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*. 1–2.

[20] Yong Min Kim, Yushin Lee, Ilsun Rhiu, and Myung Hwan Yun. 2021. Evaluation of locomotion methods in virtual reality navigation environments: An involuntary position shift and task performance. *International Journal of Human-Computer Studies* 155 (2021), 102691.

[21] Eike Langbehn, Paul Lubos, Gerd Bruder, and Frank Steinicke. 2017. Bending the curve: Sensitivity to bending of curved paths and application in room-scale vr. *IEEE transactions on visualization and computer graphics* 23, 4 (2017), 1389–1398.

[22] Eike Langbehn and Frank Steinicke. 2018. *Redirected Walking in Virtual Reality*. Springer International Publishing, Cham, 1–11.

[23] Joseph J LaViola Jr, Ernst Kruijff, Ryan P McMahan, Doug Bowman, and Ivan P Poupyrev. 2017. *3D user interfaces: theory and practice*. Addison-Wesley Professional.

[24] Roberto A Montano-Murillo, Patricia I Cornelio-Martinez, Sriram Subramanian, and Diego Martinez-Plasencia. 2019. Drift-correction techniques for scale-adaptive vr navigation. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 1123–1135.

[25] Christian T Neth, Jan L Souman, David Engel, Uwe Kloos, Heinrich H Bulthoff, 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.

[26] Thinh Nguyen-Vo, Bernhard E Riecke, Wolfgang Stuerzlinger, Duc-Minh Pham, and Ernst Kruijff. 2019. Naviboard and navichair: Limited translation combined with full rotation for efficient virtual locomotion. *IEEE transactions on visualization and computer graphics* 27, 1 (2019), 165–177.

[27] Tongyu Nie and Evan Suma Rosenberg. 2021. Redirected Tilting: Eliciting Postural Changes with a Rotational Self-Motion Illusion. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, 178–182.

[28] Niels Christian Nilsson, Tabitha Peck, Gerd Bruder, Eri Hodgson, Stefania Serafin, Mary Whitton, Frank Steinicke, and Evan Suma Rosenberg. 2018. 15 years of research on redirected walking in immersive virtual environments. *IEEE computer graphics and applications* 38, 2 (2018), 44–56.

[29] Niels Christian Nilsson, Stefania Serafin, Morten Laursen, Kasper Pedersen, Erik Sikström, and Rolf Nordahl. 2013. Tapping-in-place: Increasing the naturalness of immersive walking-in-place locomotion through novel gestural input. In *2013 IEEE symposium on 3D user interfaces (3DUI)*. IEEE, 31–38.

[30] Niels Christian Nilsson, Stefania Serafin, and Rolf Nordahl. 2013. The perceived naturalness of virtual locomotion methods devoid of explicit leg movements. In *Proceedings of Motion on Games*. 155–164.

[31] Niels Christian Nilsson, Stefania Serafin, and Rolf Nordahl. 2013. Unintended positional drift and its potential solutions. In *2013 IEEE Virtual Reality (VR)*. IEEE, 121–122.

[32] Niels Christian Nilsson, Stefania Serafin, and Rolf Nordahl. 2014. A comparison of different methods for reducing the unintended positional drift accompanying walking-in-place locomotion. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 103–110.

[33] Sharif Razzaque. 2005. *Redirected walking*. The University of North Carolina at Chapel Hill.

[34] Sharif Razzaque, Zachariah Kohn, and Mary C Whitton. 2001. *Redirected Walking*. Technical Report. Department of Computer Science, University of North Carolina, Chapel Hill, North Carolina, USA.

[35] Andrew Robb, Kristopher Kohm, and John Porter. 2022. Experience matters: Longitudinal changes in sensitivity to rotational gains in virtual reality. *ACM Transactions on Applied Perception* 19, 4 (2022), 1–18.

[36] Shyam Prathish Sargunam, Kasra Rahimi Moghadam, Mohamed Suhail, and Eric D Ragan. 2017. Guided head rotation and amplified head rotation: Evaluating semi-natural travel and viewing techniques in virtual reality. In *2017 IEEE Virtual Reality (VR)*. IEEE, 19–28.

[37] Shyam Prathish Sargunam, Kasra Rahimi Moghadam, Mohamed Suhail, and Eric D Ragan. 2017. Guided head rotation and amplified head rotation: Evaluating semi-natural travel and viewing techniques in virtual reality. In *2017 IEEE Virtual Reality (VR)*. IEEE, 19–28.

[38] Patric Schmitz, Julian Hildebrandt, André Calero Valdez, Leif Kobbelt, and Martina Ziefle. 2018. You spin my head right round: Threshold of limited immersion for rotation gains in redirected walking. *IEEE transactions on visualization and computer graphics* 24, 4 (2018), 1623–1632.

[39] Frank Steinicke, Gerd Bruder, Jason Jerald, Harald Frenz, and Markus Lappe. 2009. Estimation of detection thresholds for redirected walking techniques. *IEEE transactions on visualization and computer graphics* 16, 1 (2009), 17–27.

[40] Frank Steinicke, Yon Visell, Jennifer Campos, and Anatole Lécuyer. 2013. *Human walking in virtual environments*. Vol. 56. Springer.

[41] Stéphane Vieilledent, Yves Kerlirzin, Stéphane Dalbera, and Alain Berthoz. 2001. Relationship between velocity and curvature of a human locomotor trajectory. *Neuroscience letters* 305, 1 (2001), 65–69.

[42] Betsy Williams, Matthew McCaleb, Courtney Strachan, and Ye Zheng. 2013. Torso versus gaze direction to navigate a ve by walking in place. In *Proceedings of the ACM Symposium on applied perception*. 67–70.

[43] Betsy Williams, Gayathri Narasimham, Bjoern Rump, Timothy P McNamara, Thomas H Carr, John Rieser, and Bobby Bodenheimer. 2007. Exploring large virtual environments with an HMD when physical space is limited. In *Proceedings of the 4th symposium on Applied perception in graphics and visualization*. 41–48.

[44] Jacob O Wobbrock, Leah Findlater, Darren Gergle, and James J Higgins. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proc. of the ACM SIGCHI conference on human factors in computing systems*. 143–146.

[45] Dennis Wolf, Katja Rogers, Christoph Kunder, and Enrico Rukzio. 2020. Jumpvr: Jump-based locomotion augmentation for virtual reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12.

[46] Christopher You, Brett Benda, Evan Suma Rosenberg, Eric Ragan, Benjamin Lok, and Jerald Thomas. 2022. Strafing Gain: Redirecting Users One Diagonal Step at a Time. In *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 603–611.

[47] 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*. 71–74.

[48] Michael A Zmuda, Joshua L Wonser, Eric R Bachmann, and Eric Hodgson. 2013. Optimizing constrained-environment redirected walking instructions using search techniques. *IEEE transactions on visualization and computer graphics* 19, 11 (2013), 1872–1884.